A

Dissertation report

on

“FORWARD-REVERSE SUPPLY CHAIN NETWORK DESIGN AND PLANNING WITH EMBEDDED RISK OF FACILITY AND SUPPLY DISRUPTIONS”

by

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Submitted in fulfilment of the requirement for the award of the degree of

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CERTIFICATE

This is to certify that the dissertation report on the topic "**FORWARD-REVERSE SUPPLY CHAIN NETWORK DESIGN AND PLANNING WITH EMBEDDED RISK OF FACILITY AND SUPPLY DISRUPTIONS**" prepared by **KAPIL JAIN (ID: 2013PIE5199)** in the partial fulfillment for the award of degree of Master of Technology in **Industrial Engineering** Malaviya National Institute of Technology Jaipur is a bonafide compilation of the candidate's work based on published literature in the topic.

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Candidate's Declaration

I hereby certify that work which is being presented in the dissertation entitled "**FORWARD-REVERSE SUPPLY CHAIN NETWORK DESIGN AND PLANNING WITH EMBEDDED RISK OF FACILITY AND SUPPLY DISRUPTIONS"** in the partial fulfillment of requirement for award of the degree of Master of Technology (M. Tech.) in Industrial Engineering and submitted in Department of Mechanical Engineering of Malaviya National Institute of Technology Jaipur is an authentic record of my own work carried out during a period from July 2014 to June 2015 under the supervision of **Prof. A. P. S. Rathore**, Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur.

I have not submitted the matter embodied in this dissertation for the award of any other degree. As per the availability of free plagiarism checking online system by the online website "http:// plagiarism-detect.com', I further certified that the plagiarism content of this report is 4% .

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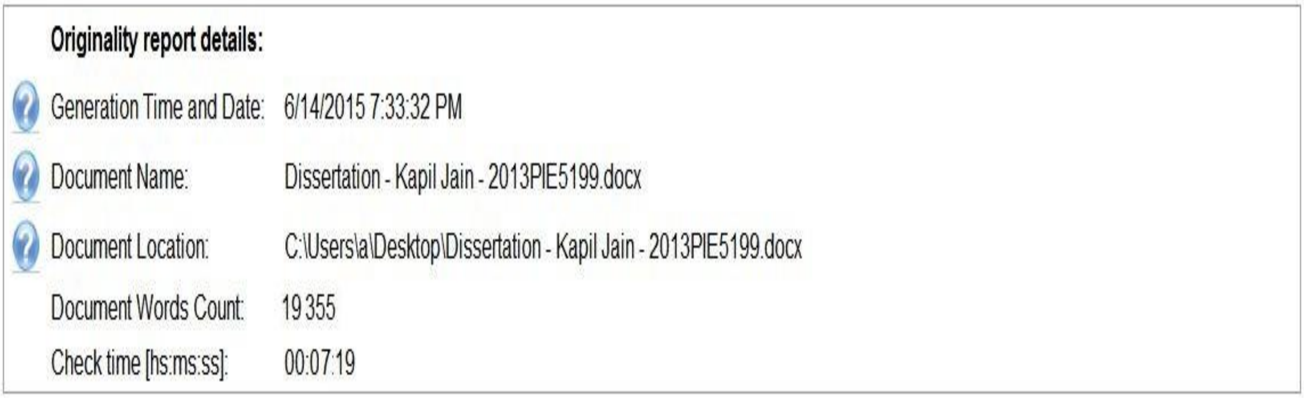

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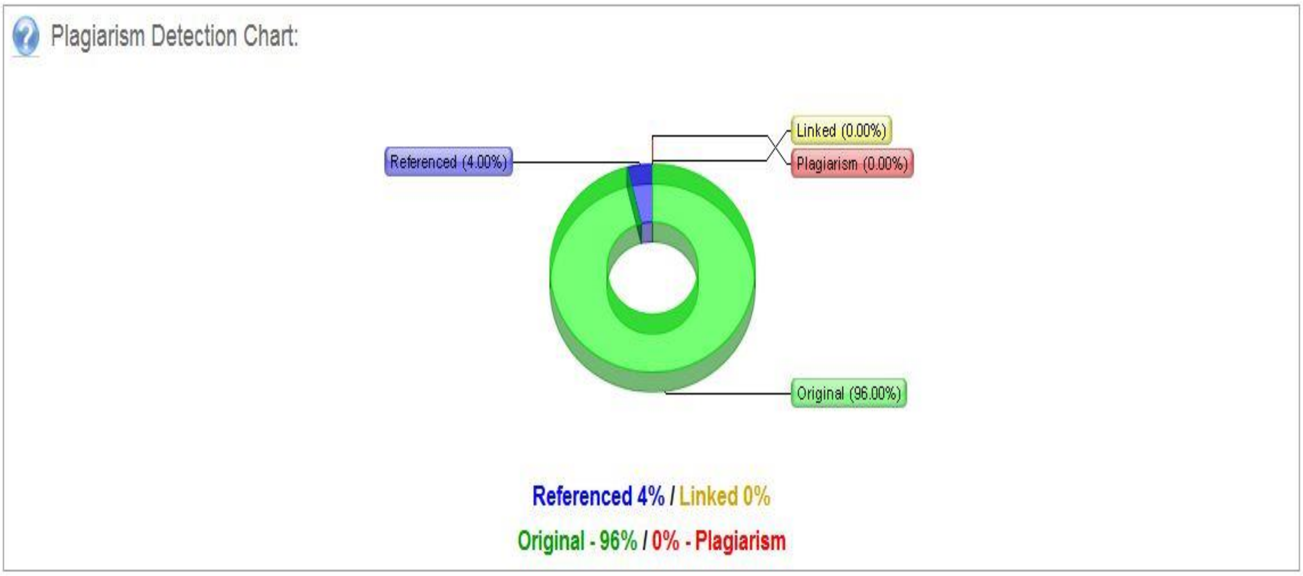

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Kapil Jain
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ABSTRACT

In today's business environment, supply chains become more complex and vulnerable. Supply chain disruptions now seem to occur more frequently and with more serious consequences. During and after supply chain disruptions, companies may lose revenue and incur high recovery costs. If supply chain managers were more capable of measuring and managing supply chain vulnerability, they could reduce the possible happening of disruptions and their impact. The process through which supply chain managers or firms take decisions to face risks, however, has not been explored much specifically strategic decisions. Despite the fact that past research highlighting the planning for certain risk events and parameters in detail, there is limited research that applies these views of risk in the literature for forward reverse supply chain network. This research addresses this gap by representations of risk and decision-making within the facility and supply disruption domain.

In this report, we designed a multi-echelon forward-reverse supply chain network incorporating a set of risk factors (such as-late shipment, quality problems, logistics and transportation breakdown, and production risks), probability of their occurrence and associated additional cost firm has to incorporate in an uncertain environment. The model includes a general network structure considering both forward and reverse processes that can be used in various industries, such as electronics, digital equipment, and vehicles. Four network sizes and number of different scenarios are considered to demonstrate the applicability of the model. Optimal decisions regarding the facility locations and inter-echelon product quantity flowing in the supply chain are optimized under select risk factors.

We test our model using four test problems with different sizes and for each size computations are performed. First, a deterministic mixed-integer linear programming model is developed for designing a closed-loop supply chain network. Then, risk of facility and supply disruptions are considered in the proposed mixed-integer linear programming model. Finally, these two methods are compared to evaluate the performance of model and managerial insights are drawn. The results of analysis shows that close loop supply chain could be made more resilient by considering risk factors that could prevent supply and quality failure and disruptions in the network.

CHAPTER-1 INTRODUCTION

In today's world, fast economic changes and the increasing pressure of market competition, lead firms to focus on supply chain. A supply chain is defined as a network of facilities that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and distribution of these products to customers (Ganeshan R., 1995). Similarly, it can be defined as the manufacturing supply chain, as an integrative approach used to manage the inter-related flows of products and information among suppliers, manufacturers, distributors, retailers and customers (Bhaskaran & Leung, 1997).

1.1 Supply chain network

A typical supply chain network comprises suppliers, production sites, storage facilities and customers. It involves two basic processes tightly integrated with each other: (i) The production planning and inventory control process, which deals with manufacturing, storage and their interfaces and (ii) The distribution and logistics process, which determines how products are retrieved and transported from the warehouse to retailers.

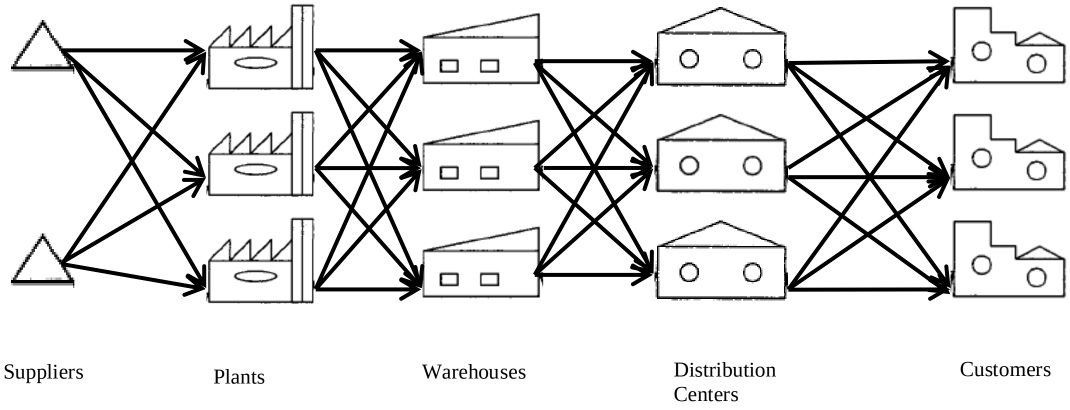


Figure 1.1 Typical supply chain network (Tsiakis, Shah, & Pantelides, 2001).

Suppliers are at the start of the supply chain network providing raw material to the manufacturers. Each manufacturer may have more than one supplier.

The manufacturing sites are multipurpose production plants where a wide range of products can be produced. The production capacity of each site is typically determined by the detailed scheduling of each plant.

Before being distributed to the customers, the final products from production plants are stored at two distinct stages in the supply chain network, namely, at major warehouses and at smaller distribution centers. Each warehouse may be supplying material to more than one manufacturing site. Similarly, a distribution center can have supply from more than one warehouse although, for

reasons of organizational simplicity (“single sourcing”), it is often the case that each distribution center is having its supply from only one warehouse. Both the material storage and handling capacities of warehouses and distribution centers are limited within certain bounds.
At the end of the supply chain network lie customers. Usually, each customer is linked to a single distribution center which in whole supplies all of the required material required by the customer, although this may not always be the case. Customers place their orders at distribution centers which passes this information to the higher levels until it reaches suppliers. Thus, the main feature of the supply chain network is the flow of material taking place from suppliers to customers and the counter flow of information from customers to suppliers. The places where inventory is kept in the supply chain network are called “echelons”. Usually the complexity of a supply chain network is related to the number of echelons that it incorporates.

The operation of supply chain networks is a complex task because of the large-scale physical production and distribution network flows, the risks associated with the external customer and supplier interfaces and the nonlinear dynamics associated with internal information flows. In a highly competitive environment, a supply chain network should be managed in the most efficient way, with the objectives of (i) minimization of costs, delivery delays, inventories and investment (ii) maximization of deliveries, profit, return on investment (ROI), customer service level and production.

The above tasks involve both strategic and operational decisions, with time horizons ranging from several years down to a few hours, respectively:

1. ***Location decisions*** consider the number, size and physical location of production plants, warehouses, and distribution centers.

2. ***Production decisions*** considering the products to be produced at each plant and also the allocation of suppliers to plants, of plants to distribution centers, and of distribution centers to customers. The detailed production scheduling at each plant must also be decided.

3. Inventory decisions are concerned with the management of the inventory levels.

4. Transportation decisions include the transportation media to be used for and the size of each shipment of material.

As supply chains network become increasingly global, additional aspects such as differences in tax regimes, duty drawback and avoidance, and fluctuations in exchange rates also become important (Vidal, 1997).

1.2 Close loop supply chain network

Now-a-days, resources and disposal capacities are limited; so recovery of used products is becoming important issue with increasing consumption and growing population. Waste reduction is becoming a major problem in industrialized countries, thus a concept of material cycles is gradually replacing a `one way' perception of economy. Increasingly, customers expect companies to minimize the environmental impact through their products and processes.

Moreover, legislation extending producer's responsibility has become an important element of public environmental policy. If we consider forward and reverse supply chains simultaneously, the result network will construct a closed-loop supply chain. Figure 1.2 illustrates a generic supply chain for both forward and reverse logistics. In figure, the classical (forward), and reverse supply chains are presented by solid lines and dashes respectively (Govindan, Soleimani, & Kannan, 2014).

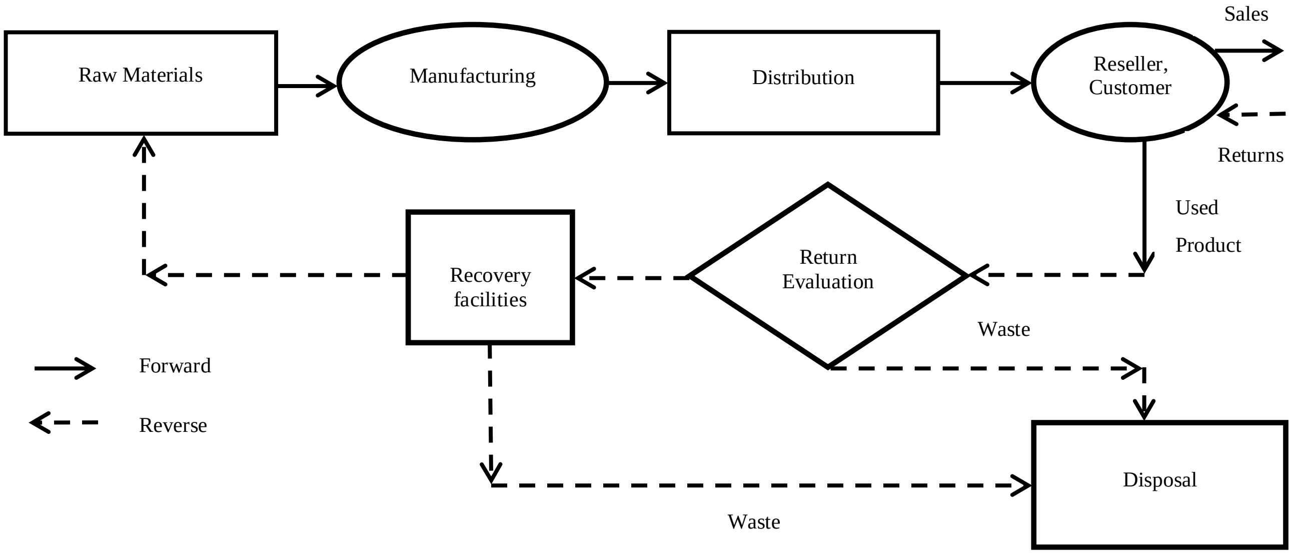


Figure 1.2 A generic form of forward/ reverse logistics (Tonanont, 2009)

Several countries, particularly in Europe, have introduced environmental legislation charging manufacturers with responsibility for the whole lifecycle of their products. Take back and recovery policies have been applied and also on going for a number of product categories, including electronic equipment, cars and packing. At the same time, companies are recognizing opportunities by combining environmental factors with financial benefits, by production cost savings and access to new market segments. It has seen an explosive growth of product recovery activities both in scope and scale. From a logistics perspective, product recovery starts additional goods flows from users to producers. The management of these flows is addressed as `Reverse Logistics'.

Reverse Logistics is "the process of planning, implementing, and controlling the efficient, effective inbound flow and storage of secondary goods and related information opposite to the traditional supply chain direction for the purpose of recovering value or proper disposal." Economic, marketing, and legislative motives are common drivers for companies to engage in Reverse Logistics.

First of all, `reverse' inbound flows may be economically attractive since used or returned products represent cheap resources from which value may be recovered. Recovery is often cheaper than building or buying new products materials. In view of low raw material prices, economic attractiveness often relies on the recovery of added manufacturing value rather than on mere material recovery.

Secondly, marketing triggers refer to the role of Reverse Logistics in improving a company's market position. On one hand, growing competition may force companies to take back and refund excess products from their customers. On the other hand, used product taken back and recovery is an important element for building up a `green' profile, on which companies are increasingly paying attention to. Today, most of the companies emphasize their reuse and recycling activities in environmental reports.

Thirdly, environmental regulation is another reason for Reverse Logistics that is of growing importance. Therefore, manufacturers are obliged to take back and recover their products after being used in order to reduce waste disposal volumes.

Fourthly, we mention asset protection as another motive for companies to take back their products after use. In this way, companies seek to prevent sensitive components from leaking to secondary markets or competitors. Moreover, potential competition between original `virgin' products and recovered products is avoided in this way.

Based on the above dimensions we can characterize a number of different categories of Reverse Logistics flows. We discussed reverse logistics as concerning the management of inbound flows of secondary goods opposite to the traditional supply chain direction.

Attention with reverse logistics networks has increased during the last decade since their economic impact has been increasingly important and as environmental legislation has been becoming strict. A multi-period multi-echelon forward–reverse logistics network design under risk model is developed (El-Sayed, Afia, & El-Kharbotly, 2010).

1.3 Supply chain risk

The multi-link feature of supply chain makes the supply chain vulnerable to affect of external environment and internal entity adverse factors and forms supply chain risk. Supply chain risk is a potential threat, which will use the vulnerability of the supply chain system, causing damage to the supply chain system. It can be said that supply chain risk is the possibility of the supply chain deviates from the intended target from the perspective of controlling objectives.

At present, there is no uniform definition of the supply chain risk, each researcher form a different distinguished angle and with its own point of view. Swedish scholar Svensson defined it as: The existence of random disturbances which can lead to bias between activities of parts and raw materials supply chain and the normal, expected or at planning time. All of these deviations in the supply chain have a negative impact on manufacturers and distributors (Göran Svensson, 2000).

Supply chain risk is the result of material flows through the supply chain, the production and circulation of large enterprise customers have commercial, logistics and the flow of information related to transportation, storage and handling, transport, packaging, distribution processing, distribution, information processing and so on the course, any one aspect of the problem would lead to the risk of the supply chain, affecting its normal operations.(1). There are environmental risks for supply chain and enterprises, which includes natural environment risks, such as natural disasters, social environment risks, such as terrorist incidents and crises; economic risks, such as depression and economic slide. (2). Supply chain risks still exists as a result of the uncertainty of market opportunities, but risks have been re-distributed in the supply chain partner enterprises. (3).Due to the instability and uncertainty of the supply chain partners, leading to greatly increased of risks in supply chain management.(4).Distrust and not standardized behaviour between inter-enterprises of supply chain partners brings information risk.(5). Supply chain is a dynamic alliance, partners are also competitors, and there are technical compatibility problems and leakage problems between each other. (6).The more complex is the supply chain, the higher is the risk degree.

The objective of supply chain risk management is to strengthen the supply chain enterprises to understand the risks information and communication. Through the analysis, recognition and measurement of potential accidents and loss, it averts risk by minimizing the cost and ensures the security, continuity and efficiency of the supply chain.

1.3.1 The source of supply chain risk

Supply chain risks occur because of many aspects, some of factors lie mainly in these areas: (1). Sole supplier problems. The sole supplier of supply chain makes huge risk to the chain. Take sole supplier policy and if one aspect has the problem, the whole chain will collapse. (2). Information technology constrains the role of the supply chain, such as network transmission speed, server stability and speed, software design error and so on. (3).The problem of transmitting information when the supply chain are increasing in scale and complex structure is becoming more prosperous, because of which supply chain information errors have taken place more and more. Information transmission delay will increase the risk of supply chain. (4).The issue of enterprise culture. Generally different corporates have their different corporate culture; it would lead to different views of the same problem, so there are differences that affect the stability of the supply chain. (5).The risk of economy fluctuations: Rapid economic growth easily leads to a shortage in enterprises supply of raw materials, affecting the normal production. Economic recession will increase domestic inventory costs. There are other unpredictable factors such as a small accident, the officers blocked, the suspension of the power failure, etc., Big factors are also affect the normal operation of the supply chain such as a political factor, war and so on. But the researchers believe that the supply chain risk is generally caused by the uncertainty. Its representation mainly in the following aspects show in Figure 1.3 below:

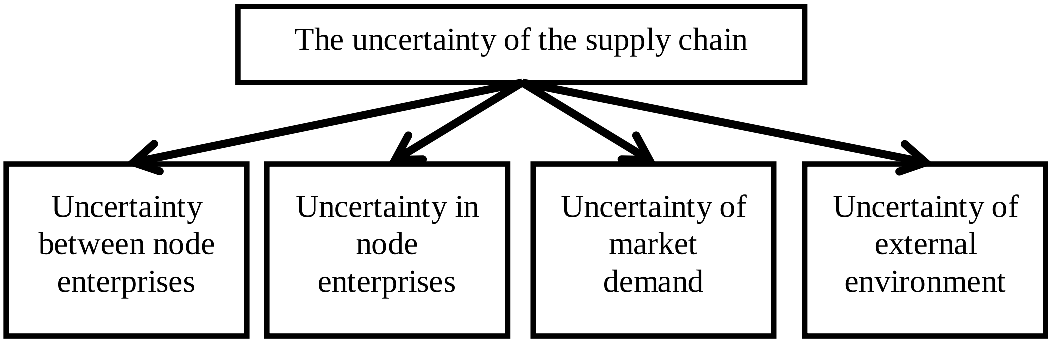


Figure 1.3 The uncertainty of supply chain (Qun, 2010).

There are a number of companies in the supply chain, which are independent economic entities. They have independent power in the operation and management activity. This situation to some extent increases the risk of uncertainty in the supply chain. This uncertainty usually from the following aspects (Feng, Jun-qi, & Dao-ming, 2010):

I. Uncertainty in node enterprises
II. The uncertainty of internal node enterprise
III. The uncertainty of market demand
IV. The uncertainty in the external environment

Supply chain risk prevention and countermeasures

The following points elaborate the prevention steps for supply chain risk and also display the counter-measuring technics (Qun, 2010).

Firstly, take fully account of the risk in supply chain design and construction.

Secondly, optimize partner selection and enhance communication and understanding among partners.

Thirdly, increase the supply chain transparency and strengthen information sharing.

Fourthly, speed information flow rate.

Fifthly, integrate supply chain process, and formulate contingency measures to deal with sudden incidents.

1.3.2 Supply chain uncertainty and modeling

In a global economy, the key to success greatly depends largely on effectively incorporating uncertainty in supply chain planning and decision making process. Most of the factors affecting the uncertainty of the supply chain network can be classified as either short-term fluctuations or long-term trends. To a certain extent, short-term fluctuations are captured implicitly in steadystate models such as deterministic modelling by averaging each flow in the network over a sufficiently long period of time. Considering the drawbacks of deterministic models in business success and continuity management in the present supply chain domain; researchers, academia and real world participants are encouraged to include uncertainty in supply chain coordination and planning in practice. On the other hand, taking into account long-term variations necessitates a more direct approach.

Most research on addressing uncertainty can be distinguished as two primary approaches, referred as the probabilistic approach and the scenario planning approach. The choice of the appropriate method is context-dependent, with no single theory being sufficient to model all kinds of uncertainty.

Probabilistic models consider the uncertainty aspects of the supply chain treating one or more parameters as random variables with known probability distributions. On the other hand, scenario planning attempts to capture uncertainty by representing it in terms of a moderate number of discrete realizations of the stochastic quantities, constituting distinct scenarios. Each complete realization of all uncertain parameters gives rise to a scenario. The objective is to find robust solutions which perform well under all scenarios. In some applications, scenario planning replaces forecasting as a way of taking into account potential changes and trends in a business environment. These are various common approaches to robust optimization seeking, for example, to optimize the expected performance over all scenarios, to optimize the worst-case scenario or to minimize the expected or worst-case “regret” across all scenarios.

Scenario approach used to decide on the design of a production and distribution network that operates under varying exchange rates. A number of scenarios for different exchange rates aim to determine the production policy of the company, which operates in more than two countries. One important issue that arises in the context of the scenario planning approach is the increase in computational complexity as the number of scenarios increases. One of the most popular and widely used techniques for planning under uncertainty is two-stage stochastic programming. In this approach, the decision variables are classified into two sets. The variables which are made prior to resolution of uncertainty are termed as first-stage variables or design variables (`here-and-now` decisions). Based on here-and-now decisions and the realization of the random events, the second stage or control variables are made to optimize in an uncertain environment. This is termed as `wait-and-see decision and reflects the way a decision maker adapts/responses to the unfolding uncertainty. The uncertainty is expressed as a stochastic nature of the costs related to second stage variable. Therefore, the objective function consists of the sum of first stage cost and the expected value of the second stage cost. A heuristic approach is also proposed for handling very large numbers of scenarios (Zimmermann, 2000).

In view of the above, it can be seen that large-scale networks are subject to numerous strategic and operational risks that hinder the smooth operation among different tiers of the forward reverse supply chain network. In this work, we have attempted to model the behaviour of a forward reverse supply chain network in a multi-criteria decision-making environment and have identified the different level of risks and their effects on the supply chain operation, with the objective of minimizing the total cost of operation.

1.5 Objective of dissertation

The key objectives of the dissertation are given below:

- To take strategic and operational decisions that the expected total cost of operating the forward reverse supply chain network is minimized.
- To model the behaviour of global supply chain networks in multi-criteria decision-making environments, and identify different levels of risk and their effect on the forward reverse supply chain network operation, with the objective of minimising the total cost of operation.

1.6 Outline of dissertation

The thesis is organized in six chapters.

The current chapter 1 introduces the thesis and emphasizes the need of conducting this research work. This chapter also identifies the aim and objective of the study.

Chapter 2 presents a critical review of past work on supply chain modeling and design. It first represents the distribution of literature across various journals and then literature review has been classified mainly into two areas. These areas are based on literature available on supply chain risk management and mathematical modelling with embedded risks.

Chapter 3 consists of the problem of optimal design of supply chains is formulated as a mixed-integer linear programming (MILP) model. It presents deterministic modelling of forward reverse supply chain network.

Chapter 4 extends this formulation to take into account the risk in designed forward reverse supply chain network. It presents a mathematical modelling of supply chain network with embedded risk of facility and supply disruptions.

Chapter 5 presents modeling results achieved and discusses insights about the work.

Chapter 6 finally concludes the whole work. Also shows scope for future work.

CHAPTER- 2 LITERATURE REVIEW

The matter of the literature review and the unit of analysis are detailed in this chapter. The study was conducted from July 2014-April 2015 covering the accepted papers (available online) in scientific English language journals from January 2010-April 2015. The search procedure was managed in three stages with the ‘‘supply chain risk’’, “supply chain risk management” and “mathematical modeling approaches of supply chain risk” keywords in the Google-scholar search engine (www.scholar.google.com) with these modifications: searching for articles in English language, and custom time range between 2010 and 2015, sorted by relevance. It should be mentioned that the search engine is updated periodically due to the acquisition of new publications, relevance, citations and so forth. So the process of collecting papers is undertaken in a short period of time. The three stages of the research procedure are as follows:

- In the initial search stage from Google Scholar, 10 pages of search results out of 100 papers from various publishers were obtained. The list includes work from Elsevier (www.sciencedirect.com), Emerald (www.emeraldinsight.com), Springer (www.springerlink.com), Taylor & Francis (www.tandf.co.uk/journals/), Wiley (http://www.wiley.com) and IEEE (ieeexplore.org). The related papers in the fields of supply chain risk and mathematical modeling are selected and reviewed.
- In the second stage, to ensure coverage of recent publications, the same search is run to locate papers published in 2015 with the same keywords. At this stage, 22 new papers are considered and related papers, which belong to previously mentioned publishers (related to scope of this research), are selected and reviewed.
- Thirdly, papers selected in the first two stages are cross-checked with results of the same keywords in Web of Science (WOS) database to ensure the reliability of the process of finding and selecting papers. In the evaluation process of selecting related state-of-the-art papers in this area of study, all collected papers in the first two phases are considered. At the conclusion of this stage, the most appropriate papers are selected based on the relevance of subjects (the papers which present a topic in supply chain risk and mathematical modeling and not just mention similar keywords in non-related topics), rank of journals (there are some papers in local journals, which they cannot count on an international level), and citations (in few cases, there are some papers with high citations in low-level journals, which we considered them in final list). Then, the rest are selected to review and analyze in this study.

Finally, 78 papers are reviewed and classified in the literature review study. They are reviewed and their differing characteristics are distinguished and recorded in a prepared spreadsheet to be analyzed holistically. This study attempts to analyse 78 scientific papers published between 2010 and 2015 as illustrated in Figure 2.1.

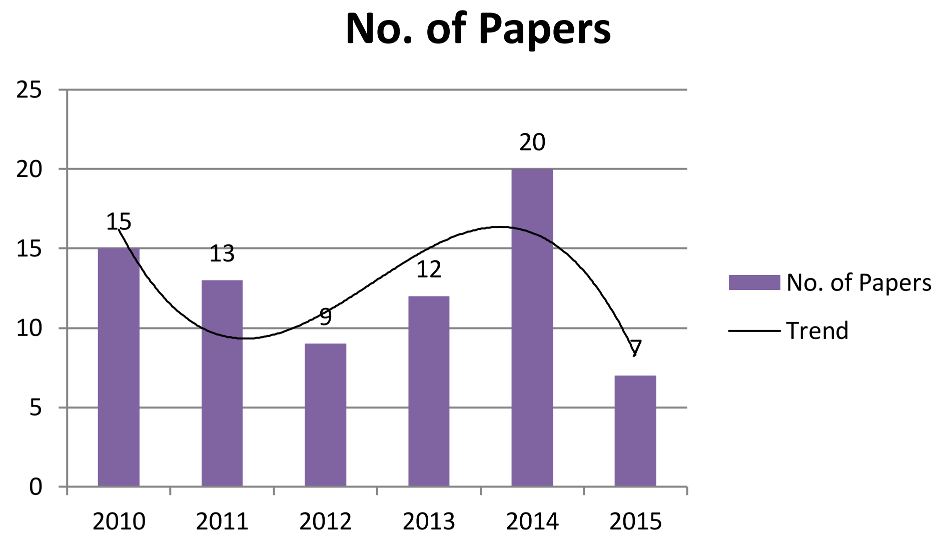


Figure 2.1 Distribution of publications per year across the period of the study (78 papers: 2010–2015).

The distribution of journals in which the selected papers are published indicates the desires of different journals in supply chain risk management and mathematical modeling. The publications and distribution of the journals are presented in Table 2.1 and Fig. 2.2.

Table 2.1 Distribution of literature based on the source of publication

S. No.	**Publications**	**Years**						**Total**
		2010	**2011**	**2012**	**2013**	**2014**	**2015**	
1	Industrial Management & Data Systems	--	--	01	--	--	--	01
2	Journal of Modelling in Management	--	--	--	01	--	--	01
3	Industrial Management & Data Systems	--	--	--	--	01	--	01
4	Supply Chain Management: An International Journal	--	02	--	--	01	--	03
5	Kybernetes	01	--	--	--	--	--	01
6	International Journal of Physical Distribution & Logistics Management	--	02	01	--	01	--	04
7	Benchmarking: An International Journal	--	--	--	01	--	--	01
8	Journal of Manufacturing Technology Management	--	--	--	01	01	--	02
9	International Journal of Operations & Production Management	--	--	--	--	01	--	01
10	Journal of Advances in Management Research	--	--	--	--	01	--	01
11	Control and Decision Conference	--	--	01	--	--	--	01
12	Management and Service Science	01	--	--	--	--	--	01
13	International Conference on E-business and Information System Security	01	--	--	--	--	--	01
14	Management of e-Commerce and e-Government	01	--	--	--	--	--	01
15	Management of Innovation and Technology	--	--	--	--	01	--	01
16	Industrial Engineering and Engineering Management	--	--	--	01	--	--	01
17	Mechatronics and Automation	--	--	--	01	--	--	01

18	Int. J. Production Economics	02	04	02	02	01	02	13
19	Computers & Industrial Engineering	--	--	--	01	02	01	04
20	Computers and Chemical Engineering	01	--	--	--	--	--	01
21	Scientia Iranica Transactions E: Industrial Engineering	--	01	--	--	--	--	01
22	Journal of Manufacturing Systems	--	--	--	--	01	--	01
23	Journal of applied research and technology	--	--	--	--	01	--	01
24	Journal of Operations Management	--	--	--	01	--	01	02
25	Engineering Applications of Artificial Intelligence	--	--	--	--	01	--	01
26	Expert Systems with Applications	--	--	--	--	--	01	01
27	OPEMAN	--	--	--	--	--	01	01
28	Proceedings	--	--	--	--	01	--	01
29	OR spectrum	01	--	--	--	--	--	01
30	Logistics Research	01	--	--	--	--	--	01
31	Computational Management Science	01	--	--	--	--	--	01
32	International Journal of Advanced Manufacturing Technology	--	--	02	--	--	--	02
33	Annals of Operations Research	--	--	--	01	--	--	01
34	International Journal of Production Research	02	02	--	02	--	01	07
35	Journal of Statistics and Management Systems	01	--	--	--	--	--	01
36	Journal of Risk Research	--	--	01	--	01	--	02
37	Journal of Industrial & Production Engineering	--	--	--	--	01	--	01
38	Journal of Business Logistics	01	01	--	--	01	--	03
39	Production and Operations Management	--	01	01	--	--	--	02
40	Decision Sciences	01	--	--	--	02	--	03
41	Systems Research and Behavioural Science	--	--	--	--	01	--	01
	Total	15	13	9	12	20	7	**78**

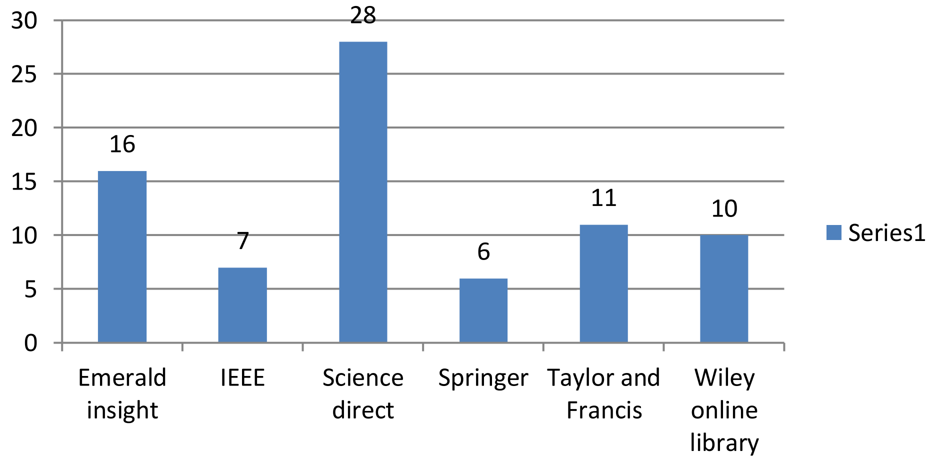


Figure 2.2 Distribution of publications based on different publishers (78 papers: 2010–2015).

Reviewing Table 2.1 and Figure 2.2 reveals that the subjects of supply chain risk and modeling approaches are considered by many journals. We have reviewed 41 journals in 6 publications. The list of papers in this category is illustrated in references. Now, our thesis work can be categorized in two sections which are discussed below.

2.1 Literature review of supply chain risk

Collected papers related to supply chain risk fall in this section. They are also classified here on the basis of 6 publishers and represented by pie chart for more clarity.

Table 2.2 Distribution of papers based on different publisher (37 papers: 2010–2015).

S. No.	Publisher name	Journal name	No of papers
1	Emerald insight	Supply Chain Mngmnt: An Int. J.	02
		Kybernetes	01
		Int. J. of Physical Distribution & Logistics Mgmnt	04
		Benchmarking: An Int. J.	01
		J. of Manufacturing Technology Management	02
		Int. J. of Opers & Prod. Mgmnt	01
		J. of Advances in Management Research	01
2	IEEE	Control and Decision Conference	01
		Management and Service Science	01
		Int. Conference on E-business and Information System Security	01
		Management of e-Commerce and e-Government	01
3	Science direct	Int. J. Production Economics	06
		Journal of Operations Management	02
		Computers & Industrial Engineering	01
		Journal of applied research and technology	01
		OPEMAN	01
4	Springer	OR spectrum	01
		Logistics Research	01
5	Taylor and Francis	J. of Risk Research	02
		J. of Industrial and Production Engineering	01
		Int J of Prod. Research	01
6	Wiley online library	J. of Business Logistics	02
		Prod. And Oper. Management	02

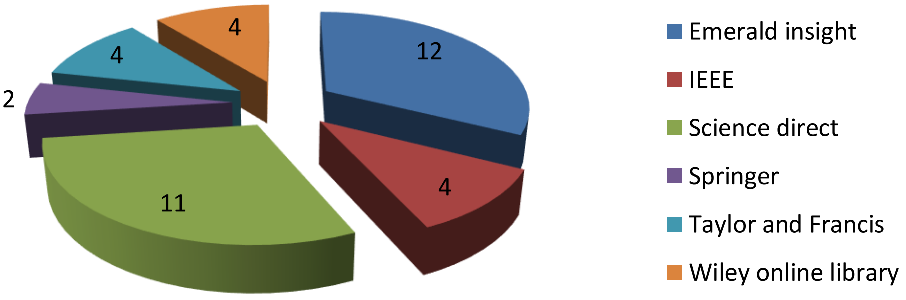


Figure 2.3 pie chart representation of distribution of papers based on six publishers (37 papers: 2010–2015).

Tummala & Schoenherr (2011) proposed a comprehensive and coherent approach for managing risks in supply chains. Vilko, Ritala, & Edelmann (2014) proposed a conceptual framework for assessing the levels and nature of uncertainty in this context. Tang & Nurmaya Musa (2011) investigated the research development in supply chain risk management (SCRM), which has shown an increasing global attention in recent years. Bode & Wagner (2011) addressed this issue with a specific focus on upstream (supply-side) supply chain disruptions. Jüttner & Maklan (2011) identified and explored empirically its relationship with the related concepts of supply chain vulnerability (SCV) and supply chain risk management (SCRM). Ma, Chen, Meng, & Yi (2014) studied the problem of disruption risk control of supply chain under the background of globalization. Punniyamoorthy, Thamaraiselvan, & Manikandan (2013) provided a reliable and accurate instrument to assess the supply chain risk of similar comparable industries. Schmitt & Singh (2012) focused on risk from both supply disruptions and demand uncertainty and compare their impacts and mitigating strategies. Ghadge, Dani, & Kalawsky (2012) identify important strategic changes in the field and to outline future requirements and research opportunities in SCRM. Manuj, Esper, & Stank (2014) investigated the effectiveness of different supply chain risk management approaches by examining how performance varies when these approaches are applied under different risk conditions.

Hao (2010) used system analysis method to study the five aspects of supply chain risk, such as supply risk, demand risk, market risk, production risk and the conventional risk caused by emergencies. Kumar Pradhan & Routroy (2014) identified, analysed, assessed and managed the risks issues involved in an Indian manufacturing supply chain. Yoo (2014) reviewed and synthesized the extant literature in SCRM in the past decade in a comprehensive manner and detailed review associated with research developments in supply chain risk definitions, risk types, risk factors and risk management/mitigation strategies. Jayaram, Dixit, & Motwani (2014) explored the relationships that “family-business” characteristics has on supply chain management capabilities of small and medium sized family businesses (SMFBs) in the Indian context. S. Kumar, J. Himes, & P. Kritzer (2014) provided the organization with a process for assessing risk associated with their supply chain and a framework from which they can build their strategy to manage risk. Blackhurst, Dunn, & Craighead (2011) use systems theory and the resource-based view of the firm as the theoretical underpinnings, their study provides an in-depth systematic investigation of supply resiliency.

Thun & Hoenig (2011) identified supply chain risks by analysing their likelihood to occur and their potential impact on the supply chain. The results are visualized in the probability-impact-matrix distinguishing between internal and external supply chain risks. Pfohl, Gallus, & Thomas (2011) demonstrated how interpretive structural modelling (ISM) supports risk managers in identifying and understanding interdependencies among supply chain risks on different levels. Christopher & Holweg (2011) establish control of the end-to-end process in order to create a seamless flow of goods. The basic idea is that variability is detrimental to performance as it causes cost in the form of stock-outs, poor capacity utilisation, and costly buffers. Their paper questions this approach and argues that in the light of increasing turbulence a different approach to supply chain management is needed. Sodhi, Son, & Tang (2012) characterize the diversity in terms of three “gaps”: a definition gap in how researchers define SCRM, a process gap in terms of inadequate coverage of response to risk incidents, and a methodology gap in terms of inadequate use of empirical methods. They also list ways to close these gaps as suggested by the researchers. Blome & Schoenherr (2011) investigated successful approaches and experiences by companies in dealing with new reality, especially as it concerns the supply side. They developed a set of propositions about how companies manage supply risks in financial crises, highlight how their risk management approaches have shifted, and illustrate how they are related to Enterprise Risk Management.

Peiying, Jiafa, & Chongjun (2012) developed a comprehensive quantitative risk evaluation and mitigation model in global supply chains is which from several disciplines – supply chain management, logistics, economics and international business. A case study is provided which in view of a company whose products are manufactured in China and sold in U.S. They identified four risks including supply risk, operational risk, demand risk and financial risk and modelled as probabilistic distributions of the outcome. Cagliano, De Marco, Grimaldi, & Rafele (2012) performed process analysis by means of the standard framework provided by the Supply Chain Operations Reference Model, the risk identification and analysis tasks are accomplished by applying the Risk Breakdown Structure and the Risk Breakdown Matrix, and the effects of risk occurrence on activities are assessed by indicators that are already measured by companies in order to monitor their performances. Tazelaar & Snijders (2013) considered the "process-performance paradox" in the assessment of operational risks by professionals in the field of operations and supply chain management (OSCM). Wieland (2013) proposed a model that enabled a company to select the supply chain strategy based on risk probability *p* (measure of how likely/often a detrimental event occurs) and risk impact *i* (expression of the significance of a loss when that event occurs).

Rotaru, Wilkin, & Ceglowski (2014) explored the coverage and integration of supply chain risk management (SCRM) within SCOR, the analysis and suggested improvements for SCRM are designed to enhance SCOR's collaborative and coordinated management of supply chain (SC) risks. Ceryno, Scavarda, & Klingebiel (2014) identified the main risks along the automotive supply chain by investigating their manifestation in three supply chains in Brazil and offer an initial risk profile for the Brazilian automotive industry. U. Soni, Jain, & Kumar (2014) proposed method could simplify the dynamic nature of environment for managing disruptions in a supply chain. Their novel approach for determining the supply chain resilience index (SCRI) advocates the consideration of resilience aspects in supply chain design, thus giving a competitive advantage to achieve market share even during a disruption. Avelar-Sosa, García-Alcaraz, & Castrellón-Torres (2014) proposed a structural equation model to assess the effects of some risk factors in the supply chain performance. Their model includes demand, suppliers and processes as risk factors. Ambulkar, Blackhurst, & Grawe (2015) operationalized firm resilience to understand how supply chain disruption orientated firms can develop resilience to supply chain disruptions. The way in which supply chain disruption oriented firms develop resilience through resource reconfiguration or risk management infrastructure depends on the context of the disruption as high impact or low impact. Wiengarten & Humphreys (2015) applied the relational view and through cross-country survey and secondary country data. They explored differences in supply chain integration efficacy based on the risk of conducting business (measured in terms of the strength of a country's rule of law) and the mitigating effect of supply chain risk management practices.

Review shows that our attentions on the absolute swings in uncertain parameters, which are important in the impact they have on business generally, but we often neglect the much more critical rate of change, which has increased in recent years.

As supply chains are extended by outsourcing and stretched by globalization, disruption risks and lack of visibility into a supplier's status can both worsen. The possible causes of product quality problem is poor material from supplier, non-conformance in coming inspection in manufacturer, product contaminated or damaged during logistics operations. Some researches focused on contract designing issue for obtaining the equilibrium outcome that the penalty clauses are adopted as recover damage in non-delivery. In the next section, we are discussing about the supply chain modeling approaches for forward-reverse supply chain risk.

2.2 Literature review of mathematical modelling approaches of supply chain risk

Collected papers related to supply chain risk fall in this section. They are also classified here on the basis of 6 publishers and represented by pie chart for making more clarity.

Table 2.3 Distribution of papers based on different publisher (41 papers: 2010–2015).

S. No.	Publisher name	Journal name	No of papers
1	Emerald insight	Ind. Mngmnt & Data Systems	02
		J. of Modelling in Management	01
		Supply Chain Mngmnt: An Int. J.	01
2	IEEE	Mngmnt of Innovation and Tech.	01
		Ind. Engg and Engg Mngmnt	01
		Mechatronics and Automation	01
3	Science direct	Int. J. Production Economics	07
		Computers & Industrial Engineering	04
		Computers and Chemical Engineering	01
		Scientia Iranica Transactions E: Industrial Engineering	01
		Journal of Manufacturing Systems	01
		Engineering Applications of Artificial Intelligence	01
		Expert Systems with Applications	01
4	Springer	Proceedings	01
		Computational Mngmnt Science	01
		Int. J. of Advanced Manufacturing Tech.	02
		Annals of Operations Research	01
5	Taylor and Francis	Int. J. of Production Research	06
		J. of Statistics and Management Systems	01
6	Wiley online library	J. of Business Logistics	02
		Decision Sciences	03
		Systems Research and Behavioural Science	01

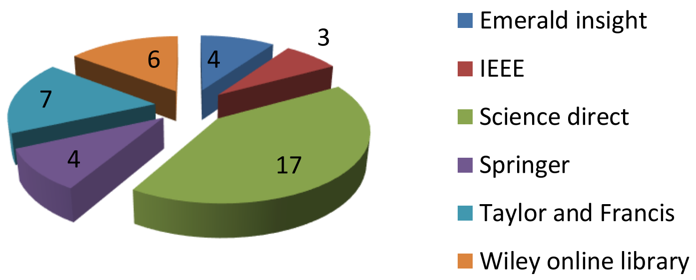


Figure 2.4 pie chart representation of distribution of papers based on six publishers (41 papers: 2010–2015).

Considering a broad spectrum of the supply chain concept, there may be various classification schemes to categorize supply chain models. To minimize confusion, we first show developed classification the mathematical models: deterministic and stochastic. Some supply chain models based on inventory theory and simulation contain both deterministic and stochastic elements and consequently should be treated as hybrids. Therefore, we added a hybrid model to the category. Another category called 'IT-driven models' was added to the classification.

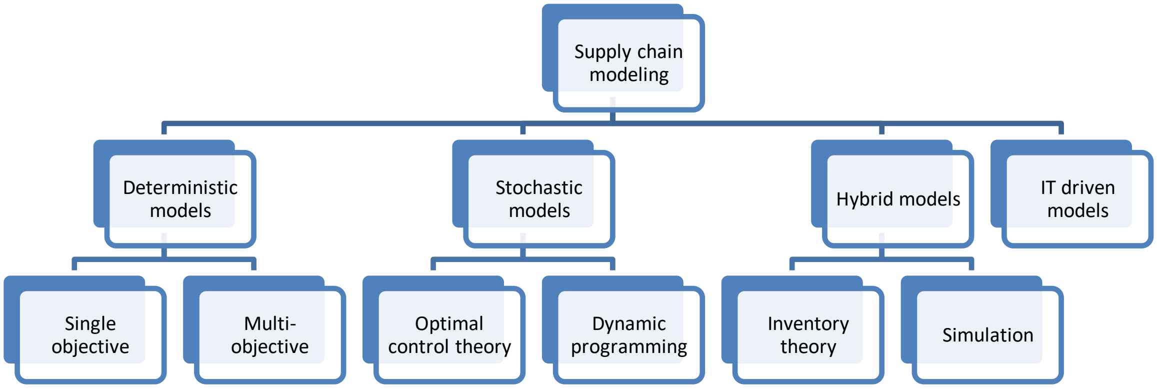


Figure 2.5 Classification of supply chain models (Ghadge, Dani, & Kalawsky, 2012b).

We classified supply chain models into four major categories: (1) deterministic (non-probabilistic); (2) stochastic (probabilistic); (3) hybrid; (4) IT-driven. Deterministic models assume that all the model parameters are known and mixed with certainty, whereas stochastic models take into account the uncertain and random parameters. Deterministic models are classified as single objective and multiple objective models. Stochastic models are sub-classified into optimal control theoretic and dynamic programming models. Hybrid models have elements of both deterministic and stochastic models.

Bassett & Gardner (2010) presented a mixed integer linear programming model in use at Dow Agro-Sciences LLC that simultaneously optimize the network design underlying global supply chains and the monthly production and shipping schedules for maximum profitability. Galbreth & Leblanc (2010) discuss how supply chain models can be developed to leverage the advantages of spread-sheets while mitigating the substantial risks inherent in a spread-sheet-based model.

Hult, Craighead, & Ketchen (2010) extend real options theory to the supply chain context by examining how different types of options are approached relative to supply chain project investments. Nagurney, Masoumi, & Yu (2012) developed a generalized network optimization model for the complex supply chain of human blood, which is a life-saving, perishable product. Zsidisin & Wagner (2010) investigated the relationship between management perceptions of supply risk and the frequency of experiencing the effects of supply disruptions. Davarzani, Zegordi, & Norrman (2011) studied a single product setting in which a firm can be sourced from multiple suppliers. One supplier has an unreliable capacity, while others are reliable but have lower product quality. Tse & Tan (2012) proposed approach has the following benefits: (a) enables firms to have a better 'visibility' of quality risks in a multi-tier supply network; (b) allows firms to establish risk indices for product components; and (c) a traceable justification path for supplier selection. Thun, Drüke, & Hoenig (2011) examine existing differences with respect to how companies deal with risk.

Zhao & Shi (2011) research focused on what supply chain structure (integration v/s decentralization) and which contracting strategy a business should choose. Singh, Mishra, Jain, & Khurana (2012) presented a model of the multi-stage global supply chain network problem incorporating a set of risk factors (such as: late shipment, exchange rates, quality problems, logistics and transportation breakdown, and production risks), their expected values and probability of their occurrence, and associated additional cost. Prasannavenkatesan & Kumanan (2012) a hybrid optimization and simulation approach is proposed to design the supply chain sourcing strategy. G. Soni & Kodali (2013) presented a tool for strategic and planning level. It supports a supply chain manager at strategic level to find the least risky location for manufacturing facility; while at the same time, the methodology supports a supply chain planning manager when selecting the least risky configuration of suppliers and distributors. Wang & Yin (2013) investigated an integrated supply chain optimization problem that optimizes facility locations, customer allocations, and inventory management decisions when facilities are subject to disruption risks. When a facility fails, its customers may be reassigned to other operational facilities in order to avoid the high penalty costs associated with losing service. The problem is formulated as a mixed integer nonlinear programming to minimize the sum of the expected total costs. Wilhite, Burns, Patnayakuni, & Tseng (2014) studied how the design of a supply chain is influenced by its economic environment.

Leerojanaprapa, Van Der Meer, & Walls (2013) provided a mechanism for identifying relevant supply risks so that visualize inter-dependencies between risks and predict their effects on supply performance. By using a belief network modelling formalism can use diagnostics to understand the key drivers of unwanted risk scenarios and to explore the efficacy of possible risk mitigating actions. He (2013) studied how firms sequentially make price and quantity decisions under stochastic demand and supply side risks. J. Chen, Sohal, & Prajogo (2012) examined three types of risks, namely supply risk, demand risk and process risk in relation to three types of collaboration, namely supplier collaboration, customer collaboration and internal collaboration, as a mechanism to mitigate those risks. Choi & Chiu (2013) focused on MV analytical models in supply chain management. S. K. Kumar & Tiwari (2013) considered the location, production–distribution and inventory system design model for supply chain for determining facility locations and their capacity. Subulan, Baykasoğlu, Özsoydan, Taşan, & Selim (2014) proposed a new scenario based stochastic and possibilistic mixed integer programming model for a multi-objective closed-loop supply chain network design problem by considering financial and collection risks. Yin & Nishi (2014) considered supply chain planning modelling including a manufacturer, a retailer and a supplier under demand uncertainty with asymmetric information. Lockamy III (2014) shown that Bayesian networks can be effectively used to assist managers in making decisions regarding current and prospective suppliers. Simultaneously, their potential revenue impact as illustrated through their corresponding disaster risk profiles.

Guillaume, Marques, Thierry, & Dubois (2014) proposed an approach based on subjective probability to evaluate the probability that a decision is optimal for the first actor and the probability that it is optimal for both. From these two evaluations, they proposed a ranking function to help the first actor to take into account the second one when selecting a decision. Lee, Zhang, Goh, & Tan (2014) developed the concept for a disruption recovery-modelling approach that provides more accurate supply forecasts during supply chain disruptions (i.e. smaller variance), which are of prime importance to supply chain risk management. Kache & Seuring (2014) claimed to provide statistical evidence of a link between the constructs of collaboration/integration and risk/performance, most notably between collaboration and performance, information sharing and rewards sharing, as well as integration and supply chain performance. Claypool, Norman, & Needy (2014) designed a supply chain in parallel to designing a new product. Yoo (2014) study aims to identify the relationship between return policy and product quality decisions in a decentralized system. Kull, Oke, & Dooley (2014) conducted a supplier selection behavioural experiment with practicing managers to test the model’s hypotheses.

Kull et al. (2014) studied the effect of profit margin and also demand dispersion under different game scenarios. Madadi, Kurz, Taaffe, Sharp, & Mason (2014) investigated a supply network design in supply chain with unreliable supply with application in the pharmaceutical industry. We consider two types of decision making policies: (1) a risk-neutral decision-making policy that is based on a cost-minimization approach and (2) a risk-averse policy wherein, rather than selecting facilities and identifying the pertinent supplier-consumer assignments that minimize the expected cost, the decision maker uses a Conditional Value-at-Risk (CVaR) approach to measure and quantify risk and to define what comprises a worst-case scenario. Basole & Bellamy (2014) examined the impact of global supply network structure on risk diffusion and supply network health and demonstrate the importance of supply network visibility. Our results show a significant association between network structure and both risk diffusion and supply network health. He (2015) modelled a closed-loop supply chain (CLSC) with a manufacturer and its supply channels - recycle channel and reliable supply channel. Luo, Li, Wan, Qu, & Ji (2014) studied the manufacturer’s optimal mixed procurement strategy that integrates the use of the real-option contract and the spot market. Moreover, they analysed the effects of the price risk and the supply risk in the spot market on market equilibrium. Soeanu et al. (2015) addressed these issues by adopting probabilistic model checking to evaluate the risk and contingency options related to transportation tasks.

Form the above reviewed literature, we can analyse that there are few researchers considering the quality and supply risk in the forward-reverse supply chain context. To address these gaps in the current report, we investigate the interaction between product quality and supply risks, supply chain visibility, penalty cost risk and multi-sourcing decision. In this context, we seek to address the following questions:

Research Question1: How to evaluate the product quality risk and its visibility in multi-layer supply chain environment?

Research Question2: How does a supply chain manager or planner select the optimized network with consideration of reliability and visibility?

In answering these questions, we develop a decision support framework for product supply and quality risk management, which incorporates various supply risk management strategies, including strategic and tactic decisions.

CHAPTER-3 FORWARD REVERSE SUPPLY CHAIN NETWORK DESIGN

In this section, the concerned closed loop supply chain network is a multi-echelon network including both forward and reverse flows in an integrated system. As it is shown in Figure, through forward flows the new products manufactured by plants are shipped to distribution centers and then to customers. Similarly, in the forward flows, the new products manufactured by plants are also directly shipped to customers. In the reverse side, the used products are first collected in a Plant cum recovery center (PCRC) and after quality testing and disassembly activities, the recoverable products are inserted in forward supply chain and redistributed to customers and unrecoverable (scraped) products are shipped to disposal centers. As it can be seen in the Figure 3.1, the considered network has a general structure which is able to support both forward supply and recovery processes and therefore can be applied to different types of industries.

Because of unavailability or incompleteness of data in real world situations, especially in long-term horizon, most of the parameters embedded in such forward reverse supply chain network design problem have an imprecise nature. So, in order to model the lack of knowledge about these ill-known parameters we use appropriate possibility distributions. We also consider a decision horizon including multiple periods in the proposed model and therefore the flow quantities between facilities belonging to different echelons are determined according to demand, return and other periodic-based parameters at each period. This approach enables us to integrate the tactical material flow decisions with strategic level location decisions. The design of supply chain network is based on the assumptions that:

- All possible echelons of the supply chain network are located at different possible locations of sites are known in advance.
- Products are shipped through a pull mechanism in the forward side of network.
- Except the shipment between disposal centers, returned products are shipped through a push mechanism in the reverse side of network.
- A predefined percent of demand from each customer in the previous period is assumed as returned products from corresponding customer in the current period.
- A predefined value is determined as an average disposal fraction.
- Without loss of generality, a single product is moved through the network.
- Each possible manufacturing facility is able to produce similar type of the product.
- The quality of the product is dependent on quality of the raw materials whereas raw material suppliers are located at different geographical locations.
- All transactions are made in common currency.
- Shipments of products from each facility are of only one type of product.

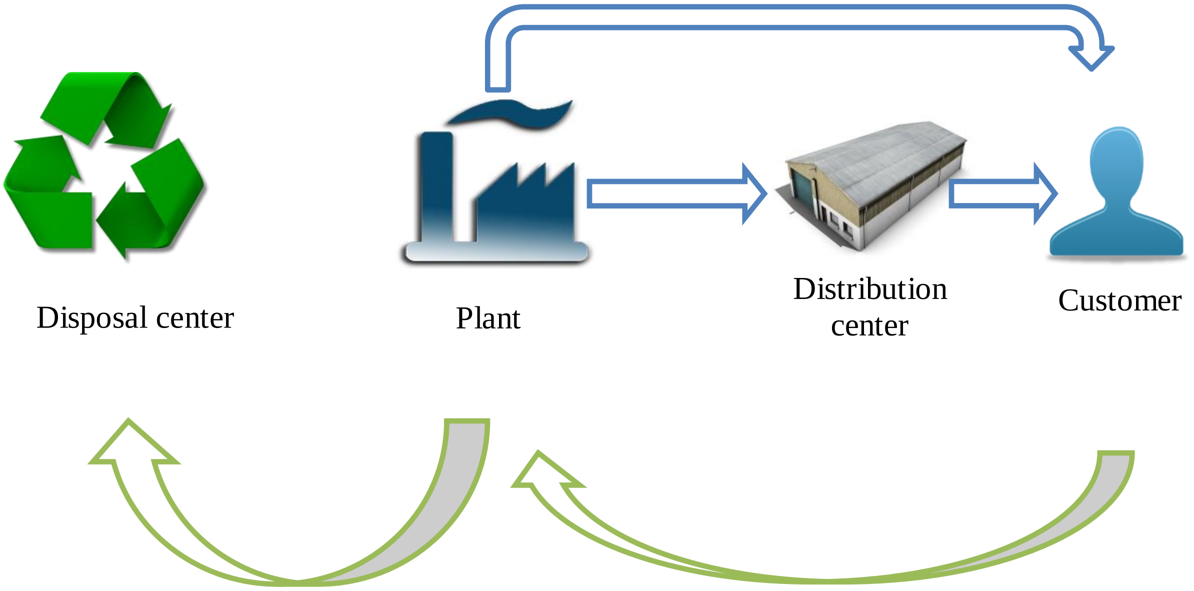


Figure 3.1 Structure of forward reverse supply chain network design

The main issues to be addressed in this forward reverse supply chain network consist of determining the numbers of plants, distribution centers and disposal centers, as well as their locations along with the flow quantities between different facilities at each period. In order to design this forward reverse supply chain network, minimization of total costs is considered as objective function. A numerical example based on forward reverse supply chain network is also shown in figure 3.2 below. This network consists of four plants, eight distribution centers, fourteen customers and two disposal centers. This network shows forward, reverse and direct shipment of new and recovered product among various partners.

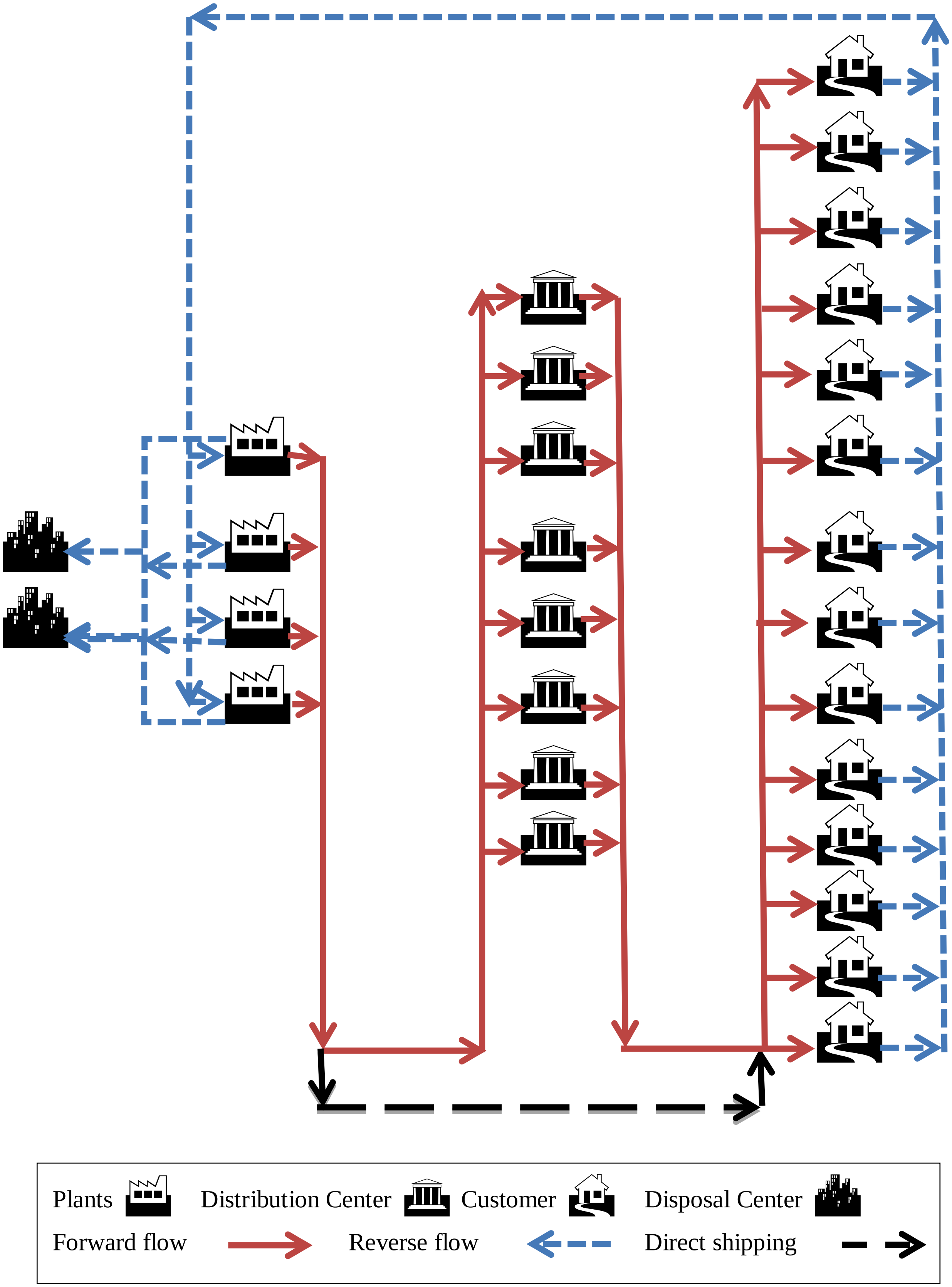


Figure 3.2 Numerical example for forward reverse supply chain network design

3.1 Mathematical formulation for forward reverse supply chain network design

3.1.1 Network parameters

The following notation is used in the formulation of the forward reverse supply chain network design model. The parameters and the decision variables used to formulate the model are listed in Tables.

Table 3.1 Set

S. No.	Set	Description
1	i	Potential number of Plants Cum Recovery Centers $i = 1,2\ldots..I$
2	j	Potential number of Distribution centers (DC) $j = 1,2\ldots..J$
3	k	Potential number of Customers $k = 1, 2 \ldots..K$
4	l	Potential number of Disposal centers $l = 1,2\ldots..L$

Table 3.2 Parameter

S. No.	Parameter	Description
1	d_k	Demand of customer k
2	rr_k	Return rate of used product from customer k
3	pc_i	Production capacity of plants cum recovery centers i in forward flow
4	dc_j	Distribution capacity of j^{th} DC in forward flow
5	cc_i	Collection capacity of plant cum recovery centers i in reverse flow
6	sc_l	Disposal capacity of disposal center l
7	df	Average disposal fraction

Table 3.3 Cost parameters

S. No.	Cost parameter	Description
1	f_i	Fixed cost for opening plants cum recovery centers i
2	g_j	Fixed cost for opening distribution centers j
3	h_l	Fixed cost for opening disposal centers l
4	m_i	Production cost per unit of product at plant cum recovery centers i
5	n_j	Distribution center per unit of product at DC_j
6	a_{ij}	Transportation cost per unit of product from PCRC i to DC j
7	b_{jk}	Transportation cost per unit of product from DC j to customer k
8	e_{ik}	Transportation cost per unit of product from plant i to customer k
9	c_i	Collection cost per unit of product at PCRC i
10	s_l	Disposal cost per unit scrap product at disposal center l
11	r_i	Recovery cost per unit of product at PCRC i
12	p_{ki}	Transportation cost per unit of returned product from customer k to PCRC i
13	q_{il}	Transportation cost per unit of scrap product from PCRC i to Disposal center l
14	μ_k	Penalty cost per unit of non satisfied demand of customer k

Table 3.4 Variable

S. No.	Variable	Description
1	M_i	Quantity recovered by PCRC *i*
2	B_{ik}	Quantity of recovered product shipped from plant *i* to customer *k*
3	Q_{ij}	Quantity of recovered product shipped from plant *i* to DC *j*
4	N_i	Quantity produced by PCRC i
5	X_{ij}	Quantity of new product shipped from PCRC *i* to DC *j*
6	T_{ik}	Quantity of new product shipped from PCRC *i* to customer *k*
7	Y_{jk}	Quantity of product shipped from DC *j* to customer *k*
8	Z_{ki}	Quantity of returned product shipped from customer *k* to PCRC *i*
9	S_{il}	Quantity of scrap product shipped from PCRC *i* to disposal center *l*
10	α_k	Quantity of non-satisfied demand of customer *k*
11	U_i	Binary variable equal to 1 if PCRC *i* is open, 0 otherwise
12	V_j	Binary variable equal to 1 if DC *j* is open, 0 otherwise
13	W_l	Binary variable equal to 1 if Disposal center *l* is open, 0 otherwise

All variables are non-negative in nature.

The total costs required to satisfy demand of all products from plants to customers. For any non-satisfied demand a penalty is assigned. The total cost within the supply chain can be divided into seven segments, depending on the organization that supports it, as presented below:

- Fixed cost (Cost for locating facilities)
- Production cost for plants
- Distribution cost
- Transportation cost between various partners
- Recovery cost for plants
- Collection cost for plants
- Disposal cost for disposal center
- Penalty cost of non-satisfied demand for customers

The objective of this model is to allocate order quantities among the combinations of plants–distribution centers, distribution centers –customers, customers –plants, plants –recovered product again in the forward loop and plants–disposal centers, such that the expected cost of operating the supply chain minimized.

This objective function is subject to the constraint that each level should fulfill the order for the next level in the supply chain. The various risk factors and their cost functions considered in this problem can be obtained by analyzing their historical performance or by taking into account the probabilities of their non-performance and the associated costs of handling the consequent undesired impacts. Each of the cost function associated with risks is formulated below.

- *Fixed cost (Cost for locating facilities)*

Each plant, distribution center and disposal center participating in the supply chain have an associated fixed cost of operation. Therefore, the fixed cost for locating the faculties can be given as-

$$\sum_{i\in I} f(i).U(i) + \sum_{j\in J} g(j).V(j) + \sum_{l\in L} h(l).W(l)$$

- *Production cost for plants*

Each plant participating in the supply chain has a defined cost per unit of production. Therefore, the total cost of production can be given as:

$$\sum_{i\in I}[m(i).N(i)]$$

- *Distribution cost*

The cost of distribution can be given as

$$\sum_{\substack{j\in J\\ k\in K}}[n(j) * Y(j,k)]$$

- *Transportation cost between various partners*

Each mode used in the supply chain has a defined cost per unit of transportation. Therefore, the total cost of transportation between plants-distribution centers, distribution centers-customers, plants-customers, plants-customers (direct shipment) in forward loop and customers-Plants Cum Recovery Centers (PCRC), PCRC-disposal centers in reverse loop and the recoverable products are inserted in forward supply chain and redistributed to customers between PCRC-Distribution centers, PCRC-customers for recovered products, can be given as:

$$\sum_{\substack{i\in I\\ j\in J}}[a(i,j) * X(i,j)] + \sum_{\substack{j\in J\\ k\in K}}[b(j,k) * Y(j,k)] + \sum_{\substack{i\in I\\ k\in K}}[e(i,k) * T(i,k)] + \sum_{\substack{k\in K\\ i\in I}}[p(k,i) * Z(k,i)] + \sum_{\substack{i\in I\\ l\in L}}[q(i,l) * S(i,l)] + \sum_{\substack{i\in I\\ j\in J}}[a(i,j) * Q(i,j)] + \sum_{\substack{i\in I\\ k\in K}}[e(i,k) * B(i,k)]$$

- *Recovery cost for plants*

For quality testing and disassembly activities, PCRC involve cost, can be given as:

$$\sum\nolimits_{i\in I}[r(i).M(i)]$$

- *Collection cost*

The used products are collected in plant cum recovery center (PCRC), the collection cost can be given as:

$$\sum_{\substack{k\in K\\ i\in I}}[c(i)*Z(k,i)$$

- *Disposal cost*

Unrecoverable (scraped) products are shipped to disposal centers, the cost can be given as:

$$\sum_{\substack{i\in I\\ l\in L}}[s(l)*S(i,l)$$

- *Penalty cost of non-satisfied demand for customers*

Penalty cost of non-satisfied demand for customers or the total penalty cost can be given as

$$\sum\nolimits_{k\in K}[\mu(k).\alpha(k)]$$

3.1.2 Objective function

The mathematical programming formulation that minimises the total supply chain cost is presented below and considers all the plants, distribution centers, customers and disposal centers costs defined above.

Total Cost = Fixed cost + Production cost + Distribution cost + Transportation cost + Recovery cost + Collection cost + Disposal cost + Penalty cost

Minimize Total Cost
This equation minimises the total cost.

3.1.3 Constraints

Recovery constraint

This constraint maintains balance between the quantity recovered and supply to the supply chain in forward flow.

$M(i) = \sum_{j \in J} Q(i,j) + \sum_{k \in K} B(i,k)$, $\forall\, i \in I$

Produced constraint

This constraint maintains the balance of flow of new products from plant to distribution center and customer.

$N(i) = \sum_{j \in J} X(i,j) + \sum_{k \in K} T(i,k)$, $\forall\, i \in I$

Demand constraint

This constraint assures that the demand for all customers is taken into account, either by being satisfied or by being allocated to the non-satisfied demand variable.

$\sum_{i \in I} T(i,k) + \sum_{i \in I} B(i,k) + \sum_{j \in J} Y(j,k) + \alpha(k) \geq d(k)$, $\forall\, k \in K$

Return shipment constraint

This constraint handles the return products from customers to plants.

$\sum_{i \in I} Z(k,i) = rr\,(k)\,[\,d(k) - \alpha\,(k)]$, $\forall\, k \in K$

Supply constraint

It’s a flow constraint for distribution centers to customers.

$\sum_{i \in I} X(i,j) + \sum_{i \in I} Q(i,j) = \sum_{k \in K} Y(j,k)$, $\forall\, j \in J$

Scrap shipment disposal constraint

This constraint maintains the scrap quantity of return product.

$\sum_{l \in L} S(i,l) = df * \sum_{k \in K} Z(k,i)$, $\forall\, i \in I$

Return quantity constraint

This constraint maintains the quantity of return product.

$M(i) = [1 - df] * \sum_{k \in K} Z(k,i)$, $\forall\, i \in I$

Plant capacity constraint

This constrain limits the maximum flow through a plant according to its maximum capacity.

$N(i) \leq pc(i) * U(i)$, $\forall\, i \in I$

Distribution capacity constraint

This constrain limits the maximum flow through a distribution center according to its maximum capacity.

$\sum_{k \in K} Y(j,k) \leq \mathrm{dc}\,(j) * \mathrm{V}\,(j), \forall\, j \in J$

Collection capacity constraint

This constrain define the return flow amount between customers and plants and restrict their maximum capacity.

$\sum_{k \in K} Z(k,i) \leq \mathrm{cc}\,(i) * \mathrm{U}\,(i), \forall\, i \in I$

Disposal capacity constraint

This constrain limits the maximum flow through a disposal center according to its maximum capacity.

$\sum_{i \in I} S(i,l) \leq \mathrm{sc}\,(l) * \mathrm{W}\,(l), \forall\, l \in L$

Binary variable constraint

Decision variable for plant, distribution center, disposal center are given as

$\mathrm{U}_i, \mathrm{V}_j, \mathrm{W}_l \in \{0, 1\}, \vee\, i \in I, \vee\, j \in J, \forall\, l \in L$

Non negativity constraint

$M_i, B_{ik}, Q_{ij}, N_i, X_{ij}, T_{ik}, Y_{jk}, Z_{ki}, S_{il}, \alpha_k \geq 0, \forall\, i \in I, j \in J, k \in K, l \in L$

CHAPTER-4 FORWARD-REVERSE SUPPLY CHAIN NETWORK PLANNING WITH EMBEDDED RISK

A typical forward reverse supply chain network consists of multiple suppliers, manufacturers, distribution centers, customers and disposal centers, each operating in a different location in a country under different environments. The proposed model considers supplier side risks, logistics risks, risks related to manufacturer, distributors and demand side risks. Such risks appear due to the uncertainty inherent to operational environments. Since the uncertainty cannot be completely eliminated, it brings several possible failure modes that can affect the supply chain network. To handle the undesired effect of operational uncertainty, resilient supply chain networks need to be built having the ability to maintain, resume and restore operations after any disruption. This section identifies the facility, supply disruptions and their costs at various levels. An optimal policy is determined on the basis of the initial available information. In the later stages of planning, by considering changes in the disruptions, a shift in the flow within the supply chain is determined among available alternatives in order to minimize disruptions, and consequently the total cost of operations. The mathematical model is based on the following assumptions:

- All manufacturers operate in different geographical locations having multiple suppliers, distribution centers and are supplying several customers in a forward reverse supply chain network.
- The lower quality of products imposes additional quality cost.
- Products are shipped through a pull mechanism in the forward side of network. Except the shipment between disposal centers, returned products are shipped through a push mechanism in the reverse side of network.
- The responsiveness has been converted to cost, based on the imposed cost of delivery after lead time.
- A predefined percent of demand from each customer in the previous period is assumed as returned products from corresponding customer in the current period. A predefined value is determined as an average disposal fraction.
- All manufactures are producing homogenous products whose quality depends upon the raw material suppliers and the country of location.
- Finished products are kept in distribution centers as inventory.
- All transactions are made in common currency.
- All decisions are made for just one planning horizon.

The main issues to be addressed in this closed-loop network under embedded risk consist of determining the numbers of plants, distribution centers and disposal centers, as well as their locations along with the flow quantities between different facilities at each period. In order to planning, this forward reverse supply chain network, two objective functions are considered:

(1) Minimization of total costs and (2) Minimization of cost of the embedded risk. The first objective is related to supply chain network efficiency and the second one is related to network robustness. Indeed, the second objective enables the supply chain to satisfy the customers' expected delivery times and therefore being the order winner in its product-markets. Notably, these two objective functions are in conflict with each other. This means that an increase in one objective leads to a decrease in another one; therefore optimizing the network involves a trade-off between these two objectives.

4.1 Mathematical formulation for forward reverse supply chain network with embedded risk

The design of supply chain network should include various risks and their remedies. These risks are caused by the uncertainty inherent to the operational environments, natural calamities, social environment, and demand of the product or market behavior. There are a lot of possibilities of failure of the design of the network due to such risks. The undesired effect of risks can be nullified by identifying the risk-associated additional costs at various levels and computing the probability of their occurrence. Further, supply chain is selected among available alternatives such that the total cost of the model embedding risks cost is minimized. The total cost within the supply chain can be divided into seven segments, as discussed in chapter 3, depending on the organization that supports it. In forward reverse supply chain network, we are considering two types of embedded risk.

- Quality disruptions
- Supply disruptions

Supply risk occurs due to the incomplete supply. Failures of the flow of goods occur when the material is not supplied within the maximum allowable lead time and with required quality.

In the present work the supply risks which are embedded between suppliers-plants and plants-distribution centers have been considered. Risk in any echelon in supply chain is dependent on the functioning of previous echelons such as the manufacturing of a product with quality, lead time, quantity etc. depends upon the supply of the raw material (Singh et al., 2012).

These disruptions do not affect here all the costs in forward reverse supply chain. It affects production, distribution and transportation cost. Remaining other discussed costs will not be affected with considering these disruptions.

4.1.1 Network parameters

- *Production cost and distribution cost*

Each plant participating in the supply chain has a defined cost per unit of production. Therefore, the total cost of production can be given as:

$$\sum_{i\in I}[m(i).N(i)] + \sum_{\substack{j\in J\\ k\in K}}[n(j) * Y(j,k)]$$

Embedding risk:

The supply risks which are embedded between suppliers and plants have been considered. Risk in any echelon in supply chain is dependent on the functioning of previous echelons such as the manufacturing of a product with quality, lead time; quantity etc. depends upon the supply of the raw material. Incorporating the risk associated with the quality of raw material for the production costs for plants becomes:

$$\sum_{i\,\in\, I} mi * [Ni/(\textstyle\sum_{\emptyset} p(\theta) *\ \theta]) + \sum_{\substack{j\in J\\ k\in K}} n(j) * [Y(j,k)/(\textstyle\sum_{\partial} p(\omega) *\ \omega])$$

Where $\emptyset$ is the set of all scenarios for supplier, comprising the reliability of availability and quality of raw material in terms of percentage of total supply; and $p(\theta)$ denotes the probability of scenario θ where $\theta \in \emptyset$, such that $\sum_{\emptyset} p\ (\theta) = 1$. Risk associated with quality of raw material has been calculated in terms of additional requirement of raw material between supplier and plant. Failure of supply of raw material can lead to loss of production and associated profit. Similarly, ∂ is the set of all scenarios for plants, comprising the reliability of availability and quality of finished product in terms of percentage of total supply; and p(ϖ) denotes the probability of scenario ϖ where $\varpi \in \partial$, such that $\sum_{\partial} p(\omega) = 1$. Risk associated with quality of finished product has been calculated in terms of additional requirement of finished product between plant and distribution center. Failure of supply of finished product can lead to loss of distribution and associated profit.

- *Transportation cost between various partners*

Without considering risk, the transportation cost can be given as

$$\sum_{\substack{i\in I\\ j\in J}}[a(i,j) * X(i,j)] + \sum_{\substack{j\in J\\ k\in K}}[b(j,k) * Y(j,k)] + \sum_{\substack{i\in I\\ k\in K}}[e(i,k) * T(i,k)] + \sum_{\substack{k\in K\\ i\in I}}[p(k,i) * Z(k,i)] + \sum_{\substack{i\in I\\ l\in L}}[q(i,l) * S(i,l)] + \sum_{\substack{i\in I\\ j\in J}}[a(i,j) * Q(i,j)] + \sum_{\substack{i\in I\\ k\in K}}[e(i,k) * B(i,k)]$$

Embedding risk:

The finished products are transported from the plants to the distribution centers, distribution centers to customers and plants to customers for further use. These products are transported in truck, ships etc. at regular intervals. Transportation costs for every shipment is dependent on time limits. The new product cost of transportation between the plants and distribution centers can be given as:

$$\sum_{\substack{i\,\in I\\ j\,\in J}} \sum_{t\geq \min LTij}^{\max LTij} p\ (\alpha ij) * a(i,j)(t) * Xij$$

Here min LT_{ij} is the minimum lead time required for plant i to deliver products to distribution center j; max LT_{ij} is the maximum allowed lead time for plant i to deliver products to distribution center j; α_{ij} is the set of all scenarios of lead times with probability p (α_{ij}) for delivering product from plant i to distribution center j. Furthermore, the risk cost due to plant's failure to deliver the raw material within the maximum allowed lead time. This cost consists of penalty cost function in term of lead time can be given as:

$$\sum_{\substack{i\in I\\ j\in J}} aij \, * \, Xij * [1 - \sum_{t \geq \min LTij}^{\max LTij} p\,(\alpha ij)] * PCij(t)$$

Where PC_{ij} (t) is the penalty cost function per shipment per unit of product supplied from plant i to distribution center j after maximum lead time.

Therefore, the plant–Distribution center supply cost for new product becomes:

$$\sum_{\substack{i\in I\\ j\in J}} \sum_{t \geq \min LTij}^{\max LTij} p\,(\alpha ij) * a(i,j)(t) * Xij + \sum_{\substack{i\in I\\ j\in J}} Xij * [1 - \sum_{t \geq \min LTij}^{\max LTij} p\,(\alpha ij)] * PCij(t)$$

Similarly, the distribution centers-customers supply cost for new product becomes:

$$\sum_{\substack{j\in J\\ k\in K}} \sum_{t \geq \min LTjk}^{\max LTjk} p\,(\beta jk) * b(j,k)(t) * Yjk + \sum_{\substack{j\in J\\ k\in K}} Yjk * [1 - \sum_{t \geq \min LTjk}^{\max LTjk} p\,(\beta jk)] * PCjk(t)$$

Similarly, the direct shipment plants-customers supply cost for new product becomes:

$$\sum_{\substack{i\in I\\ k\in K}} \sum_{t \geq \min LTik}^{\max LTik} p\,(\gamma ik) * e(i,k)(t) * Tik + \sum_{\substack{i\in I\\ k\in K}} Tik * [1 - \sum_{t \geq \min LTik}^{\max LTik} p\,(\gamma ik)] * PCik(t)$$

Similarly, the plant–Distribution center supply cost for recovered product becomes:

$$\sum_{\substack{i\in I\\ j\in J}} \sum_{t \geq \min LTij}^{\max LTij} p\,(\alpha ij) * a(i,j)(t) * Qij + \sum_{\substack{i\in I\\ j\in J}} Qij * [1 - \sum_{t \geq \min LTij}^{\max LTij} p\,(\alpha ij)] * PCij(t)$$

Similarly, the direct shipment plants-customers supply cost for recovered product becomes:

$$\sum_{\substack{i\in I\\ k\in K}} \sum_{t \geq \min LTik}^{\max LTik} p\,(\gamma ik) * e(i,k)(t) * Bik + \sum_{\substack{i\in I\\ k\in K}} Bik * [1 - \sum_{t \geq \min LTik}^{\max LTik} p\,(\gamma ik)] * PCik(t)$$

Considered risks do not affect the remaining transportation terms and other cost i.e. distribution, recovery, collection, disposal and penalty costs.

4.1.2 Objective function

The mathematical programming formulation that minimises the total supply chain cost is presented below and considers all the plants, distribution centers, customers and disposal centers costs embedded risk defined above.

Total Cost = Fixed cost + Production cost embedded risk + Distribution cost embedded risk + Transportation cost embedded risk + Recovery cost + Collection cost + Disposal cost + Penalty cost

Minimize TC

This equation minimises the total cost incorporated with risk of facility and supply disruptions. All the constraints of embedded risk model must be similar as deterministic modeling of forward reverse supply chain network design.

4.2 Model solution

4.2.1 Deterministic case

The objective is to minimize the total cost of the forward reverse supply chain operation which includes fixed cost, production cost, distribution cost, transportation cost, recovery cost, collection cost, disposal cost and penalty cost. Since high complexity is involved in the problem space, finding an optimal sequence of operation poses high computational complexity in terms of exponential growth of the search space with just a slight increase in parameter values. This hypothetical forward reverse supply chain can be structured as a multi-objective mixed integer programming (MOMIP) model.

To this aim, four test problems with different sizes are considered and for each size, the computations are performed. Deterministic model is solved under nominal data. Nominal data are randomly generated using the random distributions in a certain range specified in Table. Then, analyze the performance of the solutions obtained by the proposed deterministic model. The model is allowed to update their operation and tactical decision variables regarding the flow quantities between network facilities (i.e., the continuous variables) under each realization. However, since determining the number and location of facilities are strategic level decisions and cannot be changed in the short time, the location and the number of facilities (i.e., the binary variables) cannot be changed under realizations. These deterministic test problems are solved under nominal data on the basis of literature available in (Singh et al., 2012) and (S. K. Kumar, Tiwari, & Babiceanu, 2010). Nominal data are randomly generated using the random distributions in a certain range specified in Table 4.1 below.

Table 4.1 random generation source nominal data

Parameters	Data	Parameters	Data
d_k	Uniform (250, 500)	n_j	Uniform (10, 20)
rr_k	Uniform (0.05, 0.2)	a_{ij}	Uniform (40, 60)
pc_i	Uniform (900, 1100)	b_{jk}	Uniform (60, 80)
dc_j	Uniform (480, 550)	e_{ik}	Uniform (50, 1500)
cc_i	Uniform (80, 150)	c_i	Uniform (30, 40)
sc_l	Uniform (50, 60)	s_l	Uniform (30, 40)
df	0.1	r_l	Uniform (30, 40)
f_i	Uniform (50000, 60000)	p_l	Uniform (50, 70)
g_j	Uniform (4000, 6000)	q_{il}	Uniform (50, 70)
h_l	Uniform (11000, 17000)	μ_k	Uniform (40000, 50000)
m_i	Uniform (160, 200)		

4.2.2 Risk case

After deterministic modeling test results, we designed a model for forward reverse supply chain network with embedded risk. As the cost of operation and the risk factors are different for each level, each work order will have an assigned cost and level of risk. We consider two disruptions i.e. quality and supply disruptions at different level. Therefore, our main objective is to minimize the total cost of the forward reverse supply chain under embedded risks which include production, distribution and transportation cost. Remaining other cost will be same as deterministic model. Since the capacity of each unit, such as a plant or distribution center or disposal center, is a constraint, a near optimal solution is necessary for stabilizing the forward reverse supply chain. By selecting an appropriate combination of routing and work-order process sequence, a plan that is effective in maintaining a low cost of operation and minimizing risks can be generated for the entire forward reverse supply chain. This hypothetical forward reverse supply chain with embedded risk can also be structured as a multi-objective mixed integer programming (MOMIP) model.

Table 4.2 Random generation source nominal data for embedded risk model

Parameters	Data
$p(\theta)$	Uniform (0.5, 1)
$P(\varpi)$	Uniform (0.5, 1)
$p(\alpha)$	Uniform (0.1, 0.2)
$p(\beta)$	Uniform (0.1, 0.2)
$p(\gamma)$	Uniform (0.1, 0.2)
$PC_{ij}(t)$	Uniform (48, 72)
$PC_{jk}(t)$	Uniform (72, 96)
$PC_{ik}(t)$	Uniform (60, 1800)

All costs functions considered in these models have been assumed to be linearly increasing with the lead time. The mathematical models has been solved by academic version of optimization software AIMMS (Advanced Interactive Multi-directional Modeling System)-4.6.2.70 CPLEX 12.6.1 solver on Pentium dual-core 1.87 GHz with 1 GB RAM, 64 bit operating system for deterministic and risk models. Results discussed in chapter 05.

These test problem results and comparative analysis for both models are also shown in next chapter. To study the overall behavior of the forward reverse supply chain system with embedded risk, probability and reliability data is generated randomly.

The data required by the model to set values for the parameters. As mentioned earlier, the supply chain risk management model consists of 4 plants, 10 distribution centers, 12 customers and 2 disposal centers. The raw materials are delivered from the suppliers and transformed in to the finished products by the plants. The finished products transported to the distribution centers from where it is delivered to the customers in forward path. The used products are collected in Plants and after quality testing and disassembly activities, the recoverable products are inserted in forward supply chain and redistributed to customers and unrecoverable (scraped) products are shipped to disposal centers. To study the overall behavior of the supply chain system, initially data is generated randomly in the basic model as depicted in Tables.

Transportation cost, penalty costs, lead time, reliability of the supplied items, probability of supplying goods within the specific time limit between plants and distribution centers are shown in Table 4.3.

Table 4.3 Plants-Distribution center input parameters

Plants and distribution center parameters-1 (a)

	DC1						DC2						DC3					
	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R
P1	42	67	13	24	0.12	0.64	57	63	16	20	0.16	0.79	57	68	13	22	0.13	0.73
P2	56	50	13	20	0.19	0.69	58	57	15	24	0.19	0.56	59	55	13	24	0.12	0.54
P3	47	56	17	24	0.2	0.63	50	67	16	25	0.11	0.92	46	65	12	20	0.11	0.64
P4	54	52	17	21	0.15	0.89	49	50	17	24	0.17	0.52	57	71	15	25	0.17	0.52

Plants and distribution center parameters-2 (b)

	DC4						DC5						DC6					
	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R
P1	49	60	12	25	0.14	0.95	45	70	13	21	0.1	0.53	54	58	16	20	0.1	0.94
P2	43	57	17	20	0.13	0.83	58	58	15	20	0.18	0.95	40	61	17	23	0.18	0.66
P3	51	55	12	23	0.2	0.75	56	71	16	24	0.11	0.93	43	56	16	23	0.15	0.8
P4	55	70	14	22	0.19	0.95	55	71	13	21	0.17	0.53	54	57	15	21	0.2	0.51

Plants and distribution center parameters-3 (c)

	DC7						DC8						DC9					
	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R
P1	42	57	17	21	0.16	0.97	53	52	17	21	0.17	0.8	59	61	14	23	0.16	0.83
P2	57	54	13	23	0.12	0.83	49	66	13	20	0.13	0.6	45	70	16	24	0.15	0.88
P3	59	71	15	23	0.19	0.59	59	68	17	22	0.14	0.62	54	63	16	20	0.18	0.61
P4	56	69	17	20	0.18	0.74	44	53	12	22	0.19	0.6	42	58	16	24	0.19	0.7

Plants and distribution center parameters-4(d)

	DC10					
	TC	PC	X1	X2	P	R
P1	53	63	14	25	0.13	0.68
P2	41	67	17	21	0.19	0.58
P3	46	65	14	22	0.13	0.78
P4	41	58	16	20	0.15	0.57

Table 4.4 Distribution center-customers input parameters

Distribution center and customers parameters-1 (a)

	C1						C2						C3					
	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R
DC1	61	91	13	21	0.13	0.9	73	93	14	20	0.15	0.51	75	74	17	25	0.13	0.66
DC2	68	79	14	22	0.15	0.7	69	78	15	24	0.1	0.78	65	80	12	24	0.13	0.84
DC3	70	79	16	24	0.17	0.96	72	91	13	25	0.16	0.72	61	91	17	21	0.19	0.52
DC4	68	79	12	24	0.17	0.97	70	79	12	21	0.17	0.61	68	88	13	23	0.12	0.63
DC5	67	89	15	20	0.12	0.83	73	88	16	22	0.2	0.72	79	77	14	21	0.16	0.83
DC6	64	85	15	22	0.17	0.96	72	75	13	20	0.15	0.54	62	78	15	23	0.14	0.92
DC7	70	84	17	20	0.13	0.68	62	78	14	21	0.19	0.83	75	80	12	23	0.11	0.74
DC8	66	72	17	24	0.19	0.65	79	88	16	23	0.12	0.73	75	78	14	23	0.19	0.66
DC9	61	83	15	22	0.15	0.71	74	92	17	22	0.19	0.76	60	92	15	22	0.11	0.68
DC10	60	80	15	23	0.12	0.77	71	77	17	20	0.13	0.89	75	83	13	22	0.11	0.82

Distribution center and customers parameters-2 (b)

	C4						C5						C6					
	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R
DC1	73	79	17	21	0.11	0.97	69	86	16	21	0.2	0.79	66	73	12	22	0.16	0.94
DC2	65	94	13	21	0.19	0.84	74	84	17	25	0.13	0.9	62	86	13	24	0.15	0.53
DC3	77	77	17	21	0.2	0.75	61	75	12	21	0.2	0.52	69	94	15	20	0.17	0.74
DC4	76	82	15	23	0.19	0.95	69	90	16	21	0.15	0.81	76	90	12	21	0.15	0.71
DC5	72	88	13	21	0.11	0.78	76	86	12	24	0.11	0.51	73	92	12	20	0.15	0.71
DC6	68	95	16	23	0.15	0.72	67	91	15	23	0.19	0.77	70	91	15	24	0.13	0.56
DC7	66	92	14	22	0.15	0.86	65	78	12	21	0.17	0.72	66	76	16	21	0.17	0.97
DC8	77	85	15	25	0.15	0.74	72	75	14	25	0.13	0.97	70	92	14	21	0.16	0.61
DC9	65	80	16	25	0.18	0.76	62	76	17	24	0.16	0.53	61	75	17	21	0.17	0.76
DC10	67	93	13	24	0.1	0.58	77	93	17	21	0.17	0.6	75	83	12	21	0.13	0.82

Distribution center and customers parameters-3 (c)

	C7						C8						C9					
	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R
DC1	61	78	16	21	0.19	0.68	71	88	16	20	0.13	0.62	63	82	12	25	0.13	0.85
DC2	63	79	14	24	0.14	0.89	73	75	16	23	0.19	0.9	70	76	14	23	0.13	0.7
DC3	64	90	13	20	0.11	0.8	75	77	17	23	0.11	0.89	60	95	12	25	0.15	0.88
DC4	70	89	15	20	0.17	0.95	73	89	12	20	0.11	0.61	79	93	16	21	0.17	0.75
DC5	76	72	15	23	0.18	0.88	72	73	17	25	0.12	0.93	79	78	15	25	0.12	0.91
DC6	71	88	12	20	0.11	0.7	76	82	15	21	0.16	0.96	78	91	14	23	0.13	0.87
DC7	76	74	14	22	0.14	0.92	64	77	14	20	0.11	0.85	64	81	12	24	0.2	0.7
DC8	61	92	17	20	0.13	0.58	72	95	13	25	0.13	0.94	72	77	14	21	0.16	0.73

DC9	71	77	16	21	0.13	0.52	69	95	17	23	0.12	0.54	70	82	15	23	0.14	0.71
DC10	71	72	16	25	0.19	0.85	78	72	13	23	0.12	0.87	60	86	12	20	0.18	0.82

Distribution center and customers parameters-4 (d)

	C10						C11						C12					
	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R
DC1	79	76	13	23	0.16	0.97	68	82	17	24	0.14	0.84	66	89	15	20	0.15	0.64
DC2	69	85	15	21	0.11	0.88	61	80	16	20	0.11	0.84	64	74	16	23	0.18	0.92
DC3	74	81	16	24	0.15	0.54	74	75	16	23	0.16	0.86	64	84	12	23	0.15	0.61
DC4	69	92	14	24	0.11	0.67	79	75	15	22	0.19	0.77	76	76	16	24	0.12	0.97
DC5	73	79	16	22	0.12	0.83	73	90	12	24	0.2	0.81	62	78	17	23	0.16	0.77
DC6	67	81	14	23	0.19	0.61	77	94	12	24	0.14	0.68	72	77	16	22	0.2	0.73
DC7	66	72	15	24	0.18	0.65	71	89	17	22	0.14	0.98	78	73	12	23	0.12	0.81
DC8	78	86	12	20	0.11	0.83	73	92	14	24	0.15	0.78	60	78	16	23	0.18	0.76
DC9	76	92	12	23	0.11	0.58	63	91	12	24	0.16	0.84	71	83	13	25	0.11	0.69
DC10	64	75	16	21	0.15	0.88	64	93	16	25	0.11	0.55	61	93	17	24	0.14	0.98

Plants and customers parameters-1 (a)

	C1						C2						C3					
	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R
P1	1031	463	16	20	0.18	0.65	699	326	17	20	0.19	0.71	1483	1389	13	25	0.15	0.64
P2	287	541	17	24	0.19	0.61	557	337	14	22	0.19	0.96	1459	827	16	23	0.16	0.66
P3	971	495	12	24	0.19	0.58	142	1216	15	23	0.16	0.77	977	977	17	25	0.12	0.61
P4	876	625	16	22	0.12	0.69	591	360	12	21	0.11	0.79	656	791	15	22	0.18	0.83

Plants and customers parameters-2 (b)

	C4						C5						C6					
	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R
P1	86	1096	14	20	0.11	0.6	457	1107	12	22	0.15	0.94	927	378	15	23	0.19	0.74
P2	110	482	13	21	0.19	0.64	1047	1462	14	23	0.13	0.55	948	1439	12	22	0.16	0.9
P3	1430	775	13	25	0.13	0.86	966	346	17	24	0.17	0.81	797	1361	14	24	0.14	0.87
P4	812	1406	14	25	0.14	0.66	1164	1309	14	22	0.19	0.67	1071	812	17	21	0.13	0.68

Plants and customers parameters-3 (c)

	C7						C8						C9					
	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R
P1	1086	880	14	21	0.14	0.74	123	1231	16	23	0.11	0.79	963	576	16	23	0.16	0.99
P2	58	129	12	24	0.11	0.67	1066	944	14	20	0.18	0.95	300	485	16	23	0.12	0.86
P3	234	1005	17	20	0.18	0.53	1337	523	16	20	0.18	0.54	713	1162	13	24	0.16	0.99
P4	606	1035	13	22	0.17	0.93	393	1430	12	24	0.12	0.57	862	805	14	25	0.18	0.5

Plants and customers parameters-4 (d)																		
	C10						C11						C12					
	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R	TC	PC	X1	X2	P	R
P1	1567	496	13	20	0.15	0.53	713	573	12	23	0.16	0.73	613	655	12	21	0.16	0.78
P2	385	1029	14	25	0.11	0.56	1315	191	13	20	0.16	0.91	1125	1295	17	24	0.14	0.74
P3	1238	546	12	23	0.19	0.98	407	227	12	21	0.2	0.53	895	1139	13	23	0.1	0.89
P4	1361	469	13	20	0.12	0.82	1491	416	14	22	0.16	0.79	845	741	16	24	0.11	0.71

The smallest problem size 4 X 10 X 12 X 4 randomly generated data of supply chain network is shown in above tables between plants-distribution centers, distribution centers-customers and plants-customers respectively. Likewise, randomly generated data used for other problem sizes for solving both the models.

CHAPTER-5 RESULTS AND DISCUSSION

To demonstrate the applicability of the proposed model, the performance of organization with a deterministic model of forward reverse supply chain and with embedded risk has been examined. The related results and their comparative analysis are discussed in this section.

In this section, results of four test problems are comparatively represented. In table 5.1, initially all four test model configurations are displayed. Generating random nominal data in a above discussed range, we obtained best solution for objective function to minimize the total cost of the whole forward reverse supply chain network. Comparison between both the models i.e. forward reverse supply chain network and forward reverse supply chain network with embedded risk on the basis of various parameters are represented.

Table 5.1 Summary of objective function and nodes in test results

Problem size	**Objective Function values under nominal data**		**Risk premium**	**Increase in percentage (%)**	**Nodes**	
i*j*k*l	**Deterministic Model**	**Embedded risk model**			**Deterministic Model**	**Embedded risk model**
4 * 10 * 12 * 2	1460614	1655900	195286	13	1425	344
7 * 14 * 18 * 3	2173215	2409986	236771	11	1624	2520
9 * 20 * 25 * 3	2905086	3226048	320962	11	1028	1725
12 * 25 * 35 * 4	3985491	4822777	837286	21	1349	5469

The difference between the objective function values for both models can be called as risk premium. As the results show, the embedded risk model gained the solutions with higher values of objective functions than the deterministic model. In all problem sizes, the embedded risk model dominates the deterministic one with respect to the objective function values.

The gap between the both models with respect to problem size increases and it is shown in table 5.1 and figure 5.1.

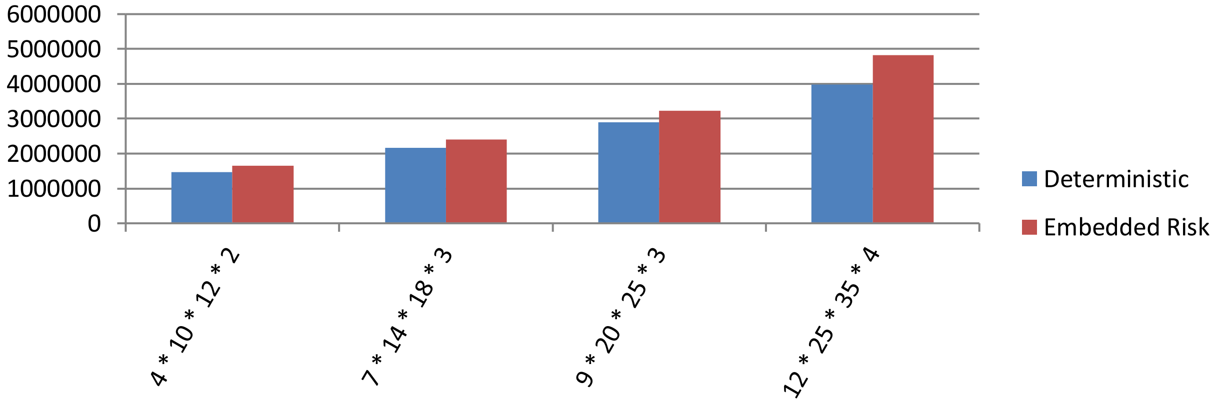


Figure 5.1 Graph between problem size and objective function value

Table 5.2 Summary of production-distribution cost and transportation cost in test results

Problem size	**Production-distribution cost**		**Difference (Risk premium)**	**Increase in percentage (%)**	**Transportation cost**		**Difference**	**Increase in percentage (%)**
i*j*k*l	**Deterministic Model**	**Embedded risk model**			**Deterministic Model**	**Embedded risk model**		
4 * 10 * 12 * 2	747156	846553.79	99397.79	13	405851	502372.54	96521.54	24
7 * 14 * 18 * 3	945672	1117330	171658	18	523789	601096	77307	15
9 * 20 * 25 * 3	1487438	1604207	116769	8	804700	996667	191967	24
12 * 25 * 35 * 4	2112180	2697420.885	585240.89	28	982620	1219535.5	236915.5	24

Tables displayed comparison between production-distribution cost and transportation cost for both models. These result shows that cost increases after considering the risk factors. These values are also comparatively analyzed. These values also increase as the problem size increases. Consideration of risk factors always increase the total cost for supply chain network. Graphical representation of best optimal solution makes more clarity in this perspective. Therefore, four test problems are presented in the form of bar charts. Figure 5.2 and 5.3 compares respective cost of both models.

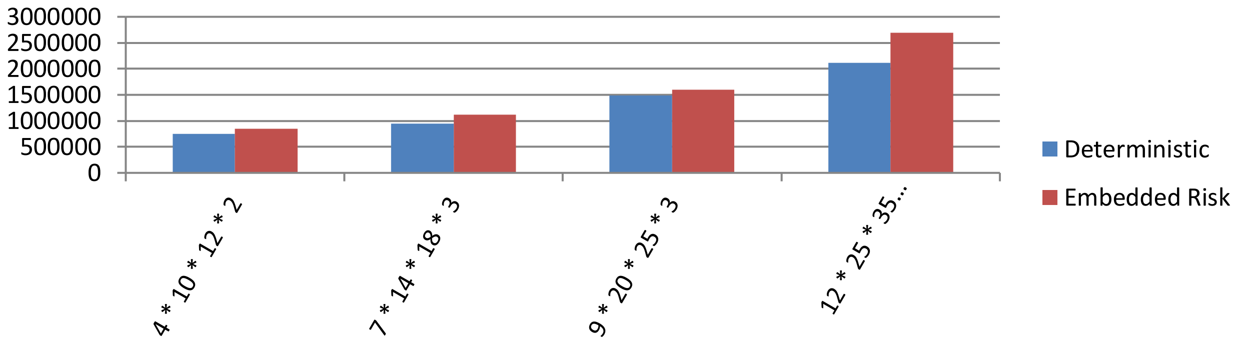


Figure 5.2 Graph between problem size and production-distribution cost

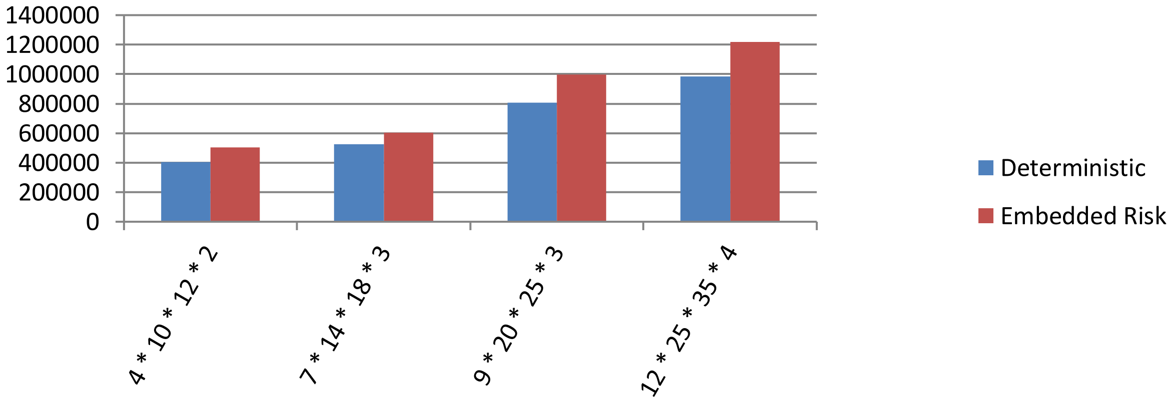


Figure 5.3 Graph between problem size and transportation cost

Table 5.3 Summary of test results

Problem size	Computational time under nominal data (seconds)		Iterations	
i*j*k*l	**Deterministic Model**	**Embedded risk model**	**Deterministic Model**	**Embedded risk model**
4 * 10 * 12 * 2	0.81	0.26	5503	1399
7 * 14 * 18 * 3	4.06	5.27	9973	13410
9 * 20 * 25 * 3	5.76	4.21	8329	13742
12 * 25 * 35 * 4	11.73	30.36	12462	67164

Total elapsed time as comparatively mapped for all four test problems. Number of iterations is also increase as the problem size and risk increases. Number of constraints, variables and non zero values must be same for both the model as per computation results. Consideration of risk factors always increase the total cost for supply chain network.

For minimization the test problem, optimization software does not use all the nodes. Some of the nodes are not active during minimization of total cost. In table 5.4, active plants, distribution centers, customers and disposal centers are represented for both the models.

Table 5.4 Summary of active nodes

Problem size	Active nodes					
i*j*k*l	**Deterministic model**			**Embedded risk model**		
	Plants	**Distribution centers**	**Disposal centers**	**Plants**	**Distribution centers**	**Disposal centers**
4 * 10 * 12 * 2	All open	1,2,3,5,6,7,8	2	All open	1,3,5, 6,7,8,10	2
7 * 14 * 18 * 3	except 1, all open	1,3,4,5,6, 7,10,11,14	1	except 1, all open	1,3,4,5,6, 7,10,11,14	1
9 * 20 * 25 * 3	except 8, all open	1,3,5,7,10, 11,12,14,18,19	2,3	except 1, all open	1,2,3,5, 7,10,11,14, 16,17,19	2,3
12 * 25 * 35 * 4	All open	1,2,3,5,6,7,10, 11,14,16,18,19,21,22	1,4	All open	1,2,3,5,6, 8,10,11,12,16, 18,19,21,25	2,3,4

Assuming profit is same for all the problem sizes for the supply chain network, manager has to decide which network should be established with minimum risk premium. Consider all the problems which we have taken as example for decision making process. In that case, managers have to pay 13%, 11%, 11% and 21% risk premium respectively. Manager will pay 11% minimum risk premium for problem size 2 and 3. Therefore, on the basic of this analysis, manager can establish smaller network from both problem sizes i.e. network 7 X 14 X 18 X 3. That means, manager can get same profit with minimum investment.

Our ideas around the impact of estimating the risk of disruption and the benefits of containment strategies were developed based on stylized mathematical models and simulation. To compare deterministic and risk model, we analyzed a network model of a supply chain that could be made more resilient by building some reliable but high-cost facilities among other lower-cost facilities that could fail and disrupt the supply chain. Our models identified the optimal proportion of reliable (but high-cost) facilities to build and then compared the relative losses from misestimating the disruption probability.

To understand the benefits of containment, we used a different model to evaluate the fragility or increase in cost of the supply chain in the event of a disruption and identified the relationship between fragility, network connectivity and the extent of the disruption. Supply chains represented by connected networks where the impact of a disruption could travel across the entire network often had a higher fragility than networks where the impact of a disruption was more localized. Results for the quantity shipped between plants-distribution centers, distribution centers-customers and plants-customers are shown below in the tabular form for the smallest problem size 4 X 10 X 12 X 2. Data for quantity shipped for other problem sizes are attached in Appendix-I.

Figure 5.4, 5.5 and 5.6 shows the forward-reverse supply chain network for deterministic and risk model of 3 problem sizes. The active nodes are shown by blank shapes and filled shaped displays the inactive nodes. These active and inactive nodes status are achieved by the computation results.

Table 5.5 Quantity shipped through deterministic model

j	DC1	DC2	DC3	DC5	DC6	DC7	DC8
i							
P1				312			460
P2			510			128	
P3				229	455	385	
P4	503	516					15

(a)

k	C1	C2	C3	C5	C6	C7	C8	C9	C10	C11	C12
j											
DC1	181		8					314			
DC2	28									488	
DC3				330	180						
DC5			171			36					334
DC6							303	152			
DC7			227						286		
DC8		367			108						

(b)

k	C4
i	
P2	385

(c)

Table 5.6 Quantity shipped through risk model

j	DC1	DC3	DC5	DC6	DC7	DC8	DC10
i							
P1			541			231	
P2		510			128		
P3				531	385	153	
P4	503					43	488

(a)

k	C2	C3	C5	C6	C7	C8	C9	C10	C11	C12
j										
DC1					245		238			20
DC3			282	228						
DC5		227								314
DC6						303	228			
DC7		179	48					286		
DC8	367			60						
DC10									488	

(b)

k	C4
i	
P2	385

(c)

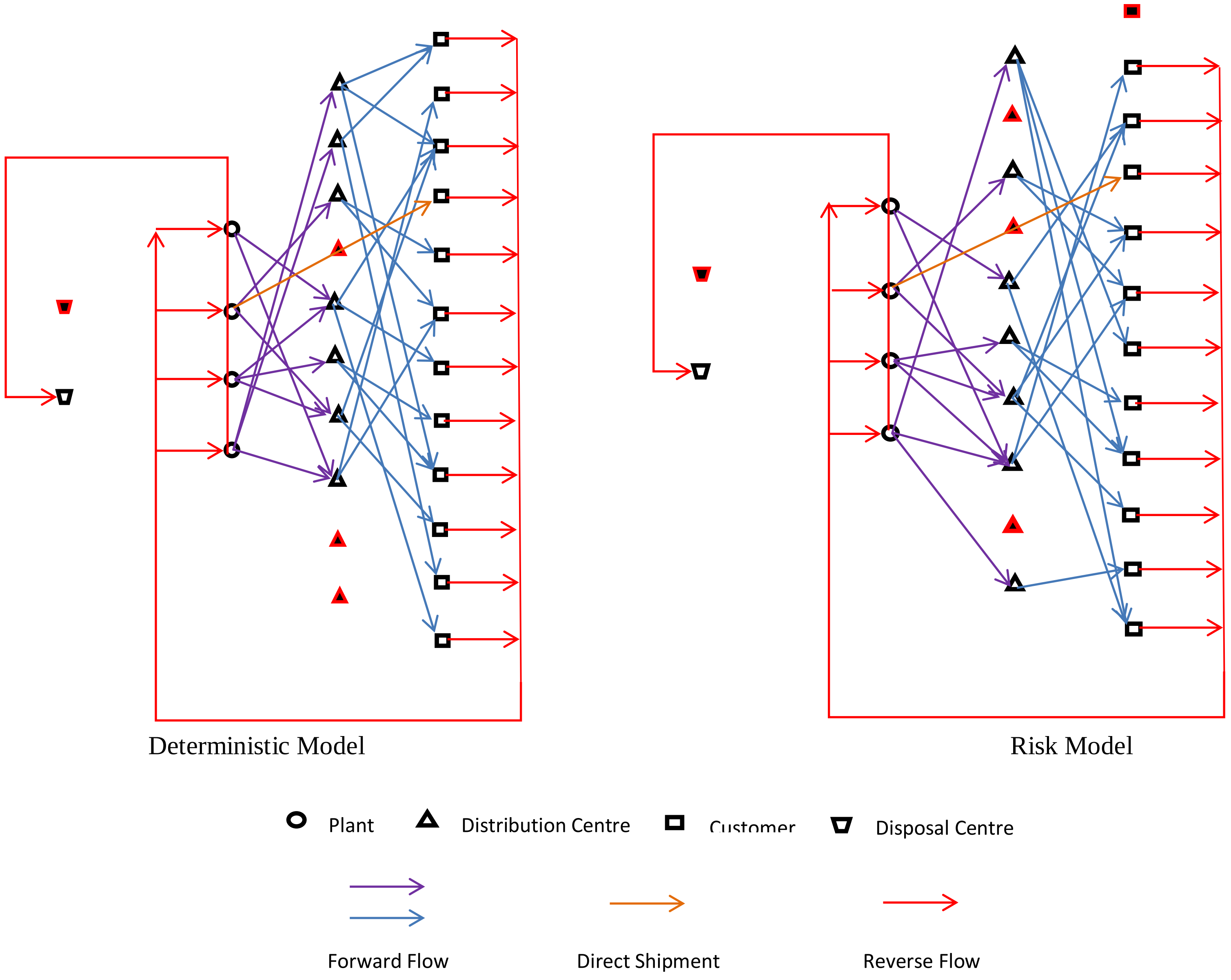
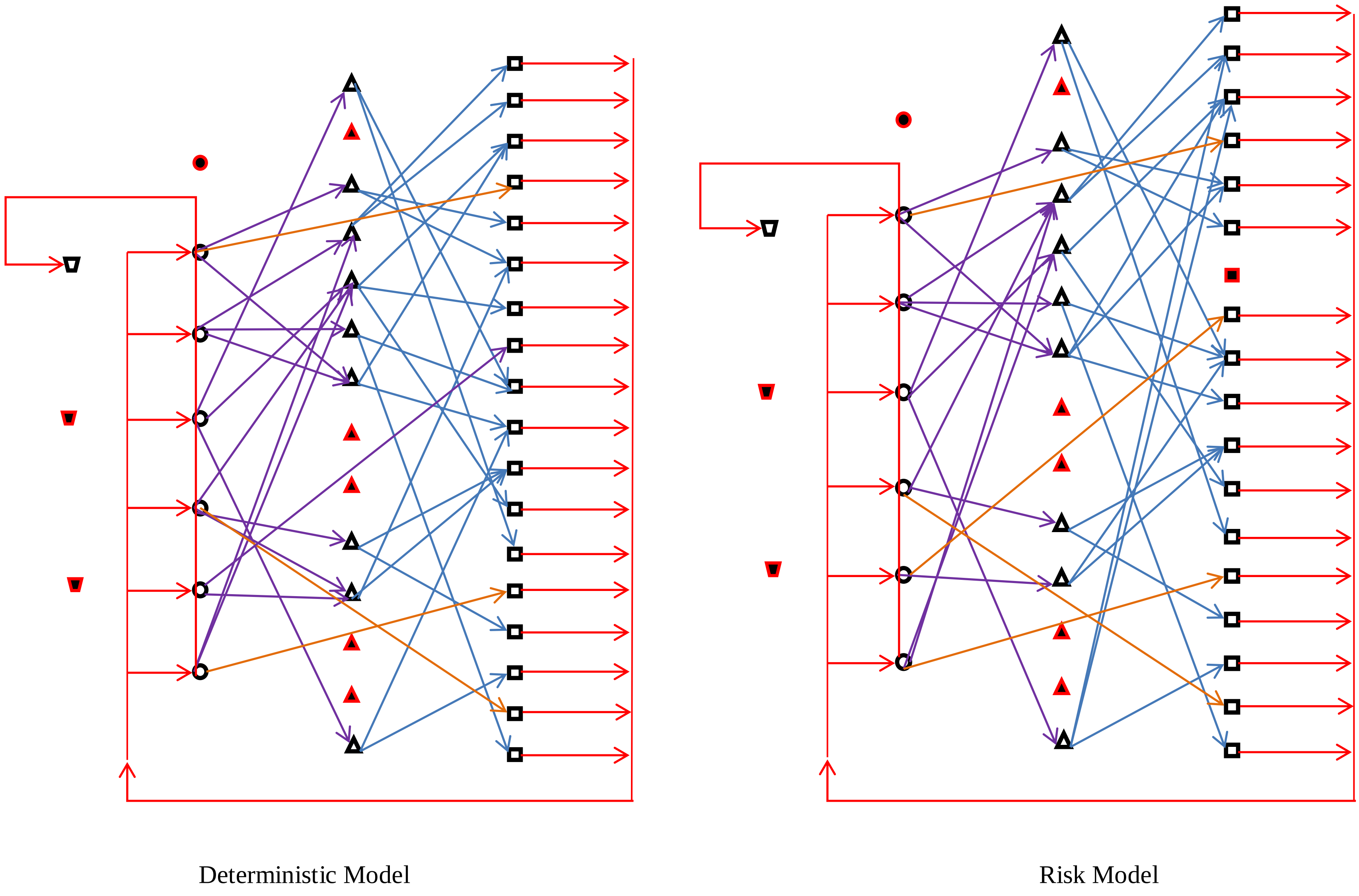


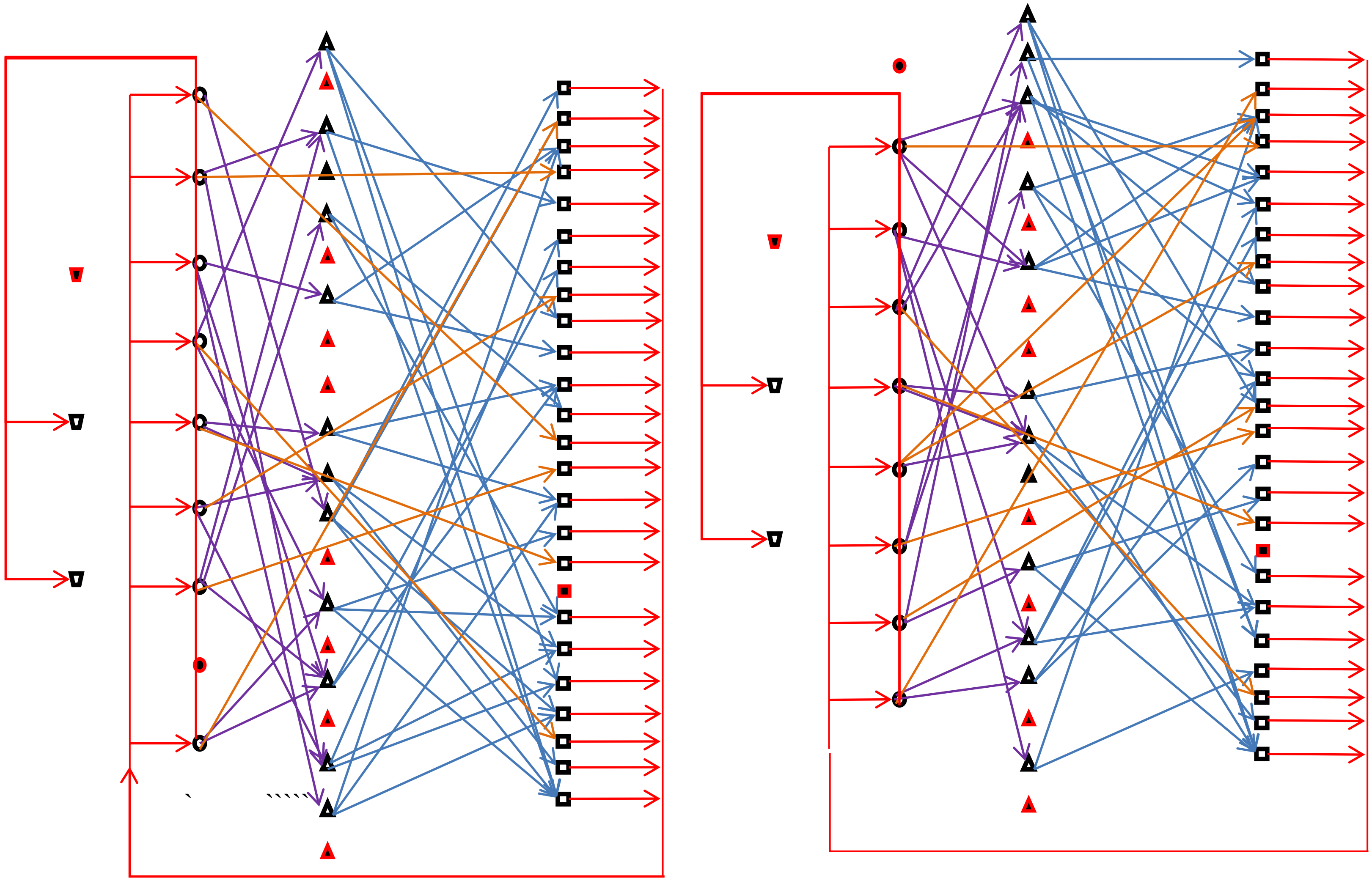
Figure 5.4 Network Comparison of Deterministic and Risk Models (Problem Size: 4 X 10 X 12 X 2)



Deterministic Model

Risk Model

Figure 5.5 Network Comparison of Deterministic and Risk Models (Problem Size: 7 X 14 X 18 X 3)



Deterministic Model

Risk Model

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Figure 5.6 Network Comparison of Deterministic and Risk Models (Problem Size: 9 X 20 X 25 X 3)

CHAPTER-6 CONCLUSION AND FUTURE SCOPE

In this section, we summarized the whole research work in conclusion section and also discussed the scope for future work in the context of embedded risk in forward reverse supply chain network.

6.1 Conclusion

The stability of supply chain is at stake in global scenario due to existence of heterogeneous environment in different regions. This in turn has made the design of supply chain network more complex. However, incorporation of risks makes the supply chain more and more pertinent to robust and reliable performance. Therefore, we have analysed the supply chain literature about close loop supply chain incorporating risks, disruptions and uncertainty so that we can identify the most important risks and address them in network design. Mathematical model of supply chain network design is done by considering these risks in later stage.

Literature has been growing quickly in the past few years, which seems motivated by recent high-profile disruptions and increased globalization. In the review process around 78 papers from standard international publishers, forward reverse supply chain modeling are taken and explore directions classified in two major sections in this report viz. supply chain risk and management and modeling approaches for supply chain risk mitigation. It was observed that forward reverse supply chains are vulnerable towards different types of risks factors (ex- supply, quality, delay in lead time etc.) that causes disturbance in the strategic and tactical decisions in supply chain. In this study a deterministic model formulation has been proposed to design supply chain and evaluates the location of the plants and distribution centers (strategic decisions) and number of the quantities to flow between supply chain echelons (tactical decisions). Simultaneously, the same model incorporates a set of risk factors, their expected values, and probability of their occurrence. Production, distribution and supply risk have been considered in the model which incorporates the late shipments, customs delays, quality control problems, and logistics and transport breakdowns. The applicability of the risk associated model has been demonstrated for following scenarios:

1. Optimization of the total cost of the supply chain for single type of products where all decisions are determined by the model subject to the constraints.
2. The uncertainty in reliability of the quality of raw materials is introduced in model.

Optimization software AIMMS has been used to arrive at optimal decisions for these scenarios. These decisions regarding the facility locations and inter-echelon quantity flows in the forward reverse supply chain are based on initial information for the risk factors. Further, if any changes in the expected value of risk factors occurred, the inter-echelons shifting take place to minimize the overall cost of the supply chain. This shift is represented by the change in production quantities among plants, while all other factors remain constant.

The results of this study show a tool for strategic and planning level. It supports a supply chain manager at strategic level to find the least risky location for facilities; while at the same time, the methodology supports a supply chain planning manager in making decisions regarding current and prospective configuration between multiple tier of forward reverse supply chain through their corresponding disaster risk profiles.

6.2 Future scope

Many possible future research directions can be defined in this area. For example, addressing the problem in a multi-product setting and maximizing the responsiveness of the network. A multi-objective cost optimization problem may be an attractive direction for future research too. Developing more general and advanced risk optimization models by taking more risk factors in to account is another attractive aspect. For example, risk in inventory, environmental, terrorist attack can be considered in developing models for forward reverse supply chain network design.

The mathematical formulation and the results obtained can be utilized for many other situations such as the outsourcing of semi-finished or finished products when in house production risks are very high.

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APPENDIX-I

Quantity shipped from plants to distribution centers, distribution centers to customers and plants to customers are shown here for three problem sizes.

For Problem size-12 X 25 X 35 X 4

a) Deterministic model

	DC-1	DC-2	DC-3	DC5	DC-6	DC-7	DC-10	DC-11	DC-14	DC-16	DC-18	DC-19	DC-21	DC-22
P2			446			56					52			
P3						110						486		
P4	503								146					
P5							481	196						65
P6								342			451			
P7			64	541										
P8		516												
P9									348					
P10						347								
P11					531		55						488	
P12										502				426

	C1	C2	C3	C5	C6	C7	C9	C10	C11	C12	C15	C16	C18	C19	C20
DC-1															
DC-2									77						
DC-3				330											
DC5										334				207	
DC-6							420						111		
DC-7								233							
DC-10									411		4				
DC-11															273
DC-14												394			
DC-16						288									
DC-18					288										42
DC-19			139												
DC-21											442			46	
DC-22	308	130						53							

DC-1	C21	C22	C24	C25	C26	C29	C30	C31
DC-2	55							448
DC-3	258					181		

DC5				180				
DC-6								
DC-7								
DC-10							280	
DC-11				121				
DC-14			265					
DC-16				100				
DC-18						214		
DC-19					173			
DC-21		347						
DC-22								

	C2	C4	C8	C13	C14	C17	C23	C27	C28	C32	C33	C34	C35
P1				280						419			311
P2		385								23			
P3									382				
P4							339						
P5						311							
P6			303										
P7					423								
P8								252		28		282	
P9	237										423	34	

b) Risk model

j	DC1	DC2	DC3	DC5	DC6	DC8	DC10	DC11	DC12	DC16	DC18	DC19	DC21	DC25
i														
P2											248			
P3												486		110
P4	503													
P5							536							
P6								538			255			
P7				541										
P8		401												425
P9					435					502				
P10		4	510						491					
P11					96	490							488	
P12		111				51								

k new	C2	C4	C8	C13	C14	C17	C23	C27	C28	C32	C33	C34	C35

i													
P1				280							103	316	311
P2		385								155	174		
P3									382				
P4							339				146		
P5						311				206			
P6			303										
P7					423					64			
P8								252					
P9	105												
P10										45			

	C2	C4	C8	C13	C14	C17	C23	C27	C28	C32	C33	C34	C35
P1				280							103	316	311
P2		385								155	174		
P3									382				
P4							339				146		
P5						311				206			
P6			303										
P7					423					64			
P8								252					
P9	105												
P10										45			

For Problem size- 9 X 20 X 25 X 3

a) Deterministic model

j	DC1	DC3	DC5	DC7	DC10	DC11	DC12	DC14	DC16	DC18	DC19
i											
P1							476				
P2		489								149	
P3				513					70		486
P4	503							192			
P5					536	223					
P6						315				354	
P7		21	541						31		
P9								302	401		

k	C1	C2	C3	C5	C6	C7	C9	C10	C11	C12	C15	C16	C19	C20	C21	C22	C24	C25
j																		

DC1							259								140			104
DC3				330														180
DC5										334			207					
DC7			227					286										
DC10									106		430							
DC11														273			265	
DC12	308	20														56		92
DC14												394	46					54
DC16						288			214									
D18					288									42	173			
D19			179								16					291		

k	C2	C4	C8	C13	C14	C17	C23
i							
P1				280			
P2		385					
P4							339
P5						311	
P6			303				
P7					423		
P9	347						

b) Risk model

j	DC1	DC2	DC3	DC5	DC7	DC10	DC11	DC14	DC16	DC17	DC19
i											
P2			266		276		96				
P3					237				346		486
P4	503		192								
P5						536	223				
P6							219				
P7			52	541							
P8		516						494			
P9									156	527	

k	C1	C3	C5	C6	C7	C9	C10	C11	C12	C1	C13	C16	C19	C20	C21	C22	C24	C25
j																		
DC1										260					105			138
DC2	308														208			
DC3			177	116		73												144
DC5		35							253				253					

DC7		74	153				286											
DC10								488										48
DC11														273			265	
DC14												394						100
DC16				172	288									42				
DC17									81		446							
DC19		139														347		

k	C2	C3	C4	C8	C13	C14	C17	C23
i								
P2			385					
P4								339
P5							311	
P6		158		303				
P7						423		
P8					20			
P9	367							

For Problem size- 7 X 14 X 18 X 3

a) Deterministic model

j	DC1	DC3	DC4	DC5	DC6	DC7	DC10	DC11	DC14
i									
P2		510				128			
P3			153		531	385			
P4	503			106					425
P5				173			536	50	
P6								456	
P7			331	262					

k	C1	C2	C3	C5	C6	C7	C9	C10	C11	C12	C13	C15	C16	C18
j														
DC1							223				280			
DC3				330	180									
DC4	308	176												
DC5			148			59				334				
DC6							243							288
DC7			258					255						
DC10									90			446		
DC11					108				398					
DC14								31					394	

k	C4	C8	C14	C17
i				
P2	385			
P5				311
P6		303		
P7			423	

b) Risk model

j	DC1	DC3	DC4	DC5	DC6	DC7	DC10	DC11	DC14
i									
P2		510				128			
P3			153		531	385			
P4	503			56					475
P5			223				536		
P6								456	
P7			108	485					

k	C1	C2	C3	C5	C6	C9	C10	C11	C12	C13	C15	C16	C18
j													
DC1						223				280			
DC3				222	288								
DC4	308	176											
DC5			207						334				
DC6						141							390
DC7			119	108			286						
DC10								90			446		
DC11						58		398					
DC14		1	80									394	

k	C4	C8	C14	C17
i				
P2	385			
P5				311
P6		303		
P7			423	