ROBUST SUPPLY CHAIN DESIGN AND OPTIMIZATION UNDER RISKS AND UNCERTAINTIES

Submitted by

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Respectfully dedicated to
My Parents, My Wife,
My Teachers
&
the beautiful soul of
My Grandmother

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY JAIPUR
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Certificate

This is to certify that the thesis entitled **"Robust Supply Chain Design and Optimization under Risks and Uncertainties"** being submitted by **Mr. Surya Prakash (ID No. 2012RME9551)** to the **Malaviya National Institute of Technology Jaipur** for the award of the degree of **Doctor of Philosophy** in **Mechanical Engineering** is a bonafide record of original research work carried out by him. He has worked under our guidance and supervision and has fulfilled the requirement for the submission of this thesis, which has reached the requisite standard.

The results contained in this thesis have not been submitted in part or full, to any other University or Institute for the award of any other degree or diploma.

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Declaration

I hereby certify that the work which is being presented in this thesis entitled **"Robust Supply Chain Design and Optimization under Risks and Uncertainties"** in fulfillment of the requirement of **Doctor of Philosophy** and submitted to the Malaviya National Institute of Technology, Jaipur is an authentic record of my own work carried out at the Department of Mechanical Engineering under the supervision of **Dr. Gunjan Soni**, Assistant Professor, Department of Mechanical Engineering, Malaviya National Institute of Technology, Jaipur and **Prof. Ajay Pal Singh Rathore**, Professor, Department of Mechanical Engineering, Malaviya National Institute of Technology, Jaipur. The results contained in this thesis have not been submitted in part or full, to any other University or Institute for the award of any degree. The content of the thesis has been checked for plagiarism and has been found under acceptable limit.

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Abstract

Management of uncertainties and related risk in supply chain network has become an integral part of a holistic supply chain management (SCM) philosophy. The contemporary organizations need to leverage performance on the frontiers of product variety, product customization, service, quality improvement, flexibility, technology, employee involvement, environmental and sustainability issues. Such expectations have put the supply chain under a lot of pressure. The literature review revealed that there are a number of uncertainties in supply chain that leads to the risks in the supply chain.

There were two ways to handle the risks and uncertainties, ex-post and ex-ante approaches. The objective of both the philosophies is keeping the performance of supply chain at an acceptable level during disruptions or risk events. Some companies do so in reactive fashion i.e. responding to risks as they appear (ex-post), while others are proactive or planning in advance to manage them (ex-ante). The proactive approach can be infusing risk or uncertainty management philosophies in strategic decision-making at supply chain designing stage. Supply chain network design (SCND) is primary strategic decision step which involves defining supply chain network topology to serve the customers in the best way. Because of interdependent decisions in the closed-loop supply chain (CLSC) environment, considering the designing of forward and reverse network disjointedly may lead to suboptimal results. Moreover, in CLSC network context, there is insufficiency of studies which has investigated direct shipping (DSP) of products to the customers parallel with routing the shipments through distribution centers (SDC). Such arrangement will affect the optimality of the supply chain network along with risk and uncertainty aspects. The aim of this study is to design, develop and optimize mathematical models representing the SCND for CLSC network context when multiple risks and uncertain network parameters are taken into consideration.

There are three distinct focus of this research. First deals with the robust supply chain design and optimization under demand uncertainty for the select CLSC. This is important because of the excessive importance is given to the demand

management from company's perspective to have a robust network, high service level even in worst situations. There is a scarcity of literature on the discussion as how the initiatives were taken to prevent these uncertainties affect firm's supply chain configurations and profitability. In this part, numerical tests and simulation are used to perform experiments on the performance of different supply chain configurations under demand uncertainty. The second part is an extension of robust network design modeling to accommodate some operation risks to improve the reliability of the network. The two parts are two separate chapters and present the much needed mathematical models in this predominantly theoretical field. Finally, a case study of an Indian furniture e-commerce firm is provided to demonstrate the practical applicability of the proposed models to redesign its supply chain. We believe that the proposed risk and uncertainty management models should improve a supply chain competence in the new uncertain business environment.

Instarting, a CLSC network design and planning problem with uncertain demand is addressed, formulated and solved. The proposed CLSC network captures DSP as well as SDC simultaneously. The deterministic modeling of this model is formulated first. This deterministic model is modified to address the demand uncertaintybased on robust optimization (RO), and robust counterpart (RC) is generated. The RC is numerically tested and programmed in AIMMS© and solved with CPLEX® for a set of test problems of different network sizes.

The computational results shows that the network configuration obtained from RO based model is capable of handlinghigher level of demand variations as compared to network structure defined by deterministic modeling. The total supply chain cost of the deterministic worst case was found to be higher than RO model. Hence, it can be argued that the solution provided by RO approach is superior to deterministic model under worst case data realization for uncertain parameters. Additionally, a high service level can be achieved by RO modeling too. The configurations obtained from RO models also ensure the low stock out rate which in turn also improves the responsiveness. Additionally, the company revenue, brand image, customer experience, stock value,etc. will also improve. But, the focus will be more on improvements in delivery side of the supply chain and making it robust and reliable. In RO model, there are more quantities shipped directly to the customers as compared to a deterministic model which shows that the network topology achieved through RO model is more capable of engaged in DSP to benefit more. Thus, this research advocated the adoption of RO methods to counter the effect of parameter uncertainty and argued that the supply chain configuration obtained from RO will be not only superior but also optimal too.

In the RO formulation, operational and tactical level risk are not considered. However, apart from demand uncertainty in SCND, the tactical and operational level challenges must be included to obtain not only a robust network topology but also reliable functioning. Hence, in next step, attempts are made to reformulate the RO model to improve network reliability under risks keeping the robust behavior of model intact. In other words, a method is proposed for robust and reliable supply chain design and optimization under supply risk, logistics risks and demand uncertainty for a single product, single period, and multi-echelon supply chain network. It is observed that supply chain configuration obtained through combined RO and risk (called RORU) model has high cost as compared to the network topology obtained from the pure deterministic case. The performance of the supply chain network realized under risk and uncertainty is also superiorregarding total supply chain cost, service level, stock out rate, total facility cost, etc. Finally, on the basis ofinsights from mathematical modeling, a unified approach for supply chain risk and uncertainty management is also proposed. The proposed approach integrates the procedure of previous chapters in a cohesive manner such that the supply chain manager can easily follow and implement them in their organizations.

The proposed integrated approach is applied to an Indian e-retailer which manufactures and sells the furniture online. Both, RO and RORU models are applied to achieve the SCND for the case company. The SCND models are developed and used for generating RSCO strategies and topology for the case company. In the end, relevant recommendations derived from the case results are discussed.

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Abbreviations

SCM	Supply chain management
SCRM	Supply chain risk management
SCND	Supply chain network design
CLSC	Closed-loop supply chain
RSCO	Robust supply chain optimization
LP	Linear programming
MILP	Mixed-integer linear programming
SLR	Systematic literature review
SCRAU	Supply chain risk and uncertainty
BRICS	Brazil, Russia, India, China and South Africa
ROI	Return on investment
PCR	Plant cum recovery center
DC	Distribution center
CZ	Customers
DIC	Disposal center
RC	Robust counterpart
OFV	Objective function value
DWC	Deterministic worst case
ROBS	RO approach based on Bertsimas and Sim approach
NPV	Net present value
RORU	Robust optimization under risk and uncertainty
NPI	Network performance indicators
DSP	Direct shipment
SDC	Shipping through DC
RO	Robust optimization
RORU	Robust optimization under risk and uncertainty
B2C	Business to customer

CHAPTER 1
INTRODUCTION

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Introduction

1.1 Introduction

In today's globalized, aggressive and uncertain business environment, companies continue to discover that designing and operating a robust and reliable supply chain is essential to meet customer demands and maintain profits (Solo, 2009). For the contemporary firms, supply chain management (SCM) is playing a vital role to remain competitive and integrated with world economies. A supply chain has to manage the flow of a large amount of information and variety of products across all its echelons. The organizations have to deliver the right quantities, to the right places at the right time with the minimum costs and at best customer service levels. Apart from it, the organizations need to leverage performance on the frontiers of product variety, product customization, service, quality improvement, flexibility, technology, employee involvement, environmental and sustainability issues. Such expectations subject the supply chain members under a lot of pressure to become efficient.

An efficient supply chain can reduce costs and raise the profit of a firm. One of the most important features of SCM is supply chain network design (SCND) (Dai and Zheng, 2015). The SCND involves defining network topology to serve the customers in the best way. When a forward and reverse logistics network is considered simultaneously, a closed-loop supply chain (CLSC) network is formed and it has a bidirectional flow of products (Dai and Zheng, 2015). Because of interdependent decisions in CLSC environment, considering the designing of forward and reverse network separately lead to suboptimal results. The interdependence in supply chain can be understood by the complex nature of relations and decisions among supply chain members such as supplier, manufacturer and end user. Thus, decisions regarding forward and reverse flow in CLSC should be considered simultaneously. Apart from it, uncertainty in designing supply chain network is the another important concern, and inherent uncertainty of reverse logistics flow makes the problem harder to address (Dai and Zheng, 2015). All such challenges have forced the organizations to embark on strategic planning, which involves SCND and risk consideration at the strategic level (Hollmann, 2011).

The aim of this study is to design, develop and optimize the mathematical models representing the SCND for CLSC network when multiple risks and uncertain network parameters are taken into consideration. Predominantly, the proposed solution methodology helps the managers in facility location and network configuration decisions under risk and uncertain environment. The research presented in this document performed the optimal design and planning of a multi-echelon closed loop supply chain network using robust optimization approach under demand uncertainty along with supply and logistics risks. A generic CLSC network case is used for mathematical modeling. The CLSC network structures are vital and very relevant in present times. The mathematical modeling is used as a foundation for proposing an integrated approach for supply chain optimization and SCND under risk and uncertainty.

The resulting robust optimization based modeling and solution methodology provides supply chain managers an efficient tool. This proposed approach can be customized as per the requirement to a particular supply chain scenario, giving both supply chain designers and operators a framework for developing and managing supply chains realistically under risk and uncertain conditions. The remaining part of this chapter provides an overview of SCM, SCND, risk and uncertainty management, research plan and thesis outline.

1.2 Overview and Motivation

1.2.1 Supply chain management

The supply chain is an integrated system of entities involved in the upstream and downstream flow of products, services, finances, and/or information from a source to a customer (Mentzer et al., 2001). In simple words, if a company makes some product or products using different parts/assemblies that are purchased from suppliers, and those products are sold to customers, then this company has a supply chain. The supply chain of a company can be very simple or complex depending upon the products and services offered. In simple words, the supply chain is the system of business entities, humans, technology, information and resources involved in moving a product or service from supplier to customer. It transforms natural resources, raw materials, and components into the finished product that are used by the end customers.

Melo et al. (2009) provided typical supply chain network structure in which they show the supply chain as a CLSC network of suppliers, plants, distribution centers, collection centers and recovery centers. Figure 1.1 shows this typical supply chain network structure. The SCM concerned with activities required to manage the firm at various levels of decision making, ranging from operational level to strategic level via tactical level (Simchi-Levi, 2005). The decision-making at the strategic level is made based on long-term objectives and have long lasting effect on the network.

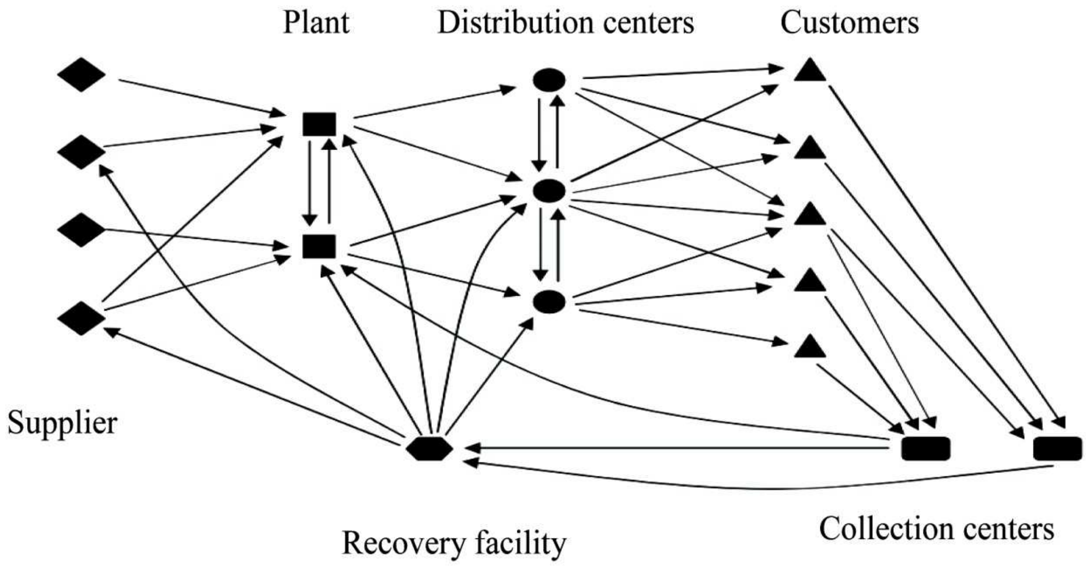


Figure 1.1: A typical closed loop supply chain network structure (adopted from Melo et al. (2009))

Due of the inherent complexities in supply chain systems and significant quantitative data used in decisions making, optimization methods offer the appropriate way to balance the trade-offs, determine the best locations for facilities, and support better decision making. In general, optimization methods rely on linear and integer programming (Watson et al., 2013). The supply chain optimization allows managers to determine the best locations for facilities, to identify details of the alternatives (where to locate, what is made where, how product flows, which customer to be served by which warehouse, etc.) (Watson et al., 2013).

Supply chain optimization (SCO) is the study of strategies and methodologies that enables the organizations to meet their objectives efficiently (Chowdhury, 2015). Again, this SCO problem can be categorized as a strategic, tactical and operational problem, leading to obtaining an optimized supply chain topology (Chowdhury, 2015). It also includes the decisions concerned with locating and selecting the facilities which play a critical role in the strategic design of supply chain networks (Melo et al., 2009). Thus, SCO is an activity related to strategic supply chain planning. Additionally, at any point of time in the decision-making process in SCO, it is likely to have some parameters that are not known exactly, but these parameters might have significant effect on the performance of supply chain. For example, product demand, product price, raw material, transportation cost, labor cost, fuel cost, etc. (Aras et al., 2008). If these uncertain parameters are not included in the SCO process, this may lead to poor operational decisions which will result in poor economic performance. This study uses SCO for the complete CLSC network configuration after risk and uncertainty taken into consideration.

The CLSC network structures have integration of traditional 'forward' supply chain processes and 'reverse' supply chain processes. The typical supply chain network structure shown in Figure 1.1 has a reverse flow of material or used products through collection centers and recovery facilities. Sometimes, the entire business model of a company depends on its forward-reverse linking such as e-commerce business. General overviews of reverse logistics and CLSC can be found in Fleischmann et al. (1997); Govindan et al. (2014); Özceylan et al. (2014). There is a practical need for closing the loop of supply chains because product returns can be very high, sales opportunities in secondary markets, end-of-life take-back regulations, reclaim value through returned products, customer service, etc.

The SCM literature is rich with CLSC studies. The CLSC differ from the reverse network as CLSC optimize the forward and reverse network although the reverse supply chain optimizes only the reverse network flow activities. For more details on CLSC, the readers can go through Lundin (2012), Vahdani et al. (2012, 2013a), Qiang et al. (2013), Ramezani et al. (2014), Soleimani et al. (2014) and Dai and Zheng (2015). Thus, in this study selection of CLSC network to demonstrate the reliable and robust SCND modeling is of high importance. The subsequent section will provide the required details of risk and uncertainty in the SCM context.

1.2.2 Risk and uncertainty in supply chain

The risk in the supply chain is the state when unexpected events disrupt the flow of materials or products on their journey from initial suppliers to final customers (Waters, 2007). Risks occur because one can never know about the future deeds or insecurities in the business environment. Additionally, each process and decision in business are prone to uncertainty (Heckmann et al., 2015). The organizations can rely on available forecasting methods and do every possible analysis to manage them, but still, there is always uncertainty about future events, and their outcome will affect the management actions (Xanthopoulos et al., 2012). These risks came either from upstream or downstream of its supply chain and are caused by external sources such as natural disasters, economic crises, terrorist attacks or internal activities within the organization such as disruptions in supply, security breach, failure of information technology and infrastructure, etc.

There is some disagreement among researchers regarding precise definition of risk and uncertainty (Khan and Burnes, 2007) but there are no doubts about its presence, and risk management is a well-understood subject in SCM. Jüttner et al. (2003) define supply chain risk as "*the noticeable variation in the possible supply chain outcomes, their likelihoods, and their subjective values*". Hetland (2003) explained that risk is an implication of a phenomenon being uncertain. Interestingly, in literature, risk and uncertainty are being used interchangeably (Peck, 2005; Ritchie and Brindley, 2007; Colicchia and Strozzi, 2012). These authors also suggested that the distinction is blurred to the extent that it is not important to distinguish between the two.

Simangunsong et al., (2012) argued that the difference exists because the type of outcome that might be expected from risk and uncertainty is very distinct as the risk is only associated with issues that may lead to negative outcomes while issues of uncertainty can have both positive and negative outcomes. Simangunsong et al., (2012) provided the example that the risks caused by any event of natural disaster only lead to supply-chain problems; whereas customer demand uncertainty can result in demand being either better or worse than expected. Additionally, the key difference between them can be that risk has some quantifiable measure for future events, and uncertainty does not (Khan and Burnes, 2007; Waters, 2007). This study considered the risk and uncertainties as a separate phenomenon and assumed that presence of risk may lead to uncertainty in the supply chain and addressing both will make the supply chain more robust and reliable Hatefi and Jolai (2014). The incorporation of such situation in practical conditions is of one of motivation behind our work.

On the similar lines, disruptions, crisis, disasters and uncertain business environment lead to the shortage in production, delay in shipments and loss of sales which are very critical to the performance of the company (Shukla et al., 2011). In recent years itself, there are many instances when supply chain of a company underwent such situations. For example, Fukushima earthquake (Japan) in the year 2011 resulted in supply disruption for many automobile and electronic goods manufacturers (e.g. Toyota, Honda, Sony, etc.). Similarly, the China floods in 2013 hit supplies for many manufacturing companies in all the key sectors and the labor unrest at one of the Maruti Suzuki India plant had significant financial implications for the company in 2012. Hence, a disruption affecting an entity anywhere in the supply chain has a direct impact on company ability to produce, distribute, operate, or provide services to customers (Jüttner et al., 2003). Thus, all such cases motivated us to understand and study various supply chain risk and uncertainty issues, necessitating robust methods to deal with them.

In this pursuit, the firms find that designing and operating an efficient and responsive supply chain is one of the key strategies to ensure their success. The prime objective is to determine the appropriate supply chain configuration which continues functioning in the worst scenario. Such robust supply chains are expected to perform at an optimal level in the time of crisis and less impacted by undesirable events. Both the reference process for risk and uncertainty management as well as the minimization of total cost of supply chain operations has given a strong motivation for supply chain risk management. The present work also considers both risk and uncertainty as the factors which hamper the supply chain performance and put forth an integrated approach to managing them jointly. The presence of uncertainty and risk in the supply chain system will impact the firm in a negative manner and their joint management will surely yield more fruitful results to achieve robust and reliable network (Shukla et al., 2011; Simangunsong et al., 2012; Heckmann et al., 2015). Robust from the uncertainty point of view and reliable because the model also addresses supply chain risks. Moreover, this joint treatment of risk and uncertainty will be more efficient at the strategic level. The subsequent section will provide the details about SCND process.

1.2.3 Designing a supply chain

Shapiro (2007) defined SCND as, "*It is the strategic planning of supply chains, concerned with the numbdistribution technology used at each facility, make-or-buy decisions, selection of suppliers, and ter, location, and capacity of facilities and distribution centers, production/ he design of the transportation network*". The risk presence results in an increase in the cost of value-added activities and therefore, risk assessment becomes critical for the supply chain design in order to have optimized process (Singh et al., 2012). Hence, in the context of supply chain design, there is the significant extent of decisions that must be made by considering relevant risks (Melnyk et al., 2014). This observation strengthens our point that along with SCND and SCO, the uncertainty and risk consideration are also vital. It also implies that firms should endeavor to achieve a level of robustness in its operations.

The strategic decisions taken in the planning stage put down the foundation for robust supply chain behavior. Research on robust SCND has only recently received significant attention. In the literature review chapter, we have investigated the available literature on supply chain risk, uncertainty, and robustness aspects. The literature review revealed the lack of research work to achieve robust and reliable SCND. It was also found that there is an absolute need for integrating the strategic decisions, tactical decisions and operational actions to make supply chain planning and operations robust for varied type of risks and uncertainties. This phenomenon is termed as robust supply chain optimization (RSCO). Furthermore, the supply chain risk and uncertainty consideration in SCND have not got much attention of researchers.

Cintron (2010) highlighted that the supply chain decisions are broadly three categories: strategic, tactical, and operational. The most significant one is the strategic decisions which are those decisions that are classically made for the long term and not easy to alter later on. The typical example of such decisions includes facilities planning and the design of the supply chain network. The second classes of decisions are tactical decisions which typically taken for a couple of quarters or year. The tactical decisions comprise of decisions such as inventory management, production planning, logistics, price promotions, discounts, etc. Lastly, the decisions that made on monthly or weekly bases are termed as operational decisions. It is worth noting here that there is not a clear demarcation of the scope of these decisions. These decisions mostly span multiple functions in each organization and are usually made at multiple levels (Fleischmann et al., 2002). The extent of one type of decisions may infringe other. Thus, it will be of great use to investigate and analyze the supply chain decisions holistically and integrate them in SCND to get maximum benefits of SCO.

1.2.4 Robust supply chain design and optimization

In the SCM and supply chain risk management (SCRM), several terms have been used in literature to describe the ability to handle the crises, such as *robustness*, *resilience* and *flexibility (or agility)*. In business setting when the crisis (e.g. disruption, strikes, plant failures, risk events, etc.) arises, *resilience* is the ability of a firm to survive, and *flexibility or agility* is the capacity to change the course, while *robustness* is the ability to regain stability. The stable supply chain is the need of the hour, and this study takes necessary steps for robust supply chain design and optimization under risks and uncertainties. Figure 1.2 presents the illustration of the concept of flexibility or agility, robustness, and resilience.

Designing robust supply chain networks help firms to maintain and enhance the competitive advantages as they encounter with a number of environmental turbulence and uncertainties (Hatefi and Jolai, 2014). For example, in the e-commerce business, the firms frequently face the uncertainty of demand and quantities of products returned. For handling such issues, companies may work proactively and should do supply chain network design/redesign considering uncertainty and risks. They must target for robust network design to accommodate uncertainty of parameters.

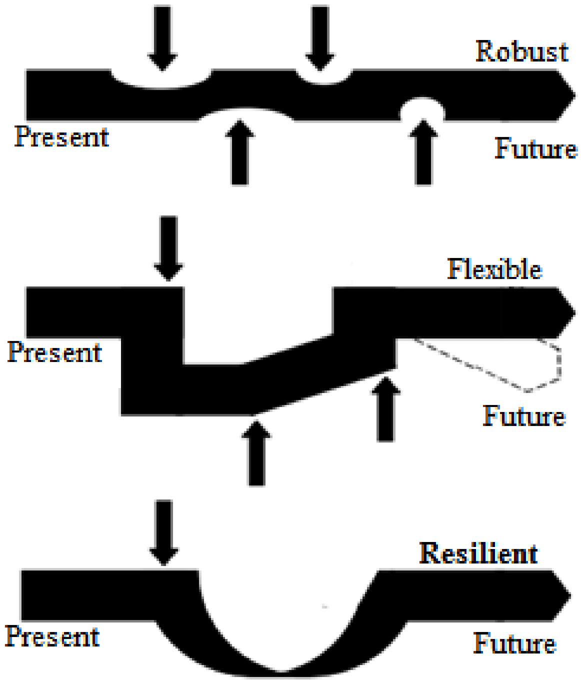


Figure 1.2 Illustration of concept of flexibility or agility, robustness, and resilience (adopted from Rusman, 2013)

For modeling the uncertainty in the supply chain, some approaches are adopted by the researchers such as stochastic programming, scenario analysis (Subulan et al., 2014), fuzzy, grey (Samvedi et al., 2013), etc. Grey theory is generic mathematical theory that deals with system characterization under incomplete information. It has been applied in various fields such as systems analysis, data processing, modeling, decision making, demand prediction and supply control (Samvedi et al., 2013). The stochastic programming is one of the most popular methods used by researchers for addressing the uncertainty (Listeş, 2007; Pishvaee et al., 2009). However, the stochastic programming has certain limitations, such as; it takes random variables with known probability distributions (Pishvaee et al., 2011). While, in real life cases, sometimes, there is not enough historical data available, thus, obtaining the actual probability distributions for uncertain parameters becomes less practical. Moreover, the complexity of applying the distribution function can limit the number of considered uncertain parameters.

Scenario-based analysis can handle this shortcoming of stochastic programming approach. To capture the real life instances, a sufficiently large number of scenarios are required; again, this could be a computationally challenging task for managers. Additionally, there is a high chance that the solution could be far from optimal as well. The fuzzy programming approaches offer the solution considering model variables as fuzzy numbers. This methodology offers the potential of dealing with problems involving noisy, incomplete or erroneous data (Ramezani et al., 2014). However, the applicability of fuzzy assessment models in actual industrial practices is questionable because the final outcome of fuzzy models depends on the qualitative judgment of the linguistic variables used in the study (Nepal and Yadav, 2015).

One of the effective framework to handle the uncertainty of parameters in optimization problems is based on robust optimization (RO) theory, which immunizes the optimal solution for any realization of the uncertainty in a given bounded uncertainty set (Pishvaee et al., 2011). We explore the potential of RO as a general computational approach to managing uncertainty, feasibility, and tractability for complex problems. The solutions are generated with the assumption that the uncertainty resides in an appropriate set and RO guarantees the viability of the solution within the prescribed uncertainty set by adopting a min–max approach (Ben-Tal et al., 2011).

The RO eliminates the limitations of stochastic programming of estimating the probability distribution from historical data to optimize the solution against parameter uncertainty specifically against the worst-case scenario (Carlsson et al., 2014). The worst case of the constraints is computed over a convex uncertainty set of the parameters, which bounds the maximum allowable deviation of the parameters from their nominal values (Ben-Tal and Nemirovski, 1999; Ben-Tal et al., 2009). Hence, the strategic issues in SCND i.e. to determine the optimized configuration of the supply chain network are modeled using RO approach. It is worth noting that uncertainty in various supply chain parameters can be modeled by RO effectively. However, the need of the hour is not just uncertainty management but risk considerations as well.

This observation is in line with the arguments of Hatefi and Jolai (2014), Vahdani et al.(2012), Simangunsong et al.(2012) and Shukla et al.(2011) that disruptions (disasters, strikes, economic, etc.) should be considered while designing supply chain to make them more reliable and efficient. Hence, the robust model is extended to accommodate the risks. The aim is to analyze the impact of various risks in supply chain context and develop a model with embedded risk and uncertainty for deriving SCND decisions. The approach proposed by Singh et al. (2012) and Kumar et al. (2010) for the design of a supply chain network with operational risk is adopted and used with suitable modifications to integrate it in RO. Thus, attempts are made for obtaining a unified model for getting insights for strategic decisions regarding supply chain topology, facility location, supply chain planning, selection of plants, distribution centers, quantity shipped, procurement planning, demand fulfillment, etc.

The robust design of supply chain network is used to propose a framework to cope with uncertainties in network design parameters. The study includes supply risks which occur due to the shortage of supplies caused by the poor status of production capabilities, and the logistics risks are incidents of missing the delivery due to variable lead time in transportation. This study tries to present a unified methodology to address risk and uncertainties in SCND, which will result in providing a RSCO framework.

1.3 Research objectives

The literature review shows that majority of the research work done has focused either on strategy formulation for SCRM aspects or addressing the uncertainty of certain parameter in an existing network. Mostly, the nature of the investigation is qualitative having more focus on risk management theories. Additionally, the SCRM mathematical models have focused on only modeling the forward flow of supply chain networks. The risk and uncertainty treatment at network design level is also not investigated much for CLSC and various shipment processes. Moreover, the demonstration of the models through numerical tests is done for small instances and only cost based network performance indicators are used. Thus, there is an acute necessity for quantitative and empirical research in SCRM and SCND domain which uses a large number of instances for demonstrating the cases related to uncertainty and risk management to find a optimal supply chain configuration.

As highlighted earlier that risk and uncertainty are closely connected terms and in literature, both are being used interchangeably (Ritchie and Brindley, 2007; Colicchia and Strozzi, 2012). This study considered the risk and uncertainties as separate entities and acknowledged the fact that presence of risk may lead to uncertainty in the supply chain and addressing both, risk and uncertainty together, will make the supply chain robust and reliable. This interlinking of risk and uncertainty supports our argument that they must be handled using in a unified manner even in CLSC context. There is a requirement of some unified approach to manage supply chain risk and uncertainty to get a robust supply chain topology. The literature review revealed that such attempts are very limited, and a research gap still exists.

The general research problem can thus be stated as, '**To contribute to the knowledge on how to develop a model of a CLSC network with simultaneous shipping using deterministic design parameters and how to design, optimize and manage such CLSC under risks and demand uncertainty so that the supply chain network design decisions are better understood, modeled, analyzed and optimized, which lead to robust and reliable supply chain configuration and planning'**. The problem has been broken into following three specific research objectives.

i. To develop a model of a closed-loop supply chain network with simultaneous shipping using deterministic design parameters.

ii. Modeling a robust and optimal supply chain configuration for the select closed-loop supply chain network under demand uncertainty.

iii. Investigating and modeling a robust, reliable and optimal supply chain configuration for the select closed loop supply chain network under demand uncertainty, supply and logistics risks.

The major contribution of this research is an in-depth investigation of the state of the art of supply chain risk and uncertainty. The findings of current research on strategic decision making and SCND under risk will be helpful for researchers and practitioners to carry out risk mitigation in CLSC environment. The mathematical models are developed for addressing risk and uncertainty which will provide an excellent tool for SCND. The study highlights the ways to embark risk and uncertainty management in an integrated manner for achieving RSCO. The models are widely tested (numerically and case data) and provides a rational approach for handling the parameter uncertainty.

The present work successfully demonstrates the modeling methods for handling operational tactical risks and uncertainties of a supply chain. This research also contributes to the knowledge by providing an integrated approach for supply chain uncertainty and risk management to achieve RSCO. The eventual goal of this research is to create opportunities for industrial managers and researchers to improve SCND decisions so that the impact of risk and uncertainty on realized supply chain network will be minimal, the total supply chain costs will be less and supply chain configuration obtained will be optimal. A brief discussion of the objectives of the study and methodologies used to tackle these objectives is given in next section.

1.4 Research methodology

The aim of this section is to explicate the research methodology adopted in the present study. It describes the research plan, mathematical modeling and programming, solution approach and resources, numerical tests, and other procedures that are appropriate for achieving the research objectives mentioned in the previous section. The overall research plan is illustrated in Figure 1.3. First, an explicit description of fundamentals of supply chain risk, uncertainty and robustness will be developed.

This discussion helps in removing the ambiguity and vagueness about the SCRM, robust SCND and RSCO. Secondly, the methodologies for designing robust and reliable supply chain will be identified. Based on the other issues synthesized from the extant literature regarding robust supply chain design and optimization under risks and uncertainties and identified methodologies for modeling and designing a CLSC, an integrated approach for robust SCND is proposed and demonstrated.

The literature review has been discussed in Chapter 2. Literature review described the fundamentals of supply chain risk and uncertainty management, SCND and the important issues regarding robust SCND. As a starting point, the critical analysis of supply chain risk and uncertainty content is carried out. It has provided the critical SCRM issues such as most common risk, causes of risk, the impact of risk on supply chain design, etc. Further, the SCM and SCND literature are investigated to synthesize the robust SCND domain. The key trends regarding SCND under risk and uncertainty, robust optimization methods, etc. are analyzed, and research gaps were identified. The steps of research approach followed in this study (Figure 1.3) are explained below:

Setting objective and scope: In this step, research objectives are set keeping in mind the findings of literature review and the research gaps. The SCND decisions along with risk and uncertainty related investigations are carried out.

CLSC network design and modeling: The study proposes a model of a CLSC network with simultaneous shipping using deterministic design parameters. The CLSC model developed here captures the direct shipments (DSP) of products from plants as well as the delivery of the products through distribution centers (SDC) in a simultaneous manner. Appropriate solution methods and resources are identified and employed to get the solutions of the deterministic data cases using AIMMS© and CPLEX® (Ashayeri et al., 2014; Setlhaolo et al., 2014).

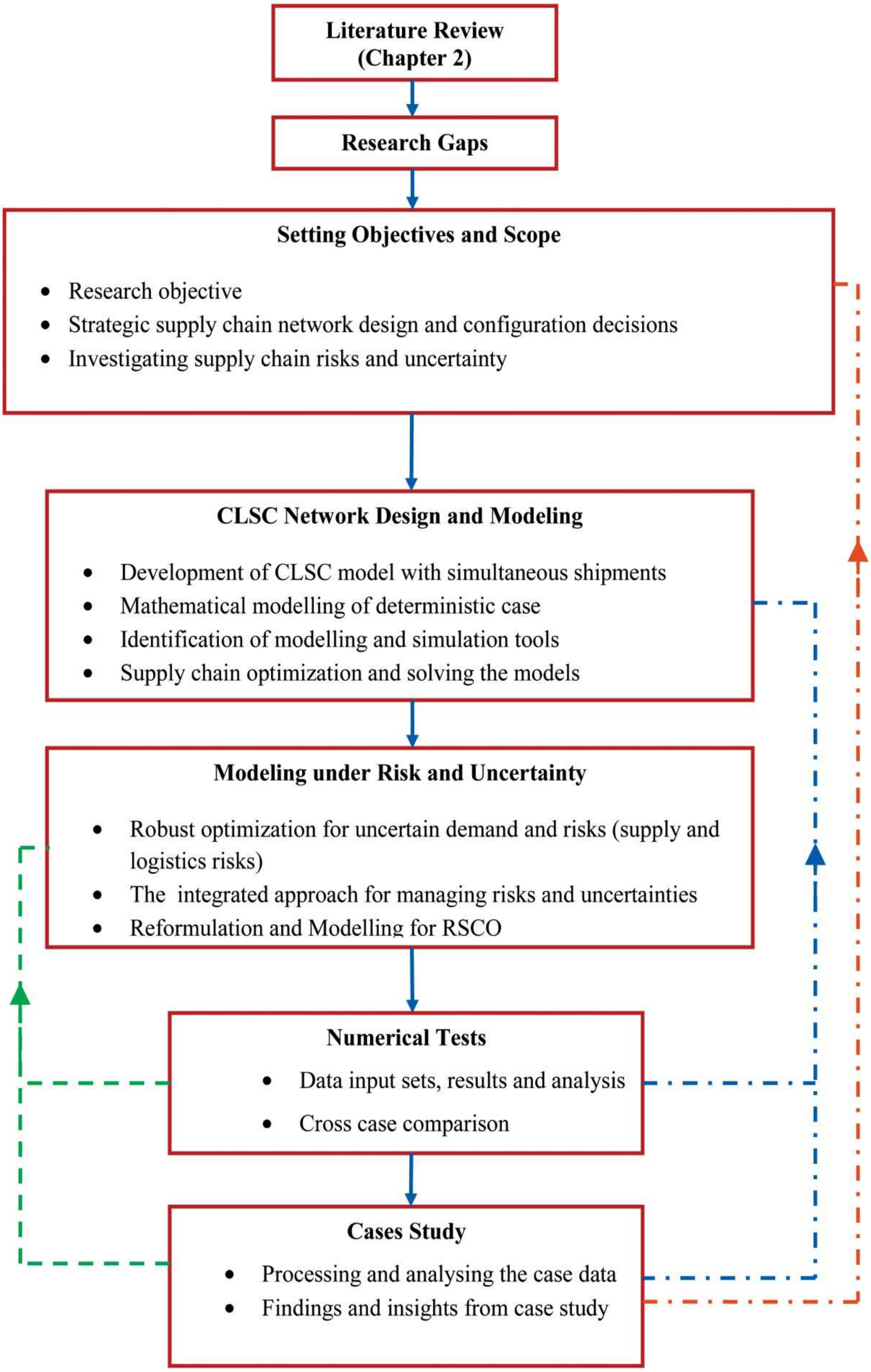


Figure 1.3: Research plan

Modeling under risk and uncertainty: First, the suitable methodology to address the uncertainty of network parameters has been identified. After this step, the appropriate modeling technique for RSCO is identified. The RO is used to accommodate the demand uncertainty and solved with AIMMS© and CPLEX®. In next step, the model is extended to accommodate critical tactical and operational risks. Finally, a unified model for incorporating supply chain risks and uncertainty is formulated. The same CLSC network is used for reformulation and modeling under demand uncertainty, supply risk, and logistic risks.

Numerical tests and case study: It is the culminating step of research plan which deals with solving the embedding risk and robust model. Numerous tests are performed, and a case of a manufacturing firm is also presented. The impact of risk and uncertainty on various network topologies is analyzed. This complete research plan is provided in Figure 1.3.

1.5 Thesis outline

The thesis is organized into five chapters. Chapter 1 highlights the aims and objectives of the research. This chapter also discusses the research methodology followed in this study.

Chapter 2 presents a comprehensive literature review of supply chain risk, uncertainty, and SCND problems. The main contribution of this chapter is that it critically analyzed the supply chain risk and uncertainty content of SCM domain. The critical analysis of supply chain risk and uncertainty content is done by following a systematic literature review (SLR) process. The SLR is an approach in which the appropriate research articles are located, identified, collected and analyzed in a structured manner. The sample of the review contains 343 articles from major academic online databases or publishers such as Science Direct, Emerald, JSTOR, Taylor and Francis, Sage and Wiley, etc. The review findings suggest that demand uncertainty, supply risk, and disruption risk have a high impact on supply chain functioning. The SCND and SCO are a highly critical area of research in SCM, and robust SCND is scantily addressed.

Chapter 3 focuses on achieving the first and second objectives of the present research. The overall aim is robust modeling of CLSC network design under uncertainty or RSCO in the context of CLSC. To perform this, the chapter illustrates the appropriate mathematical modeling paradigm for handling the demand uncertainty. Firstly, a closed loop supply chain is described from a complex SDC, DSP and return of product perspective. This generic CLSC model is mathematically formulated called as a deterministic model. It is revealed from literature that the demand side risks are one of the major issues in SCM. Hence, the deterministic model is reformulated considering demand uncertainty. This uncertainty of demand is handled by mathematical modeling of robust optimization approach. The resulted mathematical models follow mixed-integer linear programming (MILP) formulation. The robust counterpart (RC) is solved for the set of test problems of four different network sizes. The computational results of test problems indicate the superiority of the robust model for handling the uncertainty. It was observed that the robust optimization approach gives better results than the worst case of the deterministic model while addressing the uncertainty.

Chapter 4 aims at analyzing the risks present in CLSC context and how these risks can be taken account into for SCND process to achieve RSCO. It achieves the third objective of this study. The goal is to present a mathematical model for robust CLSC network design under risk as well as uncertainty. The robust optimization model is extended to accommodate some supply chain risks. First, the mathematical formulation is proposed for robust supply chain design and optimization under supply risk, logistics risks and demand uncertainty for a single product, single period, and multi-echelon supply chain network. Second, the model is solved under the similar data settings as the model presented in Chapter 3. The combined effects of risks and uncertainty management on supply chain cost are observed, and optimal supply chain configuration is obtained. The chapter concludes with providing an integrated approach for SCND under uncertainty and risk to determine robust and reliable network topology is presented.

Chapter 5 presents a case study of a furniture and home decoration products e-commerce marketplace. The proposed robust and reliable supply chain network design approach is applied to redesign the close-loop supply chain of the case company. The required inputs for SCND under supply risk and logistics risks are estimated in the first step. The optimal supply chain configuration of case company obtained without risk and uncertainty considerations is compared with risk and uncertainty topology. The chapter provides total supply chain costs, the flow of quantities and products routed through SDC and DSP for the case. It is established with case data that in the worst case of demand uncertainty and under risk environment, the robust and reliable models provides efficient and optimal supply chain configuration.

Chapter 6 concludes the thesis with a discussion of the contributions made, limitations of the present research as well as the future research directions.

CHAPTER 2
LITERATURE REVIEW

Chapter 2
Literature Review

2.1 Introduction

This chapter provides a state-of-the-art review of supply chain risk and uncertainty management literature. The purpose of this chapter is twofold; first, perform a critical analysis of supply chain risk and uncertainty related content and second, identification of research gaps from the findings of the literature review. For this purpose, the systematic literature review (SLR) approach based on Tranfield et al. (2003), Webster and Watson (2002), and Soni and Kodali (2011) has been adopted. At first, the supply chain management (SCM) domain is investigated to find the research gaps and future scope. Next, on the basis of observations from this portion of the review, a separate focused review was conducted for robust supply chain network design (SCND) and closed-loop supply chain (CLSC) content. Initially, 347 research papers are taken from peer-reviewed international journals which were used for synthesizing the review process. The selected articles are coded and classified in select categories for performing the SLR. Section 2.2 presents this initial portion of literature review work. In Section 2.3 and Section 2.4, the focused literature review related to robust SCND, CLSC and robust supply chain optimization (RSCO) under risk and uncertainty is analyzed. Lastly, Section 2.5 provides the research gaps derived from the literature review.

2.2 Critical analysis of supply chain risk and uncertainty content

Traditionally, SCM involves activities that produce value in the form of products and services in the hand of the ultimate customer with the objective of cost reduction and profit maximization (Peidro et al., 2010). Recently, a large number of researchers, as well as practitioners, have started taking a keen interest in supply chain risk management (SCRM). As discussed in the previous chapter, the risk and uncertainty are used in an interchangeable manner for describing the negative instances for the firms. We have investigated the literature related to supply chain risk and uncertainty (SCRAU) in the context of supply chain network design (SCND). The SCRAU management has drawn significant attention due to various reasons such as the competitions in the market, constant desire of firms to cut costs, reduce product lead time, etc. Moreover, the global supply chain network structure, technological change, desire for getting more customers, emphasis on providing better customer satisfaction and continual search for competitive advantage have forced firms towards more vulnerability.

Thus, SCRM has emerged as an attractive area of research. Khan and Burnes (2007) reviewed the SCRM literature to identify the key risk issues and develop a research agenda. Rao and Goldsby (2009) focused on developing a typology of risks in the supply chain. Both of these studies were an early attempt at reviewing SCRM literature and did not provide information regarding sampling and article search methods, the size of the sample, the time horizon of study, classification of articles, etc.

The paper by Tang and Musa (2011) focused on identifying risk issues to investigate the research development in SCRM for the period 1997 to 2008 in using select 21 journals data only by citation/co-citation method. Colicchia and Strozzi (2012) followed systematic literature network analysis to review the literature of SCRM from 1994 to 2010 using Science Citation Index. Ghadge et al. (2012) reviewed the SCRM literature by using search strings of keywords and obtained120 articles sample from 2000 to 2010 in selected 15 identified journals with their ABS ranking. Simangunsong et al. (2012) presented a review and established the theoretical foundation for future research.

Recently, Bandaly et al. (2013) did a review of operational, financial and integrated risks and some risk management approaches were suggested. Furthermore, few other review studies such as Natarajarathinam et al. (2009) reviewed SCM in times of crisis. Finch (2004) took up the issue of information system risk in supply chain for its review, Olson and Wu (2010) reviewed only enterprise risk management, Williams et al. (2008) investigated supply chain security (SCS), and Aloini et al. (2012) performed a review of implementation risks in the construction industry. Table 2.1 provides the summary of some relevant literature review articles from supply chain risk and uncertainty management area. It is observed that most of the review articles are informative and had focused on presenting theoretical viewpoints of the subject and methodologies. Moreover, most of the review articles did not provide complete information about selection procedure of articles, sample size or classification methods.

The systematic literature review process based critical analysis of SCRM content will be able to provide more insight into SCRM research area. This review section of this study has focused on following activities; to identify, locate, select, and analyze the extant SCRAU literature in a structured manner using the risk management process based classification, content analysis and synthesis of the extant literature.

Table 2.1: The summary of relevant literature review articles from supply chain risk and uncertainty management area

S. N.	Article	Article scope	Aim and objective	Sampling & search	Sample size	Time horizon	Journal selection	Focus
1	Finch (2004)	SCRM	Information system risk addressed	Keywords searched in e-databases	NP	1995-2001	NP	Inter-organizational network risks
2	Tang (2006)	SCRM	To develop a framework for classifying SCRM articles	NP	NP	NP	NP	SCM models for managing disruption risks
3	Khan and Burnes (2007)	Risk types and SCM	To develop a research agenda for SCRM	NP	NP	NP	NP	Key risk issues and research questions on SCRM
4	Gümüs and Güneri (2007)	Uncertain demand and lead time	Study point of view is operational research	NP	NP	1996-2005	NP	Demand and lead time uncertainty emphasized.
5	Williams et al. (2008)	Supply chain security	A categorization of Supply chain security (SCS) risk	NP	NP	NP	NP	A comprehensive literature review of SCS.
6	Rao and Goldsby (2009)	Supply chain risks	Developing a typology of risks	NP	NP	NP	NP	Typology of supply chains risks
7	Natarajarathinam et al. (2009)	SCM in times of crisis	Framework to classify literature in crisis management	Keywords databases searches for journals	118	Till-2008	SCM and OR journals	Supply chains in times of crisis
8	Olson and Wu (2010)	Enterprise risks	A generic SCRM framework developed	NP	NP	NP	NP	Chinese firms risk considered

S. N.	Article	Article scope	Aim and objective	Sampling & search	Sample size	Time horizon	Journal selection	Focus
9	Greening and Rutherford 2011)	Supply chain disruptions	Conceptual framework for network of disruption provided	Keywords searched in e-databases of journals	NP	NP	ISI Web of Science	Consideration of network context of disruption
10	Tang and Musa (2011)	Identifying risk issues	To investigate the research development in SCRM	Search on Web of Sciences	NP	1997-2008	21 journals,	The research through citation and co-citation studies.
11	Aloini et al. (2012)	SCRM	A review of implementatio n risks	Keywords searched in e-databases of journals	NP	2000-2011	NP	SCM literature in the construction domain
12	Ghadge et al. (2012)	SCRM	Identify significant strategic changes in the field	Keywords and search strings, SLR followed	120	2000-2010	15 journals with their ABS ranking	Text mining is used in this research
13	Colicchia and Strozzi (2012)	SCRM	Investigating the process of knowledge creation, transfer and development.	Keywords searched in electronic databases	55	1994-2010	Science Citation Index used, 20 journals	Systematic literature networks analysis
14	Heckmann et al. (2015)	Supply chain risk	Definition, measure, modeling	NP	NP	NP	SCM and OR journals	Setting the definition, measure, modeling for supply chain risk
15	Ho et al. (2015)	SCRM	A new definition for SCRM	Keywords searched in e-databases	244	2003 to 2013	SCM and OR journals	Supply chain risk categorization
Note: Y = Yes; NP = Not Provided, SCRM= Supply Chain Risk Management								

Jüttner et al., (2003) defined supply chain risk as "*the variation in the distribution of possible supply chain outcomes, their likelihoods, and their subjective values*". The risk is an implication of a phenomenon being uncertain. In supply chain management literature, the risk and uncertainty are used interchangeably (Colicchia and Strozzi, 2012). Hence, content analysis of SCRM is carried out keeping in mind the risk and uncertainties. In this section of the study, the critical analysis of supply chain risk and uncertainty (SCRAU) content is carried out by following a systematic literature review (SLR) approach, in which the appropriate research articles are located, identified, collected and analyzed in a structured manner. In this manner, this study can produce a comprehensive state of the art of the supply chain risk literature. The subsequent sections will present the details of review methodology and significant observations.

2.2.1 Review methodology

In this section, the issues of time horizon of review, journal selection, article selection, article classification and analysis of articles obtained from the extant literature will be discussed. Figure 2.1 shows the stages, steps and process followed for conducting content analysis and structured literature review. The systematic literature review (SLR) method based on Tranfield et al. (2003), Webster and Watson (2002), and Soni and Kodali (2011) is used. Unit of analysis is research papers (articles written in English) in peer-reviewed international journals.

The 'gate-keeping' function of the peer review system reduces the repetition and enhances quality and the acceptability of the publication source (Gosling and Naim, 2009; Piekkari et al., 2010).

The articles are then categorized to extract the meaningful information for content analysis. Figure 2.1 provides the stages and steps followed for conducting the SLR in SCRAU literature. In Stage-I, article search and sampling yielded the pool of desired relevant research articles. In the Stage-II; content coding and stratification are carried out by creating the categories. The Stage-III presents the synthesis and content analysis of SCRAU research articles. These stages and their procedure are explained in the following sub-sections.

2.2.1.1 Stage-I: Locating the studies and article sampling

The inception of SCM as a separate field of research from operations management has started in late 90's. Available literature shows that significant work on SCRM began in early 2000 (Ghadge et al., 2012). We have chosen the period of collecting the literature from 2004 to starting months of the year 2015. Most of the major academic online databases or publishers such as Science Direct, Emerald, JSTOR, Taylor and Francis, Sage and Wiley, etc., were explored to collect the relevant journal articles using a very broad set of keywords. The primary keywords used include supply chain risk, uncertainty, robustness, reliable, crisis, catastrophe, etc. Table 2.2 presents the number of articles found in each database with search criteria and keywords used in the search process. To expand the search space for locating more studies, two levels of search keywords and string are devised and utilized.

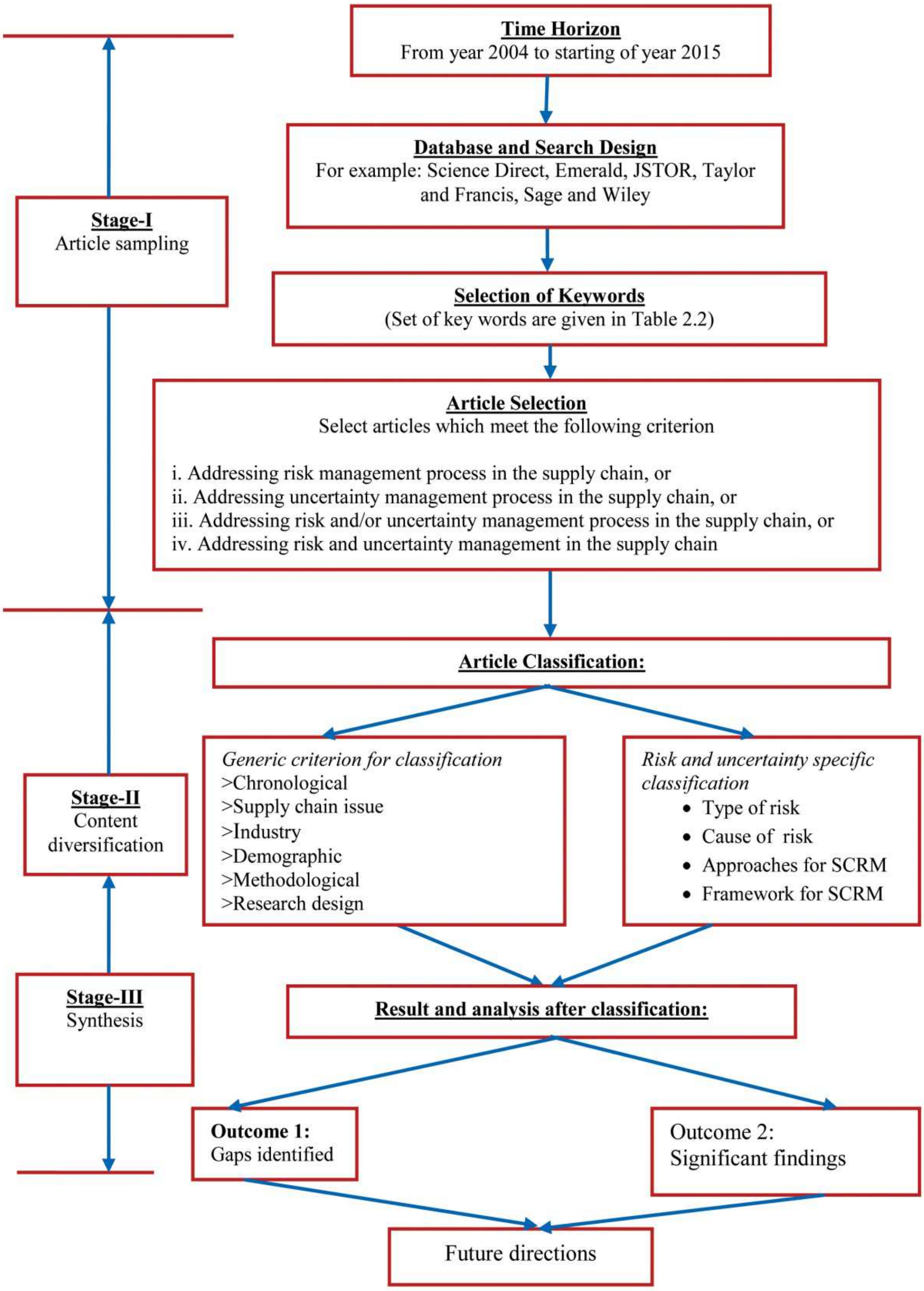


Figure 2.1: The stages and steps followed for conducting SLR and content analysis

The initial pool of articles obtained from all databases was 1620 in number. The sample was consolidated by manually eliminating the duplicate and unrelated articles. It was found that a significant number of articles were related to business risk and financial risk but not related to supply chain context, were there in the initial pool. These articles were removed manually by article title reading abstract. Additionally, cross-referencing was used to find other relevant articles, which were missed during the keyword search. Finally, 347 articles were selected for review. Complete reference list of 347 articles considered is given in Appendix-I.

Table 2.2: Number of articles in each database with search criteria and keywords used in search process

Levels of search	Search criteria and Strings	Abstract title, keyword	Abstract, title, key word	Abstract, title, keyword	All except full text	In title & abstract & keyword	In title & abstract
	Database	Science Direct	Sage	Taylor & Francis	Emerald	Wiley	JSTOR
Level-1	‘Supply chain’ in abstract, title, keyword and ‘Risk’ or ‘uncertainty’ or ‘uncertainty’ in	639	24	72	375	109	95
Level-2	‘Supply chain’ in abstract, title, keyword and ‘vulnerability’ or ‘robustness’ or ‘crisis’ or ‘disaster’ or ‘emergency’ or ‘catastrophe’ or ‘insecurity’ or ‘hazard’ or ‘resilience’ in	124	26	13	49	71	23
	Initial total	763	50	85	424	180	118
Final total of review sample		173	5	51	102	4	12

2.2.1.2 Stage-II: Content diversification

The objective of stage-II of proposed SLR is to carry out content classification based on risk and other entities of articles. In generic classification schemes, the information related to chronological data, supply chain issue, rigor of research and methodological aspects is extracted from selected articles. This category based classification approach is very useful to carry out content analysis (Croom et al., 2000; Soni and Kodali, 2011). The details of these classification categories are given as follows:

Generic classification: In generic classification, the first category is "*chronological categories"*, which extract the information related to year of publication and journal name from the published article. The class "*supply chain issues*" is devised on the lines of Soni and Kodali (2013a) and used to know the main issue of SCM discussed in the article. In this category, some of the supply chain issues are identified and used which includes strategic management**,** manufacturing management, integration, information technology, logistics management, supplier management, demand management, collaboration management, and comprehensive construct (Soni and Kodali, 2013). The class *"industry"* captures the industry for which the work has been reported.

Guo (2008) argued that the researchers from varied backgrounds and regions should work in close collaboration to make any research more fruitful. To know about the degree of such collaborations, information about "*country of sample industry"* and "*country of author"* are recorded. The remaining categories used in the review are based on Burgess et al. (2006). To find out what research methodologies are used by researchers, the class "*mode of study"* (i.e. empirical or desk based) are devised. The class "r*esearch design"* captures the information in articles about the case study, survey, focus group, Delphi study, action research, literature review, mathematical modeling, conceptual framework, etc.

Type of risk and uncertainty based classification: In this category, the type of risk or uncertainty studied in the sample article is observed. The SCRM literature provides a number of risk classifications schemes. Table 2.3 provides few major supply chain risk classifications schemes. The risk classification of this study is based on Christopher and Peck (2005), Samvedi et al. (2013), Tang (2006), Manuj and Mentzer (2008) and Kumar et al. (2010). Christopher and Peck (2004) argued that risks in the supply chain can be broadly of five types. These types of risk includes, *process risk* (risks related to value added activities, processing activities, etc.), *control risk (*risk in batch sizes, order quantities, inventories etc.), *demand risk (*fluctuations in demand, inaccurate forecasting, etc.), *supply risk (*supplier in the network, outsourcing etc.) and *environment risk (*natural disasters, economic downturns, terrorism, etc.) (Christopher and Peck, 2004).

Table 2.3: Supply chain risk classifications schemes

Authors	Risk types/classification scheme
Jüttner et al. (2003)	Environmental risk, network-related risk, organizational risk.
Chopra and Sodhi (2004)	Disruptions, delays in supply, systems risk, forecast risks, intellectual property, inventory and capacity risks.
Christopher and Peck (2004)	External to the network (example- environmental risks). External to the firm but internal to the supply chain network (example- demand and supply risks). Internal to the firm (example- process and control risks).
Manuj and Mentzer (2008)	Supply, demand, operational and other risks.
Tang (2006)	Operational risks: uncertain customer demand, uncertain supply, and uncertain cost. Disruption risks: earthquakes, floods, hurricanes, terrorist attacks, economics crises.
Wu et al. (2006)	Internal risks: internal controllable, internal partially controllable, internal uncontrollable. External risks: external controllable, external partially controllable, external uncontrollable.
Tummala and Schoenherr (2011)	Demand, delay, disruption, inventory, manufacturing (process) breakdown, physical plant (capacity), supply (procurement), system, sovereign and transportation risks.
Kumar et al. (2010)	Internal operational risks: demand, production, and distribution, supply risks. External operational risks: terrorist attacks, natural disasters, exchange rate fluctuations.
Samvedi et al. (2013)	Supply, demand, process, and environmental risks.
Wagner and Bode (2008)	Demand side, supply side, regulatory and legal, infrastructure risk and catastrophic risks.
Ho et al. (2015)	Macro-risks: catastrophic or earthquakes and weather-related disasters) or man-made risks (example- war and terrorism and political instability. Micro-risks: operational or demand risk, manufacturing risk, supply risk and infrastructural risk.

These aforementioned five types of risk are considered for classifying the extant literature. After reading the content of an article, the major types of supply chain risk were identified and corresponding categories of risk is assigned. The generic SCRM papers providing discussion on all type of risk in a paper was classified under a separate category named '*multiple risks*'. In the similar fashion, causes of risk were also assimilated. Total twenty different classes for *causes of risk* in the supply chain are identified.

2.2.1.3 Stage-III: Synthesis

In this step, the data extracted from the content of 347 articles is analyzed and synthesized. The expected outcomes are to identify the growth pattern, trends and research gaps for SCRM and supply chain uncertainty management domain.

2.2.2 Results of content analysis and significant findings

This section presents the results of the content analysis carried out as per the procedure of previous sections and summarizes the significant findings.

The growth of SCRM management area: In this review 347 articles are taken from 85 journals. It was also observed that top 21 journals have published 74 percent of articles of the sample. Figure 2.2 shows the distribution of articles in selected 21 journals (a criterion is set to present the graph of only those journals which have published five or more articles). Out of 85 journals, it was observed that 57 journals have published only one or two SCRM related articles. It signifies that more journals have started publishing in SCRAU management work and reporting of risk in the supply chain has increased. Figure 2.3 shows a graph of the distribution of articles over the years. This chart indicates that there is a considerable rise in number of articles published since the year 2007. Specially, in last four years time period (2011 to 2014) more than 50 percent of total articles have been published. It signifies that there is apparent rise in numbers of authors who had picked supply chain risk related issues and reported them.

Some of the prominent journals which are publishing the SCRM, supply chain risk, uncertainty related articles includes *Business Process Management Journal, Computers & Operations Research, Computers and Industrial*

Engineering, Computers in Industry, Expert Systems with Applications, IIE Transactions, Industrial Management and Data Systems, International Journal of Logistics Management, International Journal of Logistics Research & Applications, Journal of Manufacturing Technology Management, Journal of Operations Management, Management Science, Benchmarking: An International Journal, Omega, and Production, Planning and Control etc.

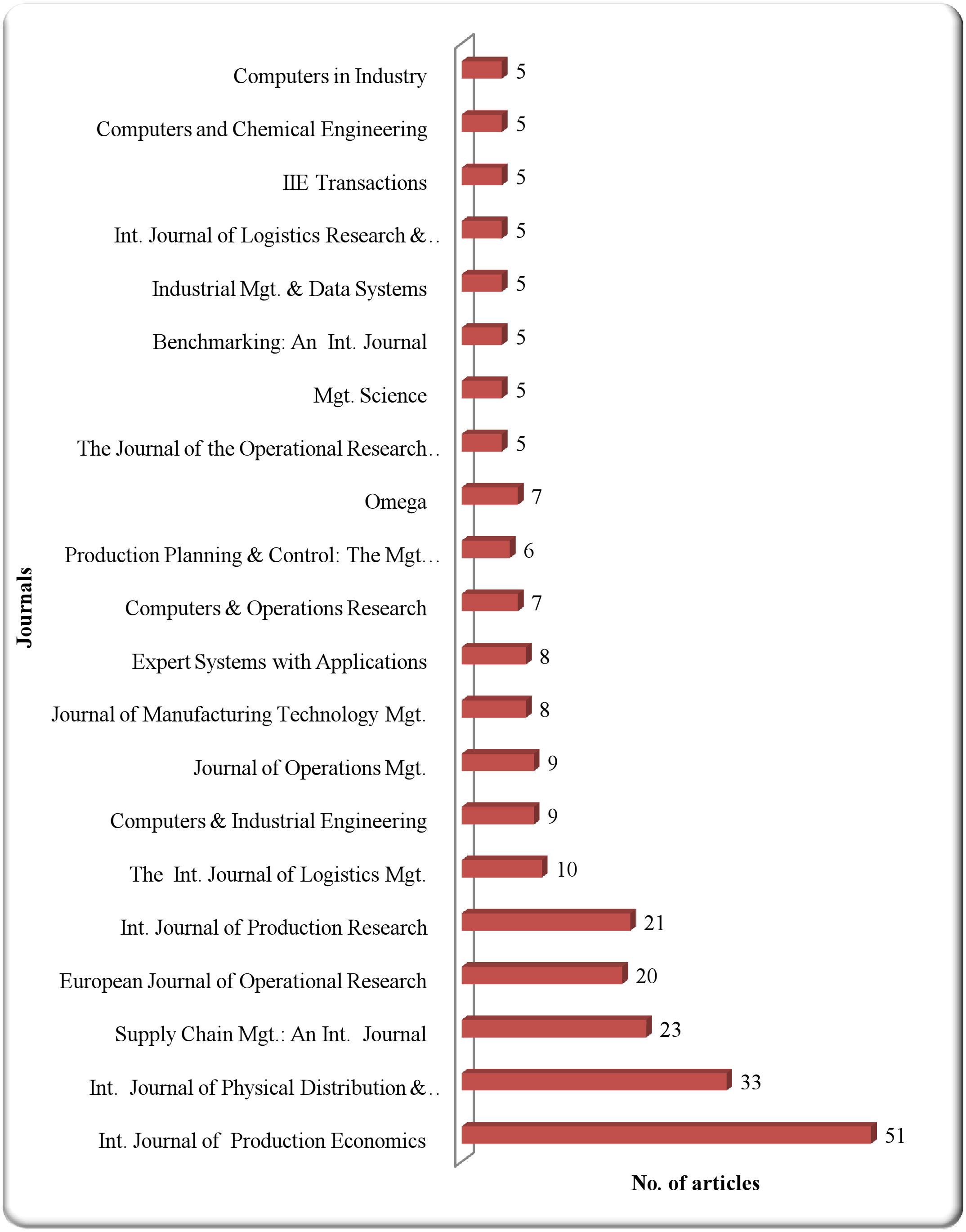


Figure 2.2: The distribution of articles in selected 21 journals

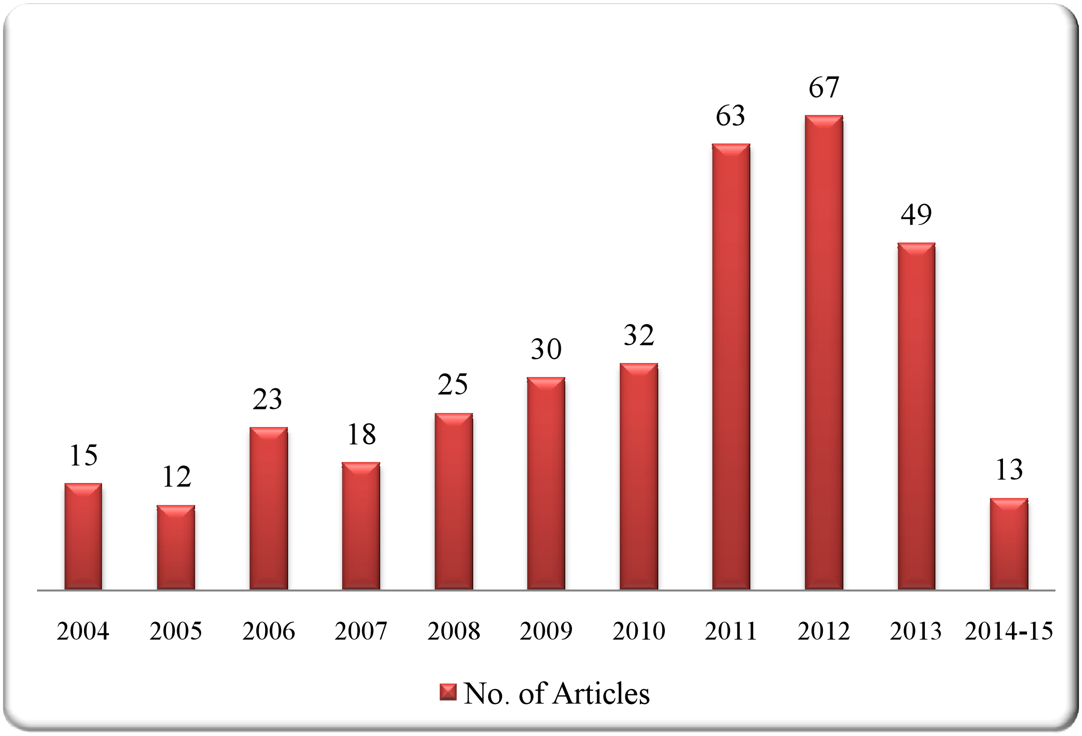


Figure 2.3: Graph of distribution of articles over the years

Supply chain issues: This class identifies the supply chain issue discussed in the paper. For example, the article by Ben-Tal et al. (2011) proposes a methodology to generate a robust logistics plan that can mitigate demand uncertainty in humanitarian relief supply chains, hence the paper is assigned the "*logistics management*" category. Figure 2.4 shows the distribution of articles for supply chain issues. From the Figure 2.4, it can be seen that the "*supplier management*" and "*strategic management*" related to supply chain issues are most critical areas.

On the upstream side of the supply chain, the "*demand management*" related issues were also got the attention of researchers. There is less number of articles which reports the issues such as the role of "*information technology*", "*integration*" and "*collaboration*" in SCM. The strategic decision making is frequently analyzed by authors. The articles which seem to address the number of supply chain issues as a collective methodology are clubbed in "*comprehensive construct*" category.

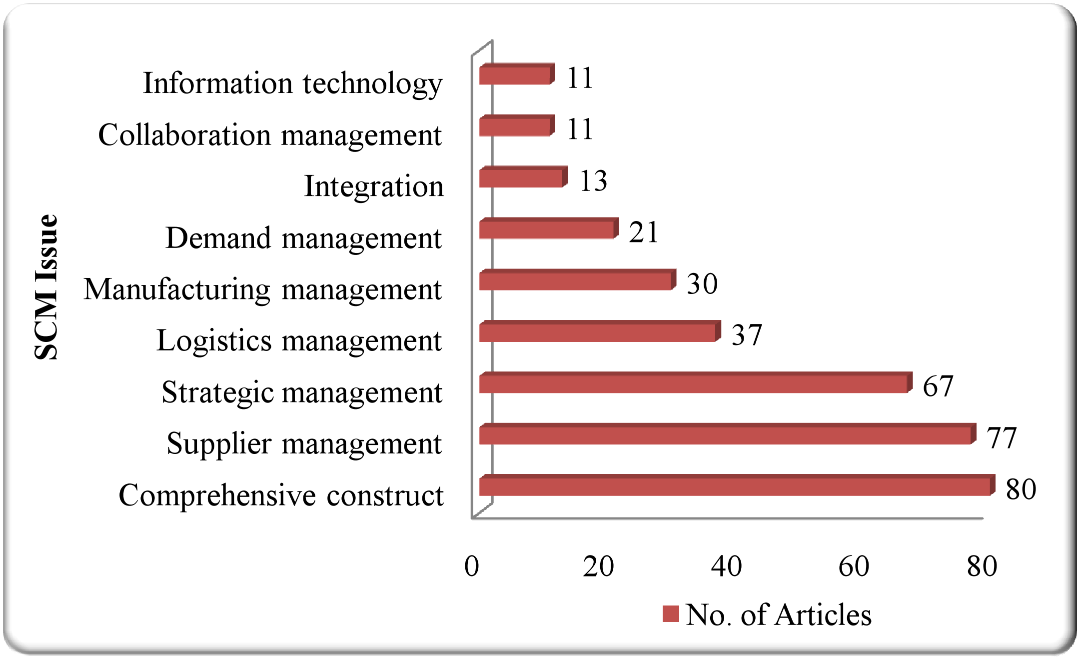
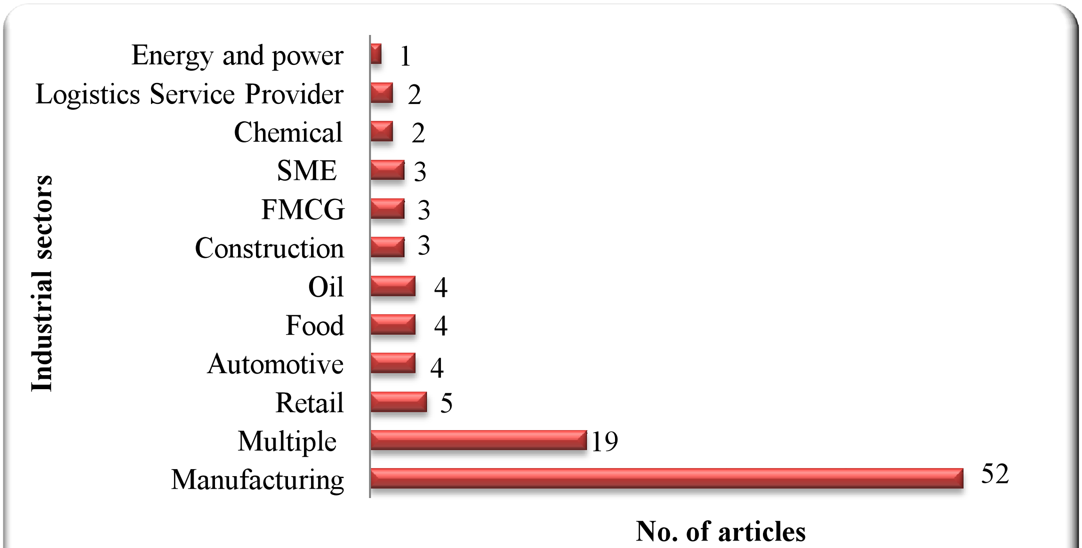


Figure 2.4: Distribution of articles for supply chain issue

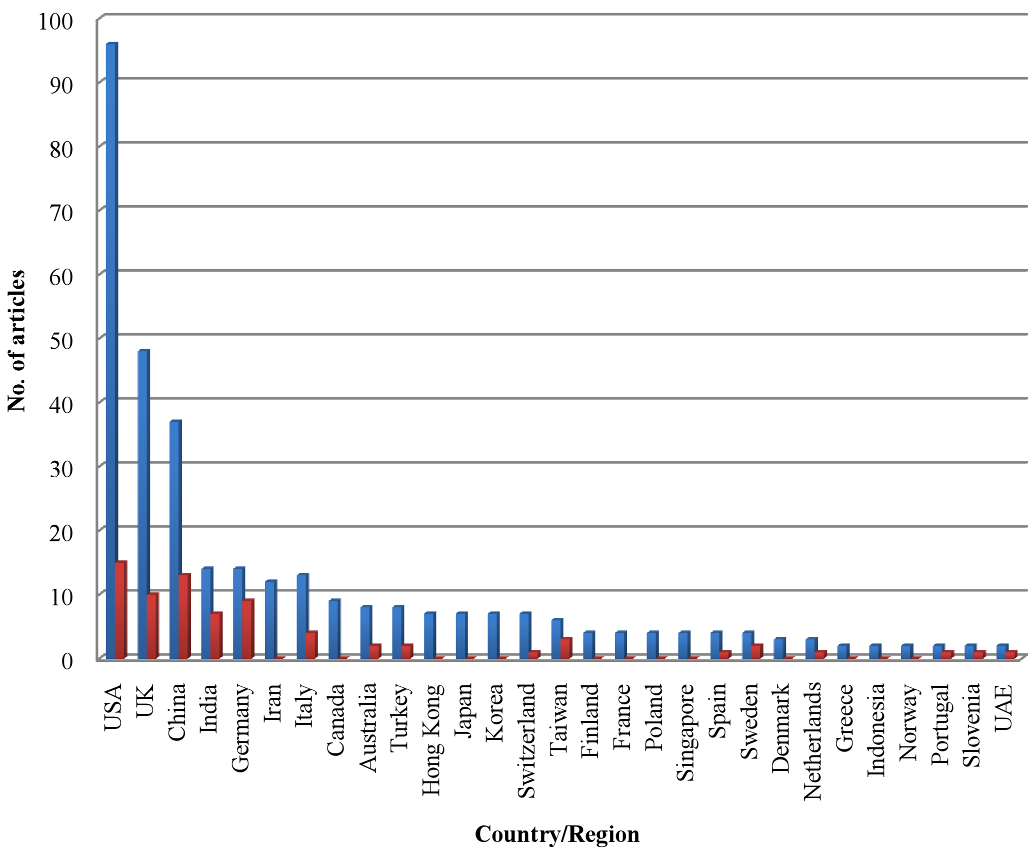
Industry: The investigation of the type of industry reported in papers revealed that more than half of studies are from manufacturing sector. Although, a large number of articles have not provided industry related information. Some of the industry sector explored by researchers includes chemical, automotive, food, retail, oil, energy and power, etc. Figure 2.5 shows the distribution of articles across different industries sectors.



Note: Remaining 241 papers have not mentioned any industry; FMCG - Fast moving consumer goods; SME - Small and medium enterprises

Figure 2.5: Distribution of articles across different industries and sectors

Demographic: Two type of demographic information is extracted from articles, first, country of authors and second, the geographical region where the research is carried out. For example, a case study by Lin and Zhou (2011) on the impacts of product design change on supply chain risk uses the data from automotive industry of China; while the associated country of authors is the UK. Figure 2.6 shows the distribution of a number of studies for the region of study and country of the author. Interestingly, the majority of the articles have not mentioned the area or geographical location from where the data of their study is taken, in other words, it may be possible that author has taken data from the host country, but they did not mention it specifically.



Note:
DC-1: Demographic criterion for number of articles having first author from concern country/region
DC-2: Demographic criterion for number of articles which have used the data from concern country/region
Austria, Brazil, Croatia, Egypt, Iceland, Ireland, Israel, Mexico, Bangladesh, Scottish, Thailand have one article in either DC-1 or DC-2

DC-1 DC- 2

Figure 2.6: Distribution of number of studies with region of study and country of author

It is evident from the Figure 2.5 that about 75 percent articles did not provide specific information regarding the geographical region or country from where research data has been collected. Largely, SCRM research is dominated by researchers from USA, UK, and Germany. However other developing countries like China, India and Iran also catching up fast. This can be attributed to the fact that Asian markets are growing at a good rate.

Methodological: Table 2.4 presents the classification scheme and article distribution for the mode of study and research design. The desk-based studies are dominant in SCRM. The most obvious explanation for 70 percent desk based articles in this area are that SCRM is a relatively new field of study. Initial research of an area is usually highly inclined towards theory building. In future, it is expected that more and more researchers and practitioners will use real life case studies, empirical methods based on these theories. Table 2.5 shows the distribution of articles for research design. From Table 2.5 it is evident that mathematical modeling is a popular approach in risk SCM.

Table 2.4: Classification scheme and article distribution for mode of study and research design

S. N.	Empirical research	Desk-based research
1	Case study	Literature review
2	Survey	Theoretical models
3	Focus group	Mathematical modeling
4	Delphi study (expert panel discussion)	Conceptual framework
5	Action research / project based research	Simulation of hypothetical data
6	Simulation of real data	Hypothetical cases
	Total articles = 100	Total articles = 247

Table 2.5: Distribution of articles for research design

S. N.	Research design	No. of Articles
1	Mathematical modeling	150
2	Case study	60
3	Theoretical model	55
4	Survey	27
5	Literature review	17
6	Hypothetical cases	13
7	Conceptual framework	9
8	Simulation using real data	7
9	Focus group	4
10	Delphi study	2
11	Action research	1
12	Simulation using hypothetical data	1

Some of the mathematical approaches used in risk and uncertainty modeling includes stochastic programming (Santoso et al., 2005), dynamic programming approach Wu et al. (2006), agency theory (Demirkan and Cheng, 2008), fuzzy possibilistic programming (Pishvaee and Torabi, 2010), normal accident theory (Yang and Yang, 2010), graph theory (Wagner and Neshat, 2010), quadratic programming (Talluri et al., 2010), linear programming (Peidro et al., 2010), Bayesian belief network (Archie, 2011), goal programming (Chiu et al., 2011), interpretive structural modeling (Pfohl et al., 2011), game theory (Yin and Nishi, 2012), Monte Carlo simulation (Vilko and Hallikas, 2012), newsvendor model (Xanthopoulos et al., 2012), fuzzy theory (Wang et al., 2012), fuzzy MCDM (Samvedi et al., 2013), non-linear integer programming (Tabrizi and Razmi, 2013), and structural Equation modeling (Punniyamoorthy et al., 2013). The combination and hybridization of more the one method are also noticed.

Types of risk: Table 2.6 provides the distribution of articles for different types of risks. It is evident from Table 2.6 that researchers are more inclined towards external supply chain risks i.e. environmental risks (98 articles in this category). The possible reason for this may be that supply chain operations are more vulnerable to disruptive external events on which it does not have any control. One of the significant findings of the study is that the SCRAU management research is heavily inclined towards ‘supply risk’ with 80 articles reporting from this domain. It means that supply-side risks are frequent. It is a vital observation because it gives an opportunity to identify few important the research gaps.

We can also observe that *supply management* and *demand management* are two important areas in which managers should aim to reduce the losses. The risk related to these regions fall under *control risk* category and their impact can be minimized through *strategic decision making*. For example, to mitigate supplier risk, a company can follow multiple supplier base philosophy. In the present time of globalization, companies are struggling with new challenges which were not there earlier. One such example can be product obsolescence due to rapid change in technology which may result in demand volatility for the company. Hence, due to these events, the supply chains start struggling for demand management. This observation has motivated us to further analyze the supply risk and demand uncertainty in the supply chain so that the network can be made robust enough to perform under these situations.

Table 2.6: Distribution of articles for different types of risk

S. N.	Type of risk	No. of Articles	Select Reference*
1	Environment	98	Papadakis (2006), Cucchiella and Gastaldi (2006), Adhitya et al. (2007), Williams et al. (2008), Natarajarathinam et al. (2009), Hung (2011), Ahsan (2011), Jüttner and Maklan (2011), Shimizu et al. (2012), Wagner et al. (2014)
2	Multiple risks	89	Finch (2004), Ratnasingam (2006), Tang (2006), Ratnasingam 2006), Ritchie and Brindley (2007), Wu and Olson (2008), Stonebraker et al. (2009), Olson and Wu (2010), Tang and Musa (2011), Ghadge et al. (2012), Punniyamoorthy et al. (2013)
3	Supply risk	80	Zsidisin et al. (2004), Blackhurst et al. (2008), Lockamy and McCormack (2010), Kam et al. (2011), Greening and Rutherford (2011), He and Zhao (2012), Li and Amini (2012), Cagliano et al. (2012), Lee et al.(2012), Ganguly and Guin (2013)
4	Demand risk	32	Gümüs and Güneri (2007), Hung and Ryu (2008)
5	Process risk	26	Farooq and O’Brien (2010), Ramanathan (2010), Lin and Zhou (2011), Tse and Tan (2011), Wang et al. (2012), Yao (2013)
6	Control risk	22	Feng and Viswanathan (2006), Rodrigues et al. (2008), Cannon et al. (2008), Sanchez-Rodrigues et al. (2010), Kang and Kim (2012)
*Note: *Complete list of references is in Appendix 1*			

Causes of risk: In every article selected for review, one major cause responsible for the risk in the respective supply chain was identified. Table 2.7 gives the distribution of articles as per causes of risk. It shows that there are about 21 percent articles which have argued that risks in the supply chain are due to multiple factors. Some of the dominant causes of risk are uncertainty in the supply chain, supply side disruption, supplier issues and various disruptions. On the other hand quality issues, collaborative issues and outsourcing activities are also reported as some of the biggest problems in the supply chain. Hence, by addressing the issues related to supply side and demand side uncertainty one can aim at effective supply chain risk management.

Table 2.7: Distribution of articles as per causes of risk

Causes of risk	No. of Articles	Select References
Risk due to multiple factors	77	Christopher and Peck (2004), Khan and Burnes (2007), Ritchie and Brindley (2007b), Wu and Olson (2008), Ghadge et al. (2012), Colicchia and Strozzi (2012), Punniyamoorthy et al. (2013)
Demand uncertainty	27	Feng and Viswanathan (2006), Gümüs and Güneri (2007)
Supply chain network uncertainty	27	Dabbene et al. (2008), Stonebraker et al. (2009), Sanchez-Rodrigues et al. (2010), Kern et al. (2012), Ho et al. (2015)
Supplier issues for SC	26	Finch (2004), Zsidisin et al. (2004), Blackhurst et al. (2008), Lockamy and McCormack (2010), Wu et al. (2010)
Supply side disruption	26	Adhitya et al. (2007), Li and Amini (2012)
Disruption in entire supply chain	25	Papadakis (2006), Greening and Rutherford (2011)
Economic environment	18	Jüttner and Maklan (2011), Ahsan (2011)
Logistics operations	18	Rodrigues et al. (2008)
Environmental factors	16	Merschmann and Thonemann (2011), Golicic and Smith (2013)
Disasters	12	Natarajarathinam et al. (2009), Shimizu et al. (2012)
Global sourcing	12	Hung (2011), Sofyalıoğlu and Kartal (2012), Cagliano et al. (2012)
Production issues	13	Farooq and O'Brien (2010), Lin and Zhou (2011), Wang et al., (2012)
SC network	11	Nagurney and Qiang (2012), Wagner et al. (2014)
Security issues for SC	9	Cannon et al. (2008), Williams et al. (2008)
Inventory issues	7	Hung and Ryu (2008), Kang and Kim (2012)
Enterprises issues	6	Ratnasingam (2006), Ramanathan et al. (2011)
Outsourcing activities	5	Kam et al. (2011), Lee et al. (2012)
Collaborative issues	4	Yao (2013)
Quality issue	4	Tse and Tan (2011)
Supply & demand issues	4	He and Zhao (2012)
<u>Note</u>: **Complete list of references is in Appendix-1*		

Approaches and framework for SCRM: In this section, the available approaches and comprehensive framework for supply chain risk and/or uncertainty management are reviewed. In this process, first, the information related to conceptual and theoretical frameworks or procedures (qualitative or quantitative based) for supply chain risk and/or uncertainty management is collected from suitable articles selected from the pool of 347 papers. Second, how these models had employed the tool and techniques of risk and uncertainty management with special focus on SCRM.

A large number of authors have provided comprehensive methods and tools for SCRM. A model-based rescheduling framework is proposed by Adhitya et al. (2007). The dual-sourcing supply chains disruption risk management framework is suggested by Xanthopoulos et al. (2012) to manage the risks in supplier side. Very recently, a number of a research frameworks for SCRM and uncertainty management are proposed by authors using multi-agent theory. The majority of these studies are mainly contributing to theory building and not employed much in industries. For example, a multi-agent based SCRM framework is proposed by Giannakis and Louis, (2011). Some studies have presented a highly focused framework for risk assessment and mitigation activities such as Faisal et al. (2007), and Elleuch et al. (2013). Some other relevant studies includes risk identification, evaluation and mitigation techniques for SCRM by Musa (2012), an integrated framework for outsourcing risk management (Lee et al., 2012), a conceptual framework for analyzing risk in supply networks (Cheng and Kam, 2008), an integrated framework for drivers of supply chain vulnerability (Peck, 2005), a framework for sustainable SCM (Carter and Rogers, 2008), supply chain risk management and performance framework (Ritchie and Brindley, 2007b) and a framework for understanding the interaction of uncertainty and information (Prater, 2005).

From above studies, we observe that there are five major components (process) in risk management approaches which are risk identification, risk assessment, risk consequences, risk management response and risk performance outcomes (Ho et al., 2015). It was also observed that some of the articles have their focus on two specific component of SCRM processes, such as risk identification and assessment in Zsidisin et al. (2004), Peck (2005), Cheng and Kam (2008), Blackhurst et al. (2008), Tuncel and Alpan (2010) and Musa (2012). A process such as risk identification and mitigation in Christopher and Peck (2004), Oke and Gopalakrishnan (2009), Diabat et al. (2012) and Taylor et al. (2013). The majorities of these articles are qualitative in nature and mainly explain the steps or phases of the SCRM. These papers also lack the applicability aspects on how SCRM approach can be applied in real situations under risk and uncertainty conditions. This observation has become the foundation of one of the research gap identified in the later part of this chapter.

The **important observations** and findings of this portion of literature review are presented and summarized as follows:

The SCRM related research is growing and had shown highest growth during a recent period of 2009-2013. This increase signifies that handling risk and uncertainties are a critical issue and getting the attention of many more researchers. However, most of the research is in a nascent stage and contributing largely to theory building. As a result, the large numbers of articles published are of desk-based research type (approx. 43 percent). Hence, use of the methodologies such as action research, Delphi study and simulation, etc. should be encouraged. There is a clear need for more empirical research in this domain.

The literature review consolidates the fact that almost all set of business and companies are affected by risk and uncertainties. The supply chain risk management for business domain such as e-commerce, perishables, FMCG, logistics service providing etc., should be attempted more in future studies. Persistence of demand uncertainty, supply chain uncertainty, supplier side issues, and disruptions are some of the foremost causes of risks in the supply chain. Hence by addressing the issues related to supply side and demand side uncertainty one can aim at effective SCRM. There is a need for addressing operational level risks such as process risk, security issues, inventory issues, enterprise issues, outsourcing activities in a dedicated manner. The closed loop supply chain networks structures are also not investigated much and addressing the risks ex-ante by incorporating SCRAUM in SCND is also not practiced much.

The developing countries such as BRICS nations witnessing a healthy growth in their respective economies, but very less amount of research work is reported from these nations. There is an absolute need for carrying out supply chain risk and uncertainty management related studies in the companies located and operating in these regions.

The supply chains of the modern era are vulnerable to many external risk factors as well as internal risk. Very less amount of work is reported on methods to integrate, models, and provide solutions for both types of risk. Thus, it is strongly desirable that supply chain should be robust enough to perform under uncertain environment and must show high reliability under risks and uncertainties. This robustness can be incorporated in the supply chain by using a number of modeling methods and tools. The next section will present the review of supply chain area with a focus on the robust design of supply chain.

2.3 Supply chain design under risk and uncertainty

Supply chain network design (SCND) involves strategic decisions on the number, location, capacity and mission of the production distribution facilities of a company, in order to provide goods to the customer base or market (Klibi et al., 2010). In other words, SCND determines the structure of a supply chain and affects its performance. These SCND decisions may include tactical decisions such as distribution, transportation and inventory management policies as well as operational decisions such as fulfilling customers demand (Farahani et al., 2014). The SCND decision has the most significant impact on return on investment (ROI) of the supply chain (Farahani et al., 2014; Simchi-Levi et al., 2003). The scope and fundamental of SCND are detailed in next section.

2.3.1 Why to focus on supply chain design

Rice and Hoppe (2001) quoted that, "*The conventional wisdom is that competition in the future will not be company vs. company, but it will be supply chain vs. supply chain*". In later years, this proved true in many cases such as competition between Microsoft-HTC and Nokia-Symbian supply chain in the electronic industry, amazon.com and barnesandnoble.com in the online book market and Toyota and GM in automobile sector (Farahani et al., 2014). It was observed that the companies are competing and winning based on their supply chain capabilities. The robust supply chain is need of the hour to remain competent. The firms with a robust network will be able to handle the negative incidents in a better way. These negative incidents may be caused by uncertainties or risks under which most of the companies functions.

The risk in supply chains is perceived as the potential negative impact of events on firm's objectives. Its presence results in an increase in the cost of value-added activities and therefore, risk assessment becomes critical for the supply chain design in order to have optimized process (Singh et al., 2012). Thus, it is argued that firm should act proactively to handle the risks and make appropriate strategies to include possible "worst scenarios" in decision making. Thus, in SCND, there are number of decisions that must be made by considering relevant risks (Melnyk et al., 2014). Investigating the supply chain network design process under numerous risks (i.e. supply risks, demand risk, process risk, environment risk, etc.) is a humongous task and required considerable time and resources. The most important one which is of strategic nature such as locating the facilities in different echelon of the chain should be investigated with higher priority (Farahani et al., 2014).

2.3.2 Classification of SCND decisions

In summary, the physical entities in a supply chain are following: (a) plants (b) suppliers (c) distribution centers (d) retailers, and (e) customers. The entities have arrangements for logistics and material handling activities. The goal of SCND activities is to design an efficient and optimal value-creating network structure for a new company or to re-designing for existing one. In this process, various decisions about the number of chain members, their location and capacities and the flow of material/product throughout the network are made. Farahani et al. (2014) proposed three levels of decision making in SCND: strategic, tactical and operational decisions.

These all aspects cover a vast set of decisions. The strategists prioritize these set of decisions and act as per requirement. Farahani et al. (2014) argued that the most important one is locating the facilities in a different echelon of the chain. Figure 2.7 illustrates the various decisions made in SCND. Some of the prominent strategic-tactical-operational aspects of SCND process includes identification of suitable location of supply chain's facilities, number of supply chain's facilities, their capacities, transportation mode (costs), inventory volume (shipment quantities), quality of facilities (functioning in worst times), type of technology used, contract providers, supplier selection etc.

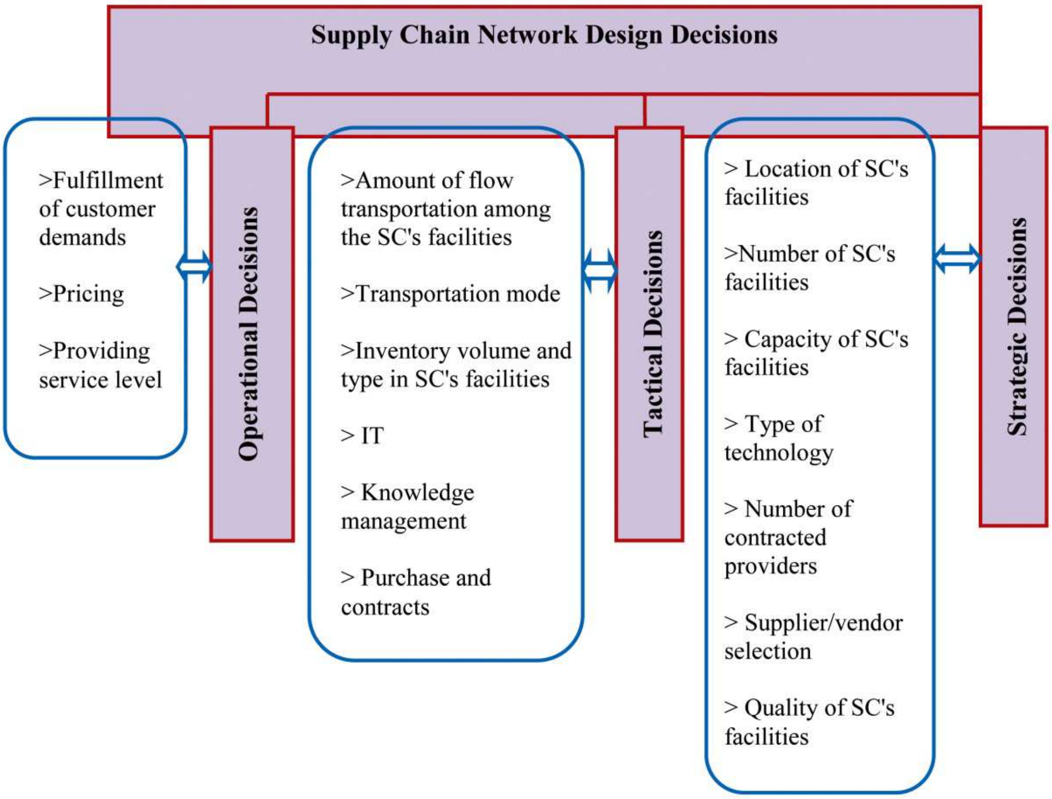


Figure 2.7: Different decisions made in SCND (Adopted from Farahani et al., 2014)

Inherently, the supply chain design is a dynamic concept (Feng and Viswanathan, 2006; Melnyk et al., 2014). The future business environment under which a supply chain network (SCN) will operate is unknown and vulnerable to risks (Klibi et al., 2010). A separate and dedicated section on a literature review of SCND under risk and uncertainties with a focus on CLSC and robust SCND is also presented.

Supply chain design and facility location decisions: The SCND is the primary and the most important step for optimizing the whole supply chain costs and SCND decision has a significant impact on the performance of the firm (Simchi-Levi et al., 2003). Facility location is one of the prime examples of a strategic decision in SCND context (Owen and Daskin, 1998). Thus, it is essential that firms must strive for risk management, and the strategic decisions must be taken with considering them.

Facility location decisions play a critical role in the strategic design of supply chain networks (Melo et al., 2009). The facilities (plants, distribution centers, sales, stores, etc.) generally function for years or decades, during such long period the environment in which facilities operate may change considerably. In this long run, parameters such as costs, demands, lead times, logistics assets, and other inputs variables to facility location models may be highly uncertain (Snyder, 2006). This has turned the facility location activities under risk and uncertainty into a high priority research field.

Hence, this study presents an integrated approach for SCND under demand uncertainty and few operational risks. As an outcome, strategic decisions (for example, facility location, supply chain configuration, etc.) tactical and operational decisions (for example, network optimization, demand management, capacity planning, and logistics, etc.) are evaluated.

2.3.3 Network design approaches and supply chain optimization under risk and uncertainty

It has been highlighted earlier that 'risk' and 'uncertainty' are used interchangeably in SCRM context. The SCM literature provides a number of methods for robust supply chain design. These methods includes, stochastic programming (Listeş, 2007; Pishvaee et al., 2009), robust optimization (Pishvaee et al. 2011), possibilistic programming (Pishvaee and Torabi, 2010; Fallah-Tafti et al., 2014), fuzzy based approaches (Ramezani et al., 2014), Bayesian network (Nepal and Yadav, 2015) etc.

The stochastic programming which uses probability distribution or historical data is one of the efficient methods for addressing the uncertainty in the SCND parameters. However, in real life cases, there is not enough historical data available for SCND and obtaining the actual probability distributions for uncertain SCND parameters becomes challenging. Moreover, the complexity of applying the distribution function can limit the number of uncertain parameters considered. This shortcoming of stochastic programming approach can be handled by incorporating scenario-based analysis (Subulan et al. 2014). In this method, to capture the real life instances, a sufficiently large number of scenarios are required; again, this could become a computationally challenging task for managers. Additionally, there are chances that the scenario-based analysis fails to capture the all important possibly realized instances.

In literature, another method used for handling the uncertainty is fuzzy systems and theory. The fuzzy programming offers the potential of dealing with problems involving noisy, incomplete or erroneous data (Ramezani et al., 2014). However, the applicability of fuzzy assessment models in actual industrial practices is questionable because the final outcome of fuzzy models depends on the qualitative judgment of the linguistic variables used (Nepal and Yadav, 2015).

The other important method to address the uncertainty is robust optimization (RO) approach. The RO eliminates the limitations of stochastic programming of estimating the probability distribution from historical data to optimize the solution against parameter uncertainty specifically against the worst-case scenario (Carlsson et al. 2014). The solution obtained from RO is the best solution against the worst possible data realization within the uncertainty set (Ben-Tal and Nemirovski, 2000). The worst case of the constraints is computed over a convex uncertainty set of the parameters, which bounds the maximum allowable deviation of the parameters from their nominal values. This method gives a potential approach for modeling risk and uncertainties in SCND process.

The reliability of the supply chain network means the ability of the firm to keep function if some of its critical entity fails under some risk. It is taken as the measure of performance of supply chain when its configuration realized while in robust supply chain design focus is on proactive methods to prevent the loss in worst case situation. Table 2.8 presents a summary of important studies which considered supply chain risk aspects in SCND. Table 2.9 presents summary of important studies with uncertainty aspects in SCND. The studies summarized in Table 2.8 and Table 2.9 show that there are very few articles are there on an integrated aspect of robust and reliable supply chain. Mostly, the reliability of the supply chain is modeled by considering risks and disruptions in the network. This is an important observation because it signifies that SCND process must include risk if reliable operations are required. This fact has consolidated our objective to include the risk and uncertainty, both in SCND and decision making.

Table 2.8: Summary of important studies which considered supply chain risk aspects in SCND

S. N.	Study	Comment
1	Klimov & Merkuryev (2008)	Simulation for supply chain reliability evaluation under uncertainty and risk using system approach for reliability. Thus, the supply chain network system's reliability calculated.
2	Mahnam et al. (2009)	A fuzzy inventory model based on periodic review policy of network supply chain is developed. The demand and suppliers reliability are uncertain modeled using fuzzy sets. The model is solved via particle swarm optimization (PSO).
3	Hsu & Li (2011)	The reliability evaluation method is developed for plants under demand fluctuations using MILP and solved by simulated annealing.
4	Peng et al. (2011)	Facility disruptions taken for reliable logistics networks design. The MILP model with the objective to minimize the nominal cost while reducing the disruption risk using the p-robustness criterion with genetic algorithms.
5	Vahdani et al. (2013)	A reliable design of a closed-loop supply chain network under uncertainty of external environmental is modeled using an interval fuzzy chance-constrained MILP model.
6	Vahdani et al. (2012)	A robust queuing model based design for the closed-loop network under uncertainty using fuzzy multi-objective programming.
7	Lin et al. (2013)	The reliability evaluation of a stochastic-flow distribution system with delivery spoilage. In mathematical programming to evaluate network reliability under the delivery spoilage consideration with the budget constraint.
8	Benyoucef et al. (2013)	An integrated facility location and supplier selection decisions for the design of supply chain network with a focus on the reliability of suppliers solved by Lagrangian relaxation-based approach.
9	Jia & Cui (2012)	A copula-based method is proposed for analyzing the reliability of supply chains.
10	Zhang et al. (2012)	Study on reliable facility location. A bi-level programming model by using the methods of scenario analysis and robust optimization.

Table 2.9: Summary of important studies considering uncertainty in SCND

S. N.	Study	Comment/Observation
1	Salema et al. (2007)	A generic reverse logistics network model where capacity limits, multi-product management and product demands and returns are uncertain in modeling.
2	Fleischmann et al. (2001)	CLSC network for forward flow and reverse flow together for obtaining simultaneous optimality for these forward and reverse flow networks.
3	Pishvaee and Torabi (2010)	The model proposes a bi-objective possibilistic MIP model to deal with uncertain and imprecise parameters in closed-loop supply chain network design.
4	Shi et al. (2011)	Optimal production planning for a multi-product closed loop system with uncertain demand and return using Lagrangian relaxation method.
5	Georgiadis et al. (2011)	Time-varying demand uncertainty modeling in multi-product production facilities system design with the constraint of shared resources.
6	Kenné et al. (2012)	Production planning of a hybrid manufacturing–remanufacturing system under uncertainty within a closed-loop SC was presented.
7	Qiang et al. (2013)	The authors have discussed the closed-loop SC network with competition, distribution channel investment, and uncertainties.
8	Zeballos et al. (2014)	The authors have taken uncertain demand and supply with multiple scenarios with parameter's occurrence probabilities are assumed to be known.
9	Listeş (2007)	A generic stochastic model to design the network comprising both supply and return channels which were part of a closed loop system.
10	Pishvaee et al., (2009)	The modeling using scenario-based stochastic approach for an integrated forward/reverse logistics network design under uncertainty.
11	Zeballos et al.(2012)	The uncertainty in quality and quantity of returns for CLSC network using stochastic scenarios solution methodology.
12	Amin and Zhang (2013a)	The proposed model considered environmental factors by weighted sum and ε-constraint methods with demand and return uncertainties using scenario-based stochastic programming.
13	Amin and Zhang (2013b)	A three-stage model for closed-loop SC configuration under uncertainty configured by a stochastic MILP.
14	Baghalian et al. (2013)	Developed a stochastic model for designing SC network of agri-food firm under demand and supply uncertainties. Only forward flow of products is modeled.
15	Subulan et al. (2014)	A scenario based stochastic and possibilistic MILP for a multi-objective closed-SCND by considering financial and collection risks.
16	Wang and Hsu (2010)	The authors have proposed a closed-loop green logistics generalized model where fuzzy numbers express the uncertainty.
17	Vahdani et al. (2013)	The authors have developed a fuzzy multi-objective RO which minimizes the total costs and the expected transportation costs after the failure of facilities in a logistics network.
18	Ramezani et al. (2014)	The authors have used fuzzy sets to design a multi-product, multi-period, closed-loop supply chain network.

2.4 Robust and reliable CLSC network design

As discussed in earlier sections, the presence of various risk and uncertainty factors makes the supply chain quite vulnerable. Robustness and reliability are the capabilities of the supply chain to perform as expected under worst cases. These disruptions in the supply chain can be originated by disturbances from demand side or supply side or both. The supply chain risk and uncertainty management are practiced at a strategic level as well as operations level. To handle the risk and uncertainty, one requires efficient SCND and planning at the strategic level.

Pishvaee et al. (2011) used the mixed-integer linear programming (MILP) model in a number of realizations under different uncertainty sets. However, the model is tested for hypothetical data and small network size. Moreover, the return is considered to fulfill the demands of second market customers, which has narrowed the scope to the study. Hasani et al. (2012) proposed a comprehensive model considering various assumptions such as multiple periods, multiple products, and multiple supply chain echelons for strategic CLSC network design under uncertain demand and purchasing cost. The uncertainty of parameters in the proposed model was handled via an interval robust optimization technique.

Chen et al. (2010) did supply chain modeling with fuzzy parameters and proposed a solution method which can calculate the fuzzy objective value. A fuzzy integrated model was provided by Aliev et al. (2007) regarding fuzzy programming and solved by genetic algorithm. Very few articles, namely, Hatefi and Jolai (2014), Baghalian et al. (2013) and Pishvaee et al. (2011) used the RO approach to design CLSC network. Recently, Hatefi and Jolai (2014) considered the parameter uncertainty in their CLSC model through RO and focused on the reliability of SC network under disruption scenarios. Apart from fuzzy programming, stochastic programming is also used in the literature. Stochastic programming can be divided into two categories: expected value model and chance-constrained model (Dai and Zheng, 2015). It can be observed that there is very limited number of articles which focuses on robust optimization for CLSC network design. Table 2.10 presents the summary of important articles for CLSC network design under uncertainty.

The robust optimization modeling addresses the uncertainty in model parameters and provides insights for strategic decisions regarding supply chain planning, selection of plants, distribution centers, quantity shipped, procurement planning, demand fulfillment, etc. The roots of RO can be traced back to Soyster (1973). Some of the seminal work to formulate the problem under uncertainty belongs to Mulvey et al. (1995), Ben-Tal and Nemirovski (1999), Ben-Tal and Nemirovski (2000, 2002), Bertsimas and Sim (2003, 2004), Ben-Tal et al. (2004) and Ben-Tal et al. (2009). Recently, number of studies have used RO in supply chain modeling for addressing uncertainty such as Pishvaee et al. (2011), Wang and Huang (2013), Baghalian et al. (2013), Hatefi and Jolai, (2014), Hasani et al. (2014) and Eslamipoor et al. (2014).

In this research, we have used RO approach for modeling the uncertainty. The other similar method is two stage stochastic programming (SP) models which have been widely applied in the supply chain literature. However, there are some fundamental drawbacks in SP modeling. First, in practical situations, we can seldom obtain the actual distribution of the uncertainties. Second, even if the distribution is identified, the subsequent SP model is computationally tough to solve. In addition, there is a significant risk that some popular solution methods of SP model such as Sampling Average Approximation (SAA) may yield meaningless first stage solutions (Muchen, 2014). To overcome these limitations, Soyster (1973) proposed the robust optimization scheme to address data uncertainty by substituting probability distribution with particular uncertainty set. However, it is observed that RO may yield excessively conservative solutions when some level of distributional of the uncertainty is accessible (Muchen, 2014).

Thus, the reliability of the supply chain is modeled by considering risks and disruptions in the network. Additionally, less attention is paid on integration of the uncertainty and risk in SCND process. Facility location problem under risk is also not investigated much and none of the papers have proposed its integration in robust SCND decisions. There are few articles which focus on robust optimization for CLSC network design under uncertainty. Additionally, every article has the focus on modeling CLSC network which considered the complex shipping scenarios such as simultaneously direct shipping of products along with shipping through distribution centers. These observations from literature provide excellent inputs to identify and define the research gaps of this study which are presented in Section 2.5.

Table 2.10: A summary of important articles for CLSC network design under uncertainty

Reference	Method	Uncertain parameters	Tool	Product/period	Remark
Pishvaee et al. (2009)	SP; MILP	Quantity Returned Demands Variable costs	LINGO 8.0	Single period & product	Closed-loop integrated forward/reverse logistics model
Subulan et al. (2014b)	SP; MILP	Parameters are uncertain	GAMS and CPLEX®	Multi-product	Handle different uncertainty types
Amin and Zhang, (2013a)	SP; MILP	Demand and return	CPLEX® 9.1.0	Multi- period and multi-product	Consider environmental factors by weighted sums and e-constraint methods
Zeballos et al.(2014)	SP; MILP	Demand. Supply	GAMS and CPLEX®	Multi-period multi-product	Design and planning of CLSC
Pishvaee et al. (2011)	RO; MILP	Return Product Demand	ILOG CPLEX®10 .1	*	They proposed a RO model for handling the intrinsic uncertainty of input data in a CLSC network design problem. The solutions are compared to deterministic model and RO.
Baghalian et al. (2013)	RO; MILP	Demand uncertainties	LINGO 10.00	Multi-product	Risk and disruption analysis for agri-food firm
Hatefi and Jolai (2014)	RO; MILP	Uncertain parameters disruptions	GAMS 23.5/ CPLEX® 12.2	*	Integrated forward– reverse network, uncertainty and facility disruptions
Wang and Huang (2013)	RO; MILP	Demand for remanufactured products	CPLEX®	Multiperiod and multi-product	A demand-driven disassembly planning problem for CLSC
Hasani et al. (2014)	RO; MINLP	purchasing costs and demand	LINDO	Multiperiod and multi-product	Global SC network design under uncertainty
Eslamipoor et al. (2014)	RO; MINLP	Demand and penalty cost	LINGO	single-period and single- product	Remanufacturing closed-loop network design problem with uncertain parameters
Rahmani et al. (2013)	FA; MILP	Parameters are made fuzzy	GAMS and CPLEX®	*	CLSC design model, a multi-echelon, multi-product, and multi-period network
Vahdani et al. (2013)	FA; MILP	Demand	GAMS	Single period and product	Model also utilizes an efficient reliability approach to finding a robust network design

Reference	Method	Uncertain parameters	Tool	Product/period	Remark
Jindal and Sangwan (2014)	FA; MILP	Demand, purchasing transportation processing, and set-up costs	LINGO 13	Multi-product	CLSC framework focusing on reuse, refurbish, recycle and disposal of parts.
Fallah-Tafti et al. (2014)	PP; MILP	cost coefficients and customer demands	GAMS and CPLEX®	Multi- period and multi-product	Conflicting objectives and constraints are taken into account
Pishvaee and Torabi (2010a)	PP; MILP	Demands Returns Costs Capacities	LINGO 8.0	*	Strategic facility location decisions support both recovery and recycling processes
Salema et al. (2007)	OT; MILP	Demand and return	GAMS and CPLEX®	Multi- period and multi-product	A mixed integer formulation is developed which is solved using standard B&B techniques
Lieckens and Vandaele (2012)	OT; MINLP	Delay and inventory level	OT	Single product	Multiple layers and multiple routings are considered and stochastic delays takes into account
Note : SP = Stochastic Programming; FA = Fuzzy Approach; RO = Robust Optimization; PP = Possibilistic Programming; MILP = Mixed Integer linear programming; LIP = Integer Linear Program; NLMIP = Nonlinear MIP; DLB: Disassembly line balancing; FFRF: Forward Flow And Reverse Flow; OT= Other Methods (Ex- Differential evolution, Branch and Bound techniques); * Not Available					

2.5 Research gaps

Based on literature review few **research gaps** are identified and discussed below.

Although literature review indicates that addressing the risk and supply chain has become an important choice for all industries to deal with possible losses and to increase robustness, however, many issues still exist that need further investigation as described below.

1) The literature review shows that most of the existing research have focused either on strategy formulation for SCRM aspects or addressing the uncertainty of certain parameter in an existing network. Also, the nature of research is predominantly qualitative having more focus on risk management theories. Thus, there is a need for more empirical studies in this area.
2) Analysis of literature also revealed that parameters used in SCND are often of deterministic nature, and there is a lack of an effective methodology for addressing the parameter uncertainty without using probability theories.

3) Additionally, the mathematical models used in the literature have mostly concentrated on modeling the forward flow of supply chain networks. Thus, there is a need for incorporating reverse supply chain practices in supply chain modeling.

4) It is found that accommodating the reverse supply chain practices in supply chain modeling is very practical in present times; there are very few studies which capture the CLSC context and practice of simultaneous shipping (directly shipping to the customer along with fulfilling demand through distribution center).

5) The review findings also suggest that by addressing the issues related to supply side and demand side uncertainty one can aim at effective supply chain risk management. There is a need for addressing operational level risks as well as risks related to tactical actions in specific manner to achieve robustness and reliability.

6) A substantial part of the available literature deals with proposing mathematical models for a particular type of risk or uncertainty. The joint treatment of both (risk and uncertainty) is not investigated much. Thus, there is a requirement of a comprehensive and unified approach to obtain robust and reliable supply chain topology i.e. achieves robust supply chain optimization.

7) There is a lack of modeling approach to embedding risks into robust supply chain design in a CLSC context to achieve robust supply chain optimization and analyze the effect of a set of risk and uncertainty on optimal supply chain configuration.

The flowchart for literature review process and research gap identification of this study is presented in Figure 2.8.

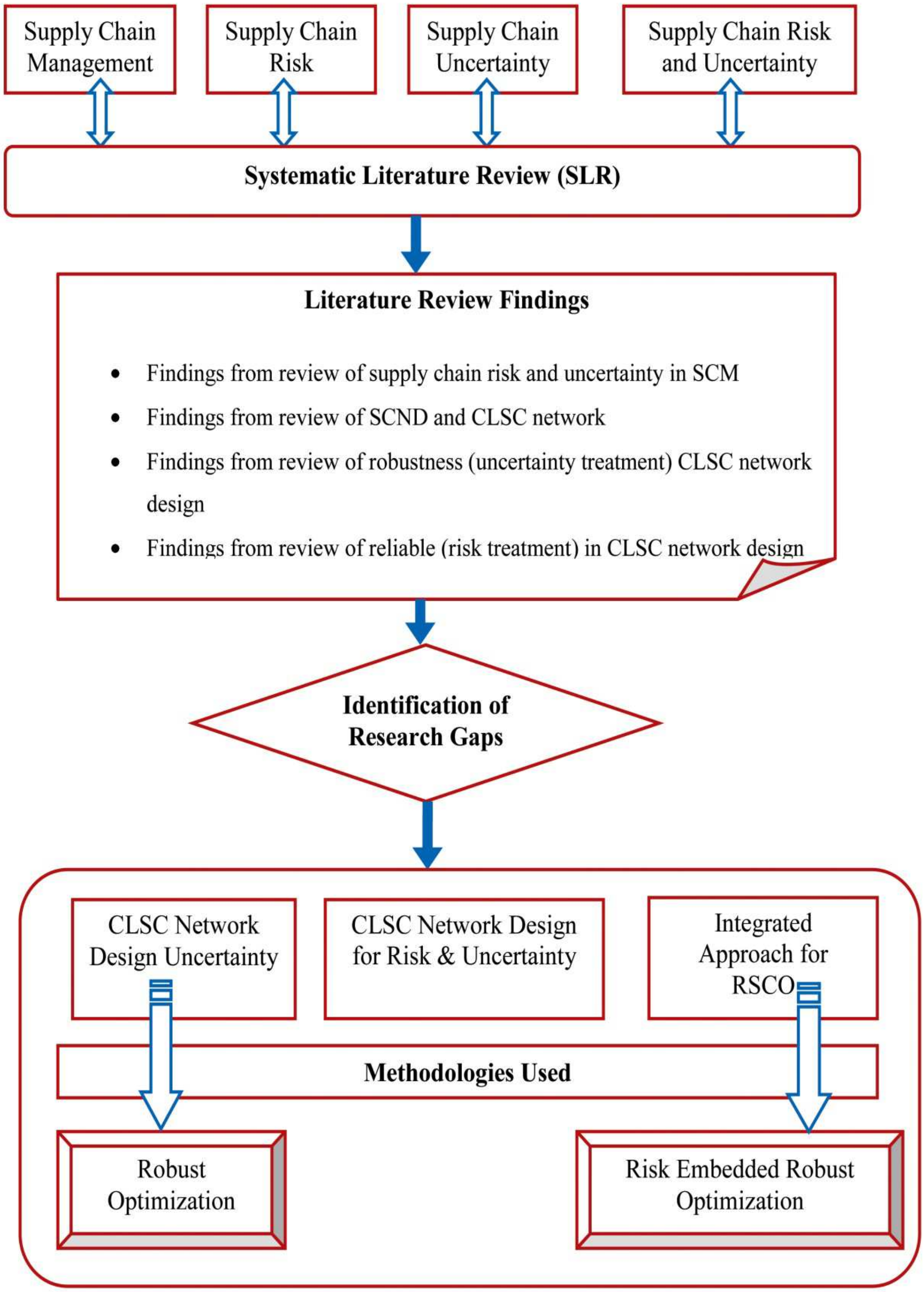


Figure 2.8: Flowchart for literature review process and research gap identification of the study

CHAPTER 3

ROBUST SUPPLY CHAIN DESIGN AND OPTIMIZATION UNDER UNCERTAINTY

Chapter 3
Robust Supply Chain Design and Optimization under Uncertainty

3.1 Introduction

The risks in the supply chain are unexpected events that might disrupt the flow of products or information from suppliers to the customers (Waters, 2007). Traditionally, a typical supply chain is characterized by its complexity and the inherent uncertainty in their operations (Blackhursta et al., 2007). In literature, risk and uncertainty are used synonymously (Colicchia and Strozzi, 2012). Most of the time, the risk is an implication of a phenomenon being uncertain about usual supply chain outcomes. It is different in the sense that uncertainty is the situation where supply chains of firms are completely deprived of information regarding some of the operational parameters. For example, the demand for the products can be quite uncertain.

Firms have adopted various forecasting methods to cope up with this problem, but the uncertainty related to the demand for the product is still very prevalent. It happens because of changes in technology, price and competition in the market which affects the consumer choices (Tabrizi and Razmi, 2013). Thus, the supply chain configuration of a firm must be able to handle these issues. Right kind of supply chain topology is the key to addressing such issues. The decisions regarding supply chain network design (SCND) should be taken cautiously. Hence, the strategic SCND process should include uncertainty of supply chain parameters in its decisions making process.

It was observed from the literature review that the practice of closing the loop of the supply chain (CLSC) is increasing in recent times, and there is a need for handling the returned products. This closing the loop bring profitability, earn goodwill and avoid sub-optimality in the operations of the firms (Lee and Dong, 2008; Pishvaee et al., 2011). There is two kinds of return possible; first, the product is returned by the customers because they do not require it and unused. Second, the products are collected from customers after they fully use it and sent for recycling, reuse, remanufacture, etc. The mechanism for collecting returned items through the closed-loop system is almost similar in both cases.

In this study, above situation is considered where the firm has to handle the returned products which are unused but sent back by customers. For example, the electronic commerce (e-commerce) firms have CLSC structure with the capacity to handle the returned products. The demand uncertainty impacts such CLSC structure in a significant manner because the demand variation is expected to affect the return as well. Thus, SCND decisions for CLSC network are not only vital but also essential too. However, the implementation of the CLSC practices in any firm is a very critical decision because it can influence the synergy among supply chain members.

In this chapter, Section 3.2 provides the details about the generic CLSC network and notations used. The deterministic modeling i.e. SCND for the proposed CLSC model is carried out. The proposed model is a single product, single period, multi-echelon supply chain structure. It is discussed in earlier sections that demand of the products can be quite uncertain and this deterministic model based model may not be able to fulfill the worst demand of future. Thus, in this Section, this demand uncertainty is incorporated in SCND stage. Section 3.3 provides the mathematical model for the select CLSC network under demand uncertainty using robust optimization (RO) approach. Section 3.4 presents the result and discussion of numerical tests carried out for the robust SCND model. The chapter ends with a discussion on validation of methodology and summary of the chapter in Section 3.5.

3.2 Problem and model overview

This chapter will aim to model uncertainties and risks in CLSC network design. The SCND modeling under demand uncertainty is carried out and the decisions regarding network configuration, supply chain planning, demand management and capacity allocation are presented. The generic network selected for the study is a modified version of Figure 1.1. These modifications are made to include the practical aspects of an e-commerce supply chain. These changes accommodates simultaneous shipping, collecting returned products at plants, etc.

The e-commerce has primarily created a large effect on the way in which orders are placed, and products have been delivered (Nagurney et al., 2005).

A recent report by leading consultancy firm PwC revealed that e-commerce market in India has grown by 34% since 2009 to touch 16.4 billion USD in 2014 and the sector is expected to be in the range of 22 billion USD in 2015 (www.pwc.in, 2015). Thus, capturing the simultaneous shipping is vital for e-commerce companies and under demand certainty, the analysis SCND decisions will be of great relevance.

3.2.1 The network

This section of the chapter describes mathematical formulation and modeling of a generic supply chain. Figure 3.1 shows the generic CLSC network under consideration. This supply chain structure is a closed-loop supply chain network that captures direct shipments of products from plants (DSP) as well as the dispatching of the products through distribution centers (SDC). The firms use DSP to take the advantage of the nearness of the production facility to the customer's sites. The literature review revealed that there is the very limited focus of researchers on analyzing SCND decisions for these shipments simultaneously under some uncertainty and/or risk.

The network has plants, distribution center (DC) in the forward flow and recovery centers, and disposal center (DIC) in reverse flow. The plants have a dual function and serve as plant cum recovery center (PCR) i.e. producing the new products and collecting and refurbishing the returned items as well. Here, the PCR not only distributes the products to the customers (CZ) or market zone directly but also route them through DCs as well.

These return products are reintroduced in the supply chain after doing refurbishing, quality checks, defects removal, repackaging, etc. as per the requirement. The defective products are sent to the DIC to dispose off. The assumptions for above supply chain model are provided in Section 3.2.2.

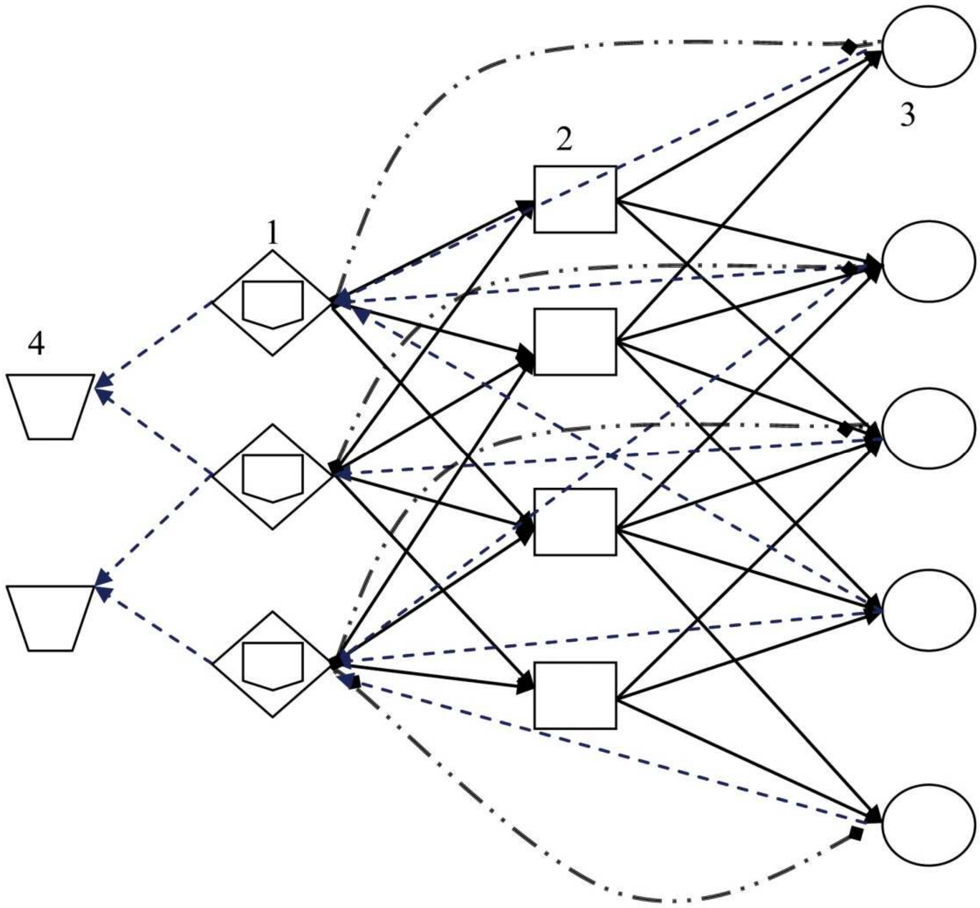


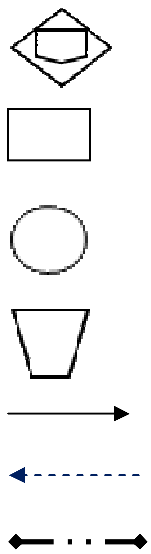
Figure 3.1: Generic CLSC network under consideration

1. Plant cum recovery center ……...
2. Distribution center ……………..
3. Customers ……………………
4. Disposal center…………………

Forward flow …………………..

Reverse flow …………………..

Direct shipment ………………..



3.2.2 Assumptions

- The supply chain considered in the model is a single period, single product, multi-echelon forward-reverse network operating in a given planning horizon.
- The back ordering is not permitted and any inventory related costs are captured in heads related to production or distribution costs.
- The possible facility locations and their respective capacities are known in advance.
- The locations of customers or market zone to be served by the network are fixed and predefine.
- The average demand of a CZ in the given planning horizon is captured by nominal demand parameter.
- The focus of study is designing the front end of the supply chain; hence, the supplier side is not included in the modeling.
- There is no restriction on multi-multi allocation (i.e. any facility can serve any DC or customer) at network nodes to satisfy the demand of a CZ.
- Salvage value or cost of the scraped products is not considered in the modelling. It is assumed that this cost will not be a deciding parameter in SCND process and focus is kept on handling risk and uncertainties.

The modeling objectives are-

- ➢ Minimization of total supply chain network costs
- ➢ Determine the optimal number of facilities at each echelon of supply chain
- ➢ Determine the optimized quantity of products flows between network facilities

3.2.3 Deterministic formulation of a single product, single period, multi-echelon supply chain network

3.2.3.1 Notations

The following notations and indices will be used for mathematical formulation of the network.

Sets

i	Potential number of PCR , i= 1, ...I
j	Potential number of DC, j= 1,....J
k	Potential number of CZ, k= 1,....K
l	Potential number of DIC, l= 1,...L

Parameters

d_k	Nominal demand for a CZ 'k'
rr_k	Return rate of products of CZ 'k'
pc_i	Production capacity of PCR 'i' in forward flow
dc_j	Distribution capacity of DC 'j' in forward flow
cc_i	Collection capacity of PCR 'i' to handle returns in reverse flow
sc_l	Disposal capacity of DIC 'l'
d_f	Average disposal fraction of returned products at PCR 'i"

Cost parameters

f_i	Fixed cost for opening PCR 'i'
g_j	Fixed cost for opening DC 'j'
h_l	Fixed cost for opening DIC 'l'
m_i	Production cost per unit of product at PCR 'i'
c_i	Collection cost per unit of product returned by CZ 'k' at PCR 'i'
r_i	Refurbishing cost per unit of product for recovering it to reintroduce again in supply chain at PCR 'i'
s_l	Per unit cost incurred in disposal activities of rejected returned products per at DIC 'l'
n_j	Per unit cost incurred in distribution of products by DC 'j'
a_{ij}	Transportation cost per unit of product from PCR 'i' to DC 'j'
b_{jk}	Transportation cost per unit of product from DC j to CZ 'k'
e_{ik}	Transportation cost per unit of product from PCR i to CZ 'k'
p_{ki}	Transportation cost per unit of returned product from CZ 'k' to PCR 'i'
q_{il}	Transportation cost per unit of product from PCR 'i' to DIC 'l'
μ_k	Penalty cost per unit of unsatisfied demand

Variables

M_i	Quantity recovered by PCR *'i'* from returned products from CZ 'k' after refurbishing
B_{ik}	Quantity of recovered product shipped from PCR 'i' to CZ 'k' directly
Q_{ij}	Quantity of recovered product shipped from PCR 'i' to DC 'j'
N_i	Quantity of new products produced at PCR 'i'
X_{ij}	Quantity of new product shipped from PCR 'i' to DC 'j'
T_{ik}	Quantity of new product shipped from PCR 'i' to CZ 'k'
Y_{jk}	Quantity of product shipped from DC j to CZ 'k'
Z_{ki}	Amount of returned product shipped from CZ 'k' to PCR 'i'
S_{il}	Amount of rejected returned product shipped from PCR 'i' to DIC 'l'
α_k	Amount of unsatisfied demand of CZ 'k'
U_i	Binary variable equal to 1 if PCR 'i' is open, 0 otherwise
V_j	Binary variable equal to 1 if DC 'j' is open, 0 otherwise
W_l	Binary variable equal to 1 if DIC 'l' is open, 0 otherwise

3.2.3.2 The objective function:

The various cost element of the objective function are defined as follows.

Total fixed costs of facilities = Fixed cost establishing PCR , i= 1, ...I + Fixed cost establishing DC, j= 1,....J + Fixed cost establishing DIC, l= 1,...L

i.e.

$$\sum_{i\in I} f(i) * U(i) + \sum_{j\in J} g(j) * V(j) + \sum_{l\in L} h(l) * W(l) \tag{3.1}$$

Total production cost = [(Production cost per unit of product at PCR 'i') * (Quantity of new products produced at PCR 'i')]

i.e.

$$\sum_{i\in I}[m(i) * N(i)] \tag{3.2}$$

Total distribution cost = [(Per unit cost incurred in distribution of products by DC 'j')*(Quantity of product shipped from DC j to CZ 'k')]

i.e.

$$\sum_{j\in J} \sum_{k\in K}[n(j) * Y(j,k)] \tag{3.3}$$

Total transportation cost of moving products from PCR to DC, PRC to CZ, PCR to DC, DC to CZ, CZ to PCR and PCR to DIC (for both new and recovered products) i.e.

$$\sum_{i\in I}\sum_{j\in J}[a(i,j)]\ Q(i,j) + \sum_{i\in I}\sum_{k\in K}[e(i,k)]\ B(i,k) + \sum_{i\in I}\sum_{j\in J}[a(i,j)]\ X(i,j) + \sum_{i\in I}\sum_{k\in K}[e(i,k)]\ T(i,k) + \sum_{j\in J}\sum_{k\in K}[b(j,k)]\ Y(j,k) + \sum_{k\in K}\sum_{i\in I}[p(k,i)]\ Z(k,i) + \sum_{i\in I}\sum_{l\in L}[q(i,l)]\ S(i,l) \quad (3.4)$$

Total recovery cost (calculated for re-introducible products at PCR) = [(Refurbishing cost per unit of product) $*$ (Quantity recovered by PCR 'i' from returned products from CZ 'k' after refurbishing)]

i.e.

$$\sum_{i\in I}[r(i) * M(i)] \quad (3.5)$$

Total collection cost (for all products returned by CZ) = [(Collection cost per unit of product returned by CZ 'k' at PCR 'i') $*$ (Amount of returned product shipped from CZ 'k' to PCR 'i')

i.e

$$\sum_{k\in K}\sum_{i\in I}[[c(i)] * Z(k,i)] \quad (3.6)$$

Total disposal cost = [(Per unit cost incurred in disposal activities of rejected returned products per at DIC 'l') * (Amount of rejected returned product shipped from PCR 'i' to DIC 'l')]

i.e.

$$\sum_{i\in I}\sum_{l\in L}[[s(l)] * S(i,l)] \quad (3.7)$$

Total penalty = [(Penalty cost per unit of unsatisfied demand) $*$ (Amount of unsatisfied demand of CZ 'k')]

i.e.

$$\sum_{k\in K}[\mu(k) * \alpha(k)] \quad (3.8)$$

Thus, the complete objective function can be rewritten as follows:

Min Total Cost $= \sum_{i\in I} f(i)U(i) + \sum_{j\in J} g(j)V(j) + \sum_{l\in L} h(l)W(l) + \sum_{i\in I}[m(i) * N(i)] + \sum_{j\in J}\sum_{k\in K}[n(j) * Y(j,k)] + \sum_{i\in I}\sum_{j\in J}[a(i,j)]\ Q(i,j) + \sum_{i\in I}\sum_{k\in K}[e(i,k)]\ B(i,k) + \sum_{i\in I}\sum_{j\in J}[a(i,j)]\ X(i,j) + \sum_{i\in I}\sum_{k\in K}[e(i,k)]\ T(i,k) +$

$\sum_{j\in J}\sum_{k\in K}[b(j,k)]\,Y(j,k)+\sum_{k\in K}\sum_{i\in I}[p(k,i)]\,Z(k,i)+\sum_{i\in I}\sum_{l\in L}[q(i,l)]\,S(i,l)+$
$\sum_{i\in I}[r(i)*M(i)]+\sum_{k\in K}\sum_{i\in I}[c(i)]\,Z(k,i)+\sum_{i\in I}\sum_{l\in L}[s(l)]\,S(i,l)+$
$\sum_{k\in K}\mu(k)\alpha(k)$ (3.9)

3.2.3.3 Constraints

The above problem is subjected to following constraints.

***Demand constraint*:** This constraint (3.10) assures that the total demand for all the CZ is taken into account, either by being satisfied or by being allocated to the unsatisfied demand variable.

i.e.

$$\sum_{i\in I}T(i,k)+\sum_{i\in I}B(i,k)+\sum_{i\in I}Y(j,k)+\alpha(k)\leq d(k),\ \forall k\in K \quad (3.10)$$

***Return constraint*:** Constraint (3.11) ensures that balance of the amount of returned products from all CZs are collected at PCRs.

i.e.

$$\sum_{i\in I}Z(k,i)\leq rr(k)[\sum_{i\in I}T(i,k)+\sum_{i\in I}B(i,k)+\sum_{i\in I}Y(j,k)],\forall k\in K \quad (3.11)$$

***Flow constraint*:** Constraint (3.12) is balancing the total quantities of products flow through PCRs.

i.e.

$$M(i)+N(i)=\sum_{j\in J}Q(i,j)+\sum_{k\in K}B(i,k)+\sum_{j\in J}X(i,j)+\sum_{k\in K}T(i,k),\ \forall i\in I \quad (3.12)$$

Similarly, constraint (3.13) balance the quantity of products flowing through DCs

i.e.

$$\sum_{i\in I}X(i,j)+\sum_{i\in I}Q(i,j)=\sum_{k\in K}Y(j,k),\ \forall j\in J \quad (3.13)$$

The constraint (3.14) balance the quantity of products flowing through DICs

i.e.

$$\sum_{l\in L}S(i,l)=df*\sum_{k\in K}Z(k,i),\ \forall i\in I \quad (3.14)$$

The constraint (3.14) balances the amount of products recovered at PCRs to do refurbishing.

i.e.

$$M(i)=[1-df]*\sum_{k\in K}Z(k,i),\ \forall i\in I \quad (3.15)$$

***Capacity constraints*:** Production capacity restriction for PCRs

i.e.

$$N(i) \leq pc(i) * U(i), \forall i \in I \tag{3.16}$$

Distribution capacity restriction for DCs

i.e.

$$\sum_{k \in K} Y(j,k) \leq dc(j) * V(j), \forall j \in J \tag{3.17}$$

Collection capacity restriction for PCRs for returned products

i.e.

$$\sum_{k \in K} Z(k,i) \leq cc(i) * U(i), \forall i \in I \tag{3.18}$$

Disposal capacity restriction for DICs

i.e.

$$\sum_{i \in I} S(i,l) \leq sc(l) * W(l), \forall l \in L \tag{3.19}$$

Binary and non-negativity restrictions

U_i, V_j, $W_l \in \{0,1\}$, $\forall i \in I, \forall j \in J, \forall k \in K$, and

$$M_i, B_{ik}, Q_{ij}, N_i, X_{ij}, T_{ik}, Y_{jk}, Z_{ki}, S_{il}, \alpha_k \geq 0, \quad \forall i \in I, \forall j \in J, \forall k \in K, \forall l \in L \tag{3.20}$$

In the above formulation, all network design parameters are deterministic in nature (parameter values are known with certainty). Hence, this mathematical model is termed as deterministic model. Moreover, the maximum transportation costs are not in constraints because we have assumed that robust model will yield optimal solution within the specified range of transportation cost i.e. nominal costs. The network considered in this formulation successfully captures the SDC and DSP method of simultaneous shipments. The above formulation helped in fulfilling the first objective of this study. Later, the model is reformulated to accommodate the demand uncertainty.

3.3 Robust optimization for addressing the demand uncertainty

3.3.1 Theory of robust optimization

In literature, the term RO has been used for numerous approaches to define the situation of protecting the decision-maker against parameter ambiguity and stochastic uncertainty. However, there is no clear definition of RO exists. The managers must define the meaning of term RO for their objectives and strategic decision making. In general, the RO has two aspects, the solution robustness and model robustness. The solution robustness means a situation where the solution feasibility must be guaranteed for any realization of the uncertain parameters, whereas, in the case of model robustness, achieving objective function value must be guaranteed (Al-e-hashem et al., 2011). The main hypothesis of RO relies on a worst-case analysis where a solution is evaluated using the realizations of the uncertainty of parameters which are most unfavorable (Al-e-hashem et al., 2011; Gabrel et al., 2014).

There are a number of ways to compute the worst cases such as using finite number of scenario analysis, historical data or using uncertainty set etc. (Gabrel et al., 2014). The formulation of the RC depends on the approach selected to address the uncertainty. This study utilized the static RO framework with a focus on solution robustness and no recourse action is allowed once the uncertainty has been realized. In this process, uncertainty set used can have solution robustness for any feasible realization. The uncertainty set is centered on the nominal values of the uncertain parameters. The aim is to optimize the objective function over the set of solutions that are feasible for all coefficient values in the uncertainty set. The selection of the this uncertainty set should be made carefully because it impacts the computational tractability of the RC (Ben-Tal and Nemirovski, 1999; Gabrel et al., 2014). Additionally, the issues of over conservatism are paramount in RO (Gabrel et al., 2014). The over conservatism is the situation where the uncertain parameter set over and results in high cost for protection against uncertainty.

The tractable reformulation that leads to the optimal solution, as well as probabilistic guarantees of constraint violation, is achieved through considering worst-case optimization. The worst-case optimization is the situation where the worst case of the constraints is computed over a convex uncertainty set of the parameters, which bounds the maximum allowable deviation of the parameters from their nominal values. The reader is referred to the studies Ben-Tal and Nemirovski (2000) and Ben-Tal et al. (2009) for finding the full details of RO. Moreover, Minoux (2009) proves that the robust network design problems under uncertain demand are NP-hard problem. The subsequent section will provide the RO based modeling of CLSC network under demand uncertainty.

3.3.2 Robust counterpart (RC) formulation

The deterministic model (Equation no. 3.1 to 3.20) is a linear programming problem and reformulated as an uncertain linear optimization problem using Ben-Tal and Nemirovski (2000) and Ben-Tal et al. (2009) to accommodate the uncertainty in the model parameters. The procedure is explained in the following sections.

Let us consider the general form of a linear optimization model as follows:

$$Min\ cx + d \tag{3.21}$$

$$subjected\ to\ (s.t.)\ Ax \leq b$$

In the above generic form, the related uncertain linear optimization problem can be represented as follows:

$$Min\ cx + d \tag{3.22}$$

$$s.t.\ Ax \leq b \tag{3.23}$$

$$c, d, A, b \in U$$

In the above Equations (3.22) and (3.23), the parameters *c, d, A, b* belongs to uncertainty set *U* and vary in that set. Let, a vector 'x' is a robust feasible solution to the problem, if it satisfies all realizations of the constraints from the uncertainty set.Using Ben-Tal and Nemirovski (1999) the RC of the problem can be defined as follows:

$$\min\{\hat{c}\ (x) = \sup_{c, d, A, b\ \in U}[cx + d\ ]: Ax \leq b\ \forall\ c, d, A, b\ \in U\} \tag{3.24}$$

The optimal solution achieved to above problem (3.24) is the optimal robust solution of the problem (3.22). Such a solution satisfies the constraints for all possible realizations of the data, and guarantees an optimal objective function value not worse than $\hat{c}\ (x)$. The RC given above is a linear optimization problem (NP hard) and may results computationally intractable (Ben-Tal and Nemirovski, 2000; Pishvaee et al., 2011). However, it turns out that for a wide variety of compact, convex uncertainty sets, the RC model is a tractable (polynomially solvable) with convex mathematical problem, typically as a linear optimization problem (Ben-Tal and Nemirovski, 1999, 2000; Ben-Tal et al., 2009; Pishvaee et al., 2011).

The choice of uncertainty set depends on various factors such as suitability of uncertainty set for the problem, tractability of the RC obtained, scope of uncertain data sets etc. There are number of uncertainty sets discussed in literature such as box, polyhedron, ellipsoid and convex Hull (Ben-Tal and Nemirovski, 1999, 2000). In this study, the RC of the proposed CLSC model for the demand uncertainty is developed by considered the parameter uncertain of box type. It is because the demand uncertainty is assumed to be vary between maximum to minimum arround a nominal values and the natural worst case will be highest possible demand realization. Thus, it is assumed that this variation follows a specific closed bounded box ($L_{k\ Lower} \leq D_k$(uncertain parameter) $\leq U_{k\ Upper}$) which captures the practical situation of the demand fluctuations. The resulted RC will also follow linear programming framework (Ben-Tal and Nemirovski, 1999, 2000; Ben-Tal et al., 2009; Pishvaee et al., 2011). The general form of this box can be shown as follows:

$$u_{box} = \{\xi \in R^n : |\xi_t - \bar{\xi}_t|\} \leq \rho\, G_t, t = 1, 2, \dots\dots, n \tag{3.25}$$

Where in Equation (3.25), $\bar{\xi}_t$ is the nominal value of the ξ_t as t^{th} parameter of vector ξ (n-dimension vector) and the positive numbers G_t represent 'uncertainty scale' while $\rho > 0$ is the 'uncertainty level'. A particular case of interest is when $G_t = \bar{\xi}_t$, which corresponds to a simple case where box contains ξ_t, whose relative deviation from the nominal data is of size up to ρ. According to the above descriptions, the RC of the concern CLSC network with DSP and SDC shipments under uncertain demand is represented as with following MILP formulation:

$$\min z \tag{3.26}$$

$s.t.$ -

$$\begin{aligned}
&\textstyle\sum_{i \in I} f(i)U(i) + \sum_{j \in J} g(j)V(j) + \sum_{l \in L} h(l)W(l) + \sum_{i \in I}[m(i) * N(i)] + \\
&\textstyle\sum_{j \in J}\sum_{k \in K}[n(j) * Y(j,k)] + \sum_{i \in I}\sum_{j \in J}[a(i,j)]\, Q(i,j) + \sum_{i \in I}\sum_{k \in K}[e(i,k)]\, B(i,k) + \\
&\textstyle\sum_{i \in I}\sum_{j \in J}[a(i,j)]\, X(i,j) + \sum_{i \in I}\sum_{k \in K}[e(i,k)]\, T(i,k) + \sum_{j \in J}\sum_{k \in K}[b(j,k)]\, Y(j,k) + \\
&\textstyle\sum_{k \in K}\sum_{i \in I}[p(k,i)]\, Z(k,i) + \sum_{i \in I}\sum_{l \in L}[q(i,l)]\, S(i,l) + \sum_{i \in I}[r(i) * M(i)] + \\
&\textstyle\sum_{k \in K}\sum_{i \in I}[c(i)]\, Z(k,i) + \sum_{i \in I}\sum_{l \in L}[s(l)]\, S(i,l) + \sum_{k \in K}\mu(k)\alpha(k) \leq z
\end{aligned} \tag{3.27}$$

$M(i) \ = \ \sum_{j\in J} Q(i,j) + \sum_{k\in K} \ B(i,k), \forall i \in I$ (3.28)

$N(i) \ = \ \sum_{j\in J} X(i,j) + \sum_{k\in K} \ T(i,k), \forall i \in I$ (3.29)

$\sum_{i\in I} T(i,k) + \ \sum_{i\in I} B(i,k) \ + \ \sum_{i\in I} Y(j,k) + \alpha(k) \geq \ d(k) + \rho^{d} G^{d}(k), \forall k \in K$ (3.30)

$\sum_{i\in I} Z(k,i) = rr(k)[\, d(k) - \alpha(k)] + [rr(k)\, d(k)\, \rho^{d} G^{d}(k)], \forall k \in K$ (3.31)

$\sum_{i\in I} X(i,j) + \ \sum_{i\in I} R(i,j) = \sum_{k\in K} Y(j,k), \forall j \in J$ (3.32)

$\sum_{l\in L} S(i,l) = df * \sum_{k\in K} Z(k,i), \forall i \in I$ (3.33)

$M(i) = [1 - df] * \sum_{k\in K} Z(k,i), \forall i \in I$ (3.34)

$N(i) \leq \ pc(i) * U(i), \forall i \in I$ (3.35)

$\sum_{k\in K} Y(j,k) \leq \ dc(j) * V(j), \forall j \in J$ (3.36)

$\sum_{k\in K} Z(k,i) \leq \ cc(i) * U(i), \forall i \in I$ (3.37)

$\sum_{i\in I} S(i,l) \leq \ sc(l) * W(l), \forall l \in L$ (3.38)

$U_i, V_j, W_l \in \{0,1\}, \forall i \in I, \forall j \in J, \forall k \in K$ (3.39)

$M_i, B_{ik}, Q_{ij}, N_i, X_{ij}, T_{ik}, Y_{jk}, Z_{ki}, S_{il}, \alpha_k \geq 0, \forall i \in I, \forall j \in J, \forall k \in K, \forall l \in L$ (3.40)

With the above mathematical formulation, we have achieved the second research objective is achieved. To assess the performance of this model, several numerical experiments are performed and results are reported in the next section.

3.4 Numerical tests

3.4.1 Input data sets

This part of the chapter provides the detailed numerical simulation and analysis of the test results. The approach followed in this study for numerical simulation and testing is similar to Pishvaee et al. (2011) and Hatefi and Jolai (2014). The input data is randomly generated in specified ranges two models numerically tested under this data. In the solution approach, a total of four different network structures (PCR*DC*CZ*DIC) of sizes (3*5*7*2, 8*20*28*3, 4*8*14*2, and 6*14*22*2) are the considered. Table 3.1 lists the randomly generated nominal input data. The deterministic and robust models are programmed in AIMMS© 4.2

with solver CPLEX® 12.6 (www.aimms.com) on Intel-based PC of 1.73 GHz with 1 GB memory. The AIMMS© program code is provided in Appendix-II.

Table 3.1: List of randomly generated nominal input data

Parameters	Data Range	Parameters	Data Range
d_k	(400,500)	n_j	(10,20)
rr_k	(0.05, 0.1)	a_{ij}	(40,60)
pc_i	(2500,4000)	b_{jk}	(60,80)
dc_j	(700,1200)	e_{ik}	(50,1500)
cc_i	(300,500)	c_i	(20,50)
sc_l	(100,300)	s_l	(20,50)
d_f	(0.1,0.2)	r_i	(20,50)
f_i	(500000,700000)	p_{ki}	(50,70)
g_j	(50000,70000)	q_{il}	(50,70)
h_l	(10000,20000)	μ_k	(2200,3000)
m_i	(1500,2000)		

The AIMMS© (An Advanced Integrated Multidimensional Modeling Software), provided by *www.aimms.com*, is a tool with multiple capabilities for programming and scores of solver choices. It has been used by a number of researchers for building decision support and optimization applications. Ashayeri et al. (2014) used it for solving MIP model for re-designing the supply chain network under bankruptcy to optimize the business survival capability and profits of a company. There are number of other studies which have used AIMMS©, such as Setlhaolo et al. (2014) used it for modeling and solving scheduling of household appliances by Setlhaolo et al. (2014) and a MILP based formulation for optimization under uncertainty of the petroleum product supply chain by Oliveira et al. (2014).

Some more examples of use of AIMMS© are, a MIP based tactical planning for a biomass power plant supply chain under uncertainty by Shabani et al. (2014), a

MILP based model to optimize multi-biomass and natural gas supply chain strategic design by Pantaleo et al. (2014). The mathematical formulations of this research are of MILP type and can be effeciently programmed in AIMMS©.

Thus, use of AIMMS© for solving this research problem is defensible. First, the deterministic model is solved using nominal data (without considering uncertainty) and then the RC based model is solved under different levels of demand uncertainty (ρ). Total four levels (0.2 to 0.8) of uncertainty are devised. Use of such level of uncertainty (from 0.2 to 0.8) is also popular in literature. Pishvaee et al. (2011) has varied the uncertainty from 0.1 to 0.9 to observe its impact on a CLSC network. Hatefi and Jolai (2014) analyzed a CLSC problem under the uncertainty range of 0.2 to 1.0. A relatively small range of level of uncertainty, 0.2 to 0.5 was considered by Zeballos et al. (2014).

The study uses various network performance indicators (NPIs) such as total objective function value (i.e. total supply chain costs), network flow related costs (i.e. transportation, production, distribution etc.), number of facilities open or close (i.e. PCR, DC and DIC), amount of products flowing through supply chain echelon etc. These NPIs are based on Ballou (2003), Pishvaee et al. (2011), Hatefi and Jolai (2014), Al-e-hashem (2011), Carlsson et al. (2014) in SCND context to benchmark and compare the results of set of networks structures.

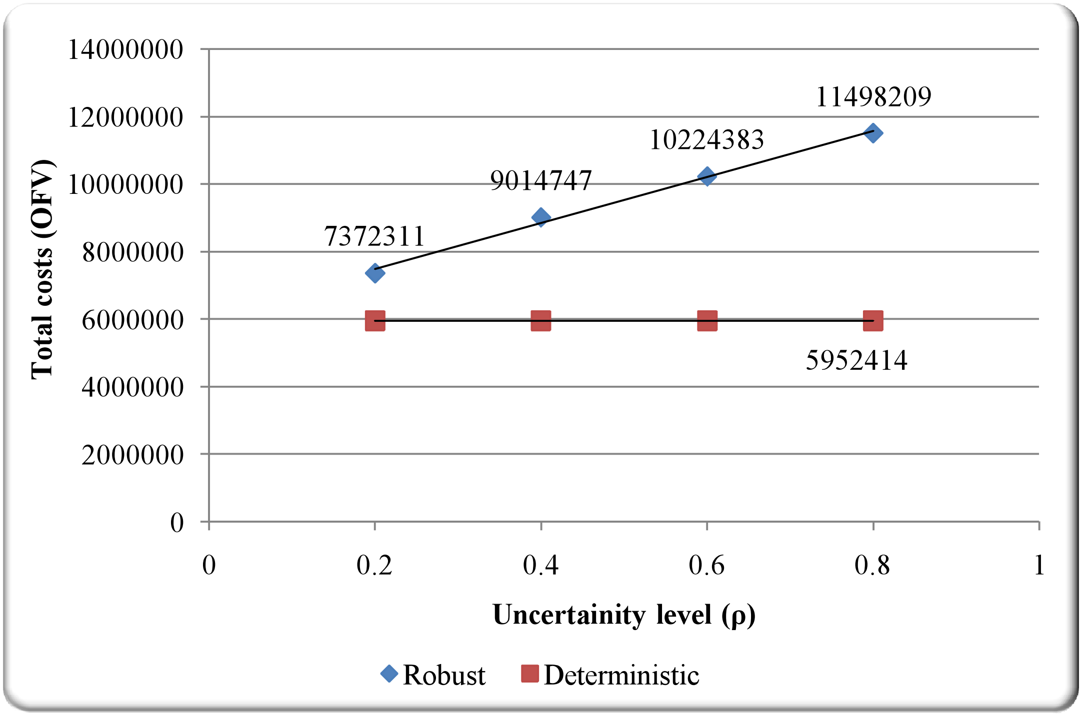
Apart from it, few observations related to result statistics such as solution time, number of iterations, number of constraints, and numbers of variables are also recorded. Table 3.2 presents the summary of results of numerical tests and values of various NPIs for all four network sizes. The highest number of constraints, variables and iterations were 264, 1712, and 5309 respectively. These observations depict the level of complexity of the problem undertaken.

Table 3.2: Summary of results of numerical tests and values of various NPIs for all four network sizes

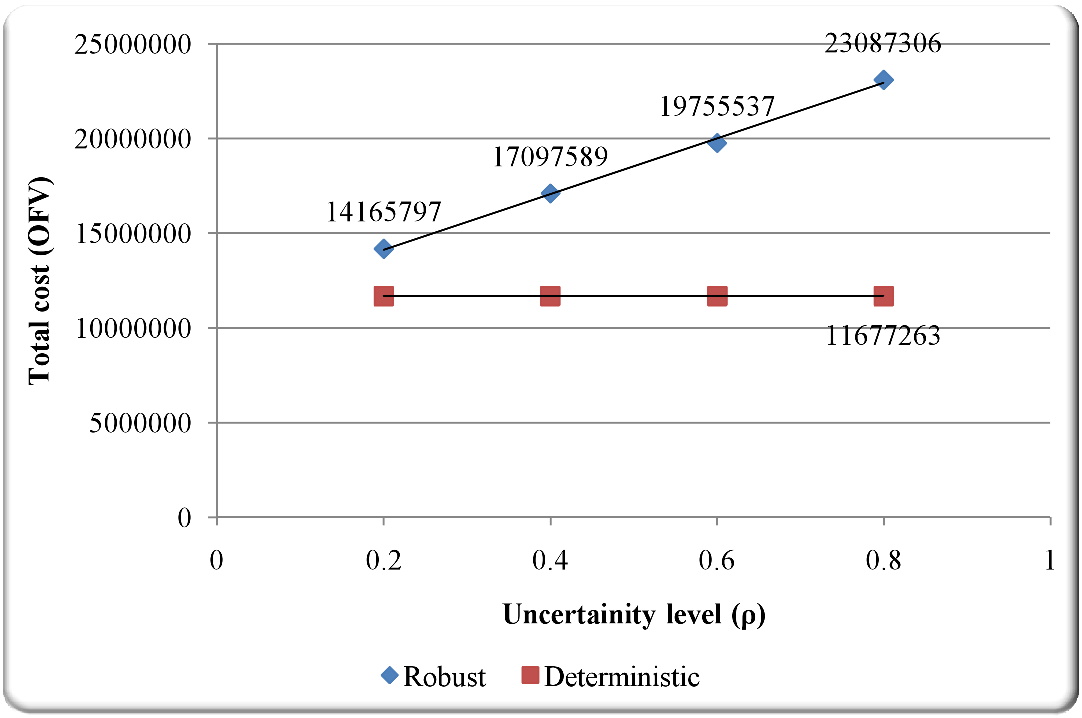
Network Size	ρ	Total Supply Chain Costs (OFV)		Solution Time (Sec)	No. of Constraints	No. of Variables	Non zero	Integer	No. of Iterations	Gap (RO Model)
		Robust	Deterministic	For RO Model						(%)
Network-1 3*5*7*2	0.2	7372311	5952414	0.45	77	176	627	157	310	0.00
	0.4	9014747		0.55					378	0.00
	0.6	10224383		0.85					458	0.01
	0.8	11498209		0.92					572	0.00
Network-2 4*8*14*2	0.2	14165797	11677263	3.12	131	421	1583	388	410	0.00
	0.4	17097589		15.52					603	0.00
	0.6	19755537		19.23					738	0.00
	0.8	23087306		31.98					878	0.00
Network-3 6*14*22*2	0.2	22445176	18055167	32.2	203	989	3825	940	372	0.03
	0.4	26675143		59.83					627	0.00
	0.6	31014787		62.12					751	0.00
	0.8	35869587		85.4					1054	0.02
Network-4 8*20*28*3	0.2	29085690	23412801	58.25	264	1712	6675	1651	954	0.08
	0.4	34727810		67.77					1046	0.03
	0.6	40370735		89.73					3047	0.03
	0.8	46377225		110.97					5309	0.02

3.4.2 Test results and discussion

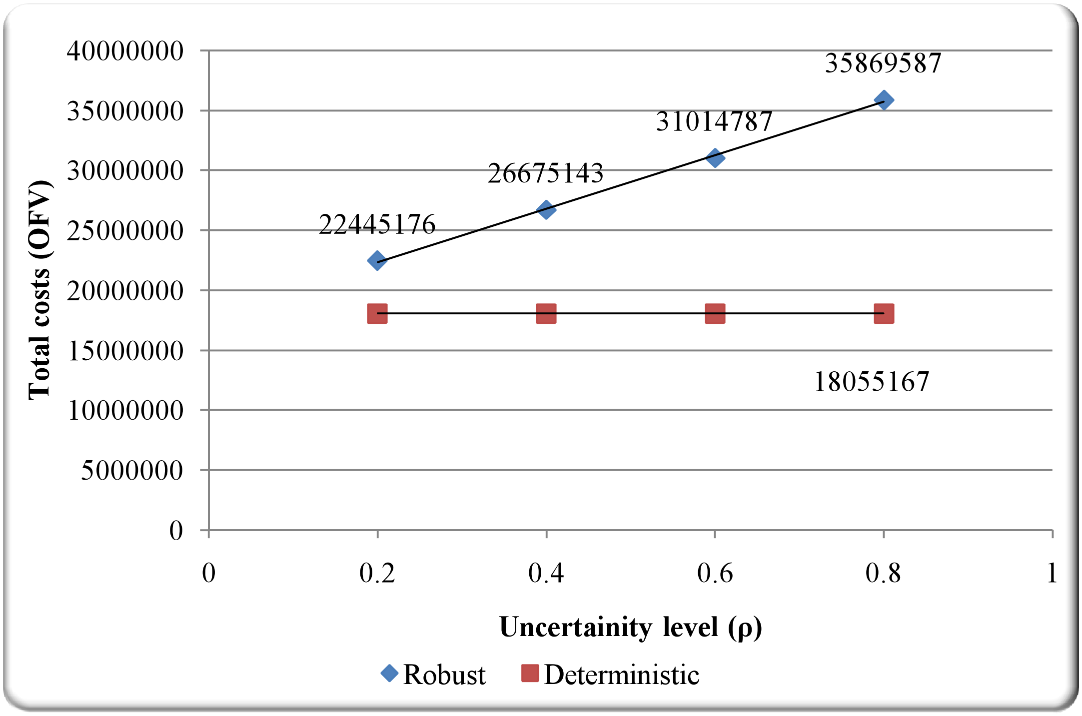
In Table 3.2, the first NPI observed is the objective function value (OFV) obtained from solving the Equation 3.9 and Equation 3.26. This NPI 'OFV' i.e. total supply chain cost reflects the efficiency of supply chain network. The test results exhibits that the OFV of RO model increases as the size of network increases. For example, Network-1 (i.e. 3*5*7*2) at $\rho = 0.2$ has OFV equal to 7372311, while, Network-2 which is larger in size has OFV equal to 14165797 at same level of uncertainty. It depicts that to accommodate the demand uncertainty; there is some additional cost which firm should be ready to bear. In the similar manner, within a specific network, OFV always increases with the increase in level of uncertainty. On the other hand, the model computational performance statistics revealed that the smaller size of network with less complexity (e.g.Network-1) has taken less time as compared to other larger networks. It is worth noting that while executing the programme here was a stopping criterion applied such that the CPLEX® solver is allowed to minimize the gap up to the level 0.1 (the gap is the relative difference between best LP bound and best solution).



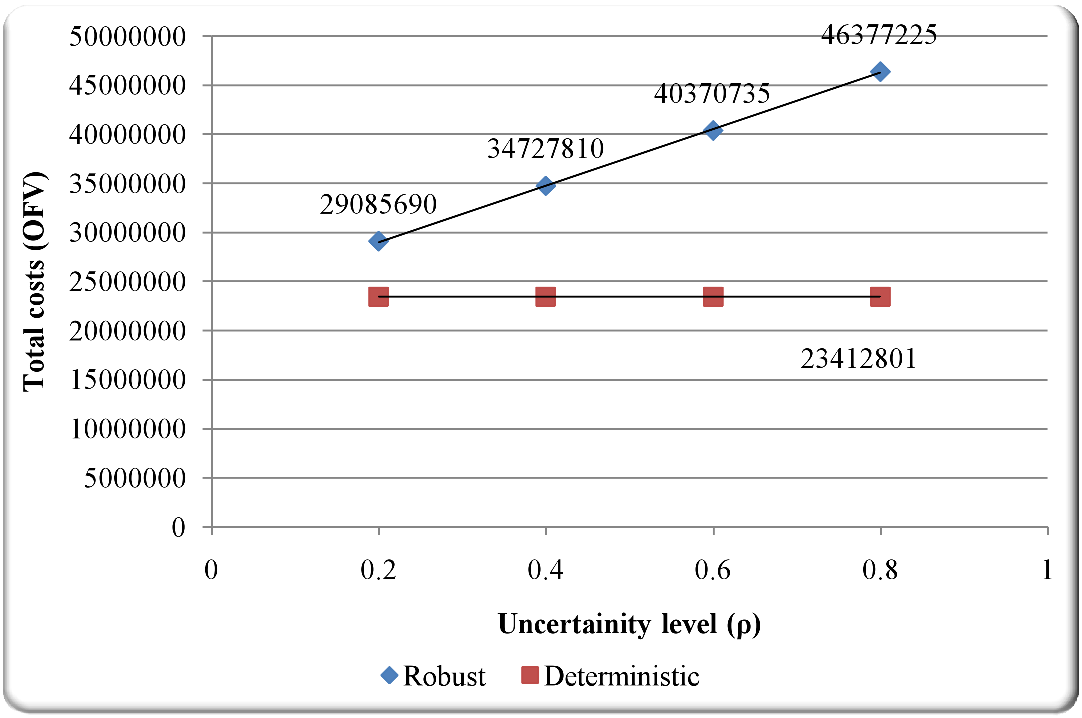
(a) For Network-1 (3*5*7*2)



(b) For Network-2 (4*8*14*2)



(c) For Network-1 (6*14*22*2)



(d) For Network-4 (8*20*28*3)

Figure 3.2: Total supply chain costs variations for robust and deterministic model for all four test networks sizes

However, the largest network witnesses the highest jump in costs. These findings can be visualized in a better way in Figure 3.2 where the slope of the (RO model OFV) line is high for Network-4 as compared to other three networks. Figure 3.2 presents the total supply chain costs variations for robust and deterministic model for all four test networks sizes.

One of the important NPI is the cost of robustness which can be defined as the difference in OFV between deterministic and RO model. A keen observation of Table 3.2 also reveals that this cost of the robustness also increases as the level of uncertainty raised for a particular size of the network and among all network sizes; it is highest for the largest one. It is a vital observation because this study has used the largest network (Network-4 with 8*20*28*3) for some more numerical experimentation. Figure 3.3 provides the closer look at this variation of cost of robustness in all four networks.

Figure 3.3 presents the behavior of cost of robustness for all four network sizes. For example, the costs of robustness at = 0.4 for all four networks are 51.44%, 46.41%, 47.74% and 48.32% higher than their respective deterministic counterparts. A simple deduction follows here that at about 40% to 50% higher cost, the firm will be able to handle about 40% more demand without altering the network topology. Thus, the network configuration obtained from RO based model is capable of handing higher level of demand variations as compared to network structure defined by deterministic modeling.

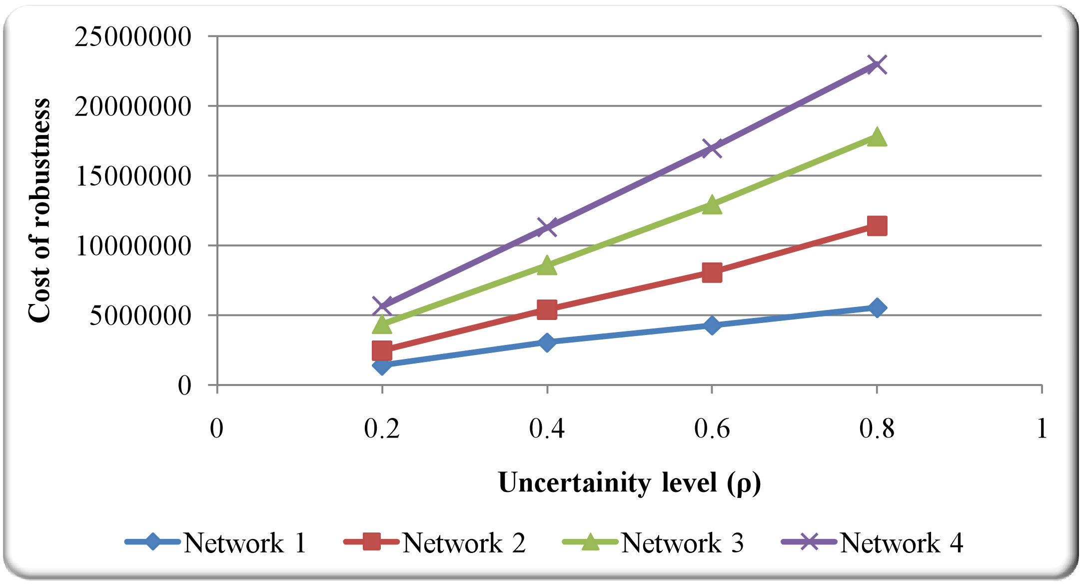


Figure 3.3: Behavior of cost of robustness for all four network sizes

However, this observation fails to provide the whole picture of the situation as it do not provide sufficient insight as to what degree the robust approach is good? As we know that the uncertainty will be realized in future and only afterward its impact can be felt. In other words, the NPI cost of robustness needs more investigations to justify its high figures of OFV in the robust model to compete the uncertain demand. It will be of great use if one can estimate the impact of realized uncertainty on both the models (RO and deterministic models). This study has devised “worst case scenario” analysis to dig deeper into the situation and provide the answer to the question, “How robust is better than deterministic?”

The answers of the above questions can be found by revisiting the definition of RO from Chapter 2. Ben-Tal and Nemirovski (2000) argued that the solution obtained from RO is the best solution against the worst possible data realization within the uncertainty set. In SCND context of this study, the realization of uncertainty means that the worst case of demand takes place. In supply chain management context, it will be the situation when the companies have to manage the highest demand in a planning horizon. This study has devised “worst case scenario” analysis based on lines of Eslamipoora et al. (2014). The procedure is executed in the following manner; initially, the deterministic and RO models are solved using nominal data and a specific network topology and associated costs are recorded. In the next step, under worst demand realization, both the networks configurations (RO and deterministic) are again solved and the OFVs of both models are estimated. In this course the network parameters are allowed to update their tactical variables. The impact of demand uncertainty on the network configuration obtained using RO modeling and network configuration achieved through deterministic approach is analyzed.

A separate numerical experiment on Network-4 is carried out to demonstrate the above situation. In this piece of numerical testing, total nine levels of uncertainty (ρ) is considered (from 0.1 to 0.9). Table 3.3 presents the estimation of deterministic worst-case for Network-4 under uncertain demand. The important observation is that the total supply chain cost of the deterministic worst case (DWC) is higher than RO model. Thus, apart from cost of robustness, there is always a cost benefit in adopting RO modeling to obtain an optimized supply chain topology under parameter uncertainty. Hence, it can be argued that the solution provided by RO approach is superior to deterministic model under the worst case data realization of uncertain parameters. The utility of the RO based modeling method lies in the fact that there can be situation when a supply chain has to operate under various uncertainties which can affect it in an adverse manner in future. The RO based modeling approach provides efficient tool which empowers managers and strategists to make SCND decisions to counter the uncertainties.

Table 3.3: Estimation of deterministic worst-case for Network-4 under uncertain demand

Network-4 (8*20*28*3)				
	Uncertainty level (ρ)	**OFV (Total supply chain cost)**		
S. N.	**ρ**	**Deterministic**	**DWC**	**RO model**
1	0.1	23412801.2	26248772.8	26221683.6
2	0.2		29847725.7	29085690.3
3	0.3		33737948.8	31815061.5
4	0.4		37507673.2	34736810.4
5	0.5		41293240.0	37390069.7
6	0.6		45082994.3	40370735.1
7	0.7		48873850.4	43365350.2
8	0.8		58699844.7	46377226.0
9	0.9		66517527.3	49391739.7

As discussed earlier that parameter uncertainty is likely to impact the largest network structure most. This study has extended the numerical experimentation to investigate this phenomenon further on Network-4. A set of scenarios of data realization is generated and various NPIs are estimated. The similar procedure of data and scenarios generation can be found in Hatefi and Jolai (2014). It is worth noting that as the number of scenarios increases, it leads to significant increase in computational time. If the number of scenarios grows rapidly then the model becomes too large too quickly. In the robust network design framework, in most of the cases, the total number of scenarios are about fourteen (Snyder and Daskin, 2006; Hatefi and Jolai, 2014). In this study, total sixteen scenarios of demand uncertainty for the network of size 8*20*28*3 are considered. For numerical tests, the input values of required parameters are generated as per the scheme discussed above in Section 3.4.1. Few more NPIs are also estimated which includes service level, stockout rate, unsatisfied demand and realized profit (Ballou, 2003; Pishvaee et al., 2011; Hatefi and Jolai, 2014). Table 3.4 provides the summary of test results and NPIs under uncertain demands for Network-4.

Table 3.4: Summary of test results and NPIs under uncertain demands for Network-4

S. N.	ρ	Observed values of NPI under four random cases of realization for 8*20*28*3								
		OFV		Service level (%)		Stockout rate (%)		Unsatisfied demand		Realized profit
		DWC	ROM	DWC	ROM	DWC	ROM	DWC	ROM	
1	0.2	29130022.13	28469514.06	89.36	92.03	10.63	7.96	1576	1181	660508.07
		28468267.67	27811825.64	91.20	93.92	8.79	6.07	1277	882	656442.03
		26538638.22	25830663.11	97.05	100	2.94	0	401	0	707975.11
		25260595.03	25274526.15	99.1	100	0.89	0	117	0	6068.88
	Mean	27349380.76	26841632.24							
	SD	1774159.04	1541886.158							
2	0.4	39215523.74	33664148.12	76.56	97.25	23.43	2.74	4059	476	5551375.62
		40292567.57	32318437.51	79.45	100	20.54	0	3429	0	7974130.06
		35478065.84	30196699.23	84.76	100	15.23	0	2380	0	5281366.61
		32603286.49	28820311.38	88.36	91.35	11.63	8.64	1744	1296	3782975.11
	Mean	36897360.91	31249899.06							
	SD	3528681.566	2158896.255							
3	0.6	54583928.87	38851357.96	65.90	96.61	34.09	3.31	6851	666	15732570.9
		49460089.27	36561218.51	70.95	100	29.04	0	5421	0	12898870.8
		41199030.04	32759110.76	78.39	99.51	21.60	0.48	3655	72	8439919.28
		28576689.86	27764283.74	91.24	95.61	8.750	4.38	1270	822	812406.12
	Mean	43454934.51	33983992.74							
	SD	11348533.94	4848314.235							
4	0.8	60370023.45	44897210.57	59.14	86.32	40.85	13.67	9261	3076	15472812.9
		53879447.24	38859220.08	69.05	98.16	30.94	1.83	6551	366	15020227.2
		53530026.15	38634542.51	67.37	98.51	32.62	1.48	6424	260	14895483.6
		44318299.47	35788549.09	72.52	90.38	27.47	9.61	5024	1441	8529750.38
	Mean	53024449.08	39544880.56							
	SD	6601543.604	3832158.152							

Note:
DWC = Deterministic Worst Case; DM = Deterministic Model; ROM= Robust Optimization Model; SD = Standard Deviation
Objective function values = Minimum total supply chain cost under DM and ROM respectively calculated for a particular scenario
Unsatisfied demand = Total of non-satisfied demand of all customer in a particular scenario.
Service level = Ratio of total satisfied demand of all customer to the total demand that scenario (in %).
Stock out rate = (100- service level) in %
Realized profit = The amount saved by companies if RO based modeling is used to determine the network configuration as compared to simple deterministic modeling. Numerically it is estimated as (OFV of DWC – OFV of ROM).

From Table 3.4 it can be observed that the OFV of supply chain configuration obtained through RO model dominates the DWC in each scenario. One of the significant advantages of adopting RO in SCND process is high service level of the realized network configuration. In most of the scenario, the service level of ROM model is greater than 90% (see Table 3.4, sixth column from left). It implies that the RO models are highly capable in handling worst case of demand or uncertainty. The high service level will also ensure low stockout rate which in turn improves the responsiveness of supply chain. Additionally, the company revenue, brand image, customer experience, stock value, etc. will get better. The realized profit is the amount that can be saved by following RO modeling instead of deterministic modeling in SCND when a worst case of demand uncertainty happened.

It is visible from the data of Table 3.4 that for every scenario, the realized profit is adding some value to the supply chain cost and under a higher level of uncertainty, this amount is very significant (see Table 3.4, last from right side column). Figure 3.4 presents the graph of mean and standard deviation of OFV for Network-4 under uncertain demand. From Figure 3.4 it is clear that the RO model has the OFVs with both higher quality and lower standard deviations than the deterministic model. In other words, with respect to standard deviation, the robust approach dominates the deterministic one in all scenarios with a high difference.

In addition to above observations, the supply chain configuration (network topology) obtained from the deterministic model and RO model is also analyzed. Table 3.5 provides the summary of supply chain network configuration of deterministic and RO model for Network-4. Table 3.6 presents the comparison of facility cost, transportation costs and PDR costs for network configurations obtained using deterministic and RO model for network-4.

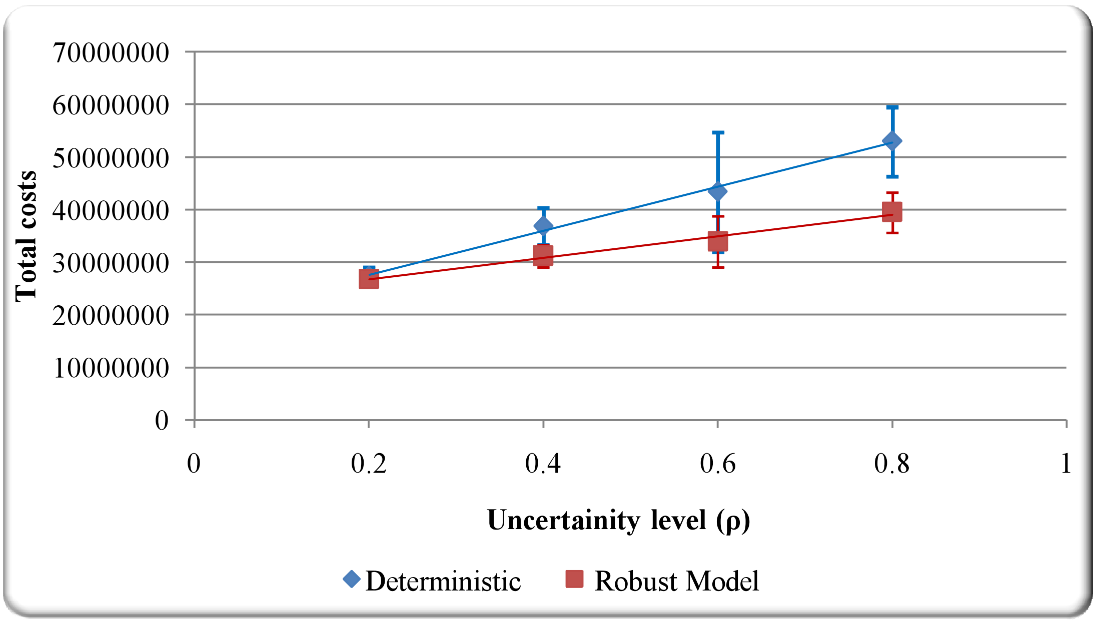


Figure 3.4: Mean and standard deviation of OFV for Network-4 (problem size 8*20*28*3) under uncertain demand

It is observed from obtained network topology that robust model has opened greater number of facilities to capture the demand uncertainty. However, these facilities are allocated in an optimized manner so that the network can handle the worst case of demand optimally. For example, the RO based optimized network has DIC-3 while the previous deterministic network structure is designed with DIC-2. There is a visible difference in the number of PCR opened by the RO model and deterministic model. RO model has opened three more PCR. In RO model, there are more quantities shipped directly to the CZ (2313 at ρ = 0.2) as compared to deterministic model (1617 at ρ = 0.2) which shows that the network topology achieved through RO model is more capable of engaged in DSP. If one look into the change in the total facility costs, the maximum premium was 41% more in the case of RO which was used to handle ρ = 0.8. Table 3.6 summarizes the costs for the supply chain configurations obtained (i.e. deterministic and RO model) for Network-4. These computational results substantiate the superiority of the RO modeling of handling the demand uncertainty.

Table 3.5: Summary of supply chain network configuration of deterministic and RO model for Network-4

<table>
<tr><th>S. N.</th><th>ρ</th><th colspan="2">PCR Open</th><th colspan="2">DC Open</th><th colspan="2">Disposal Center</th><th colspan="4">Quantity Shipped</th></tr>
<tr><th></th><th></th><th>DWC</th><th>ROM</th><th>DWC</th><th>ROM</th><th>DWC</th><th>ROM</th><th>DS (DET)</th><th>DS (RO)</th><th>SDC (DET)</th><th>SDC (RO)</th></tr>
<tr><td>1</td><td>0.2</td><td>2,3,4,5</td><td>2,3,4,5,7</td><td rowspan="4">2,3,7,10,11,13, 14,15,18,20</td><td>2,3,5,7,9,10,11,13, 14,15,18,20</td><td rowspan="4">2</td><td>3</td><td>1617</td><td>2313</td><td>10541</td><td>12696</td></tr>
<tr><td>2</td><td>0.4</td><td>2,3,4,5</td><td>2,3,5,6,7</td><td>2,3,5,7,9,11,13,14, 15,18,20</td><td>3</td><td>1617</td><td>4760</td><td>10541</td><td>11714</td></tr>
<tr><td>3</td><td>0.6</td><td>2,3,4,5</td><td>2,3,4,5,6, 7</td><td>2,3,5,7,8,9,10,11,1 3,14,15,18,20</td><td>3</td><td>1617</td><td>5427</td><td>10541</td><td>13474</td></tr>
<tr><td>4</td><td>0.8</td><td>2,3,4,5</td><td>2,3,4,5,6, 7,8</td><td>2,3,4,5,7,8,9,10,11, 13,14,15,17,18,20</td><td>3</td><td>1617</td><td>6447</td><td>10541</td><td>15043</td></tr>
<tr><td colspan="12"><u>Note:</u>
DS (DET) = Quantity of products in direct shipping for deterministic case; DS (RO) = Quantity of products in direct shipping for RO model; SDC (DET) = Quantity of products in shipped through DC for deterministic case; SDC (RO) = Quantity of products in shipped through DC for RO model</td></tr>
</table>

Additionally, to countercheck the results the above numerical tests are repeated for Network-1 of size 3*5*7*2, which has a very significant difference in problem size as compared to Network-4. Thus, a separate data set for this size of the network is prepared by following the same range of values as per Network-4. The results related to mean and standard deviation of the problem are obtained and analyzed. Figure 3.5 shows the mean and standard deviation of OFV for Network-1 under uncertain demand. The variation in mean and SD values found here is very similar to Figure 3.4. However, the RO based SCND modeling has improved performance for large-sized network and also for the higher level of uncertainty. This can be observed from the variation of mean and SD values in Figures 3.4 and Figures 3.5. Thus, this research advocates the adoption of RO methods to counter the effect of parameter uncertainty and argued that the supply chain configuration obtained from RO will not only be superior but also optimal.

Table 3.6: Comparison of facility cost, transportation costs and PDR costs for network configurations obtained using deterministic and RO model for Network-4

S. N.	ρ	Facility Cost		% Change	Transportation Costs		PDR Cost	
		Deterministic	ROM		Deterministic	ROM	Deterministic	ROM
1	0.2	2858237	2935250	2.6	1533416.4	1514763.95	20336438	21405332.85
2	0.4		3548558	19.4	1560258.8	2031465.59	20340206	27036077.25
3	0.6		4207322	32.0	1541896.3	2319241.9	20335735	31540960.4
4	0.8		4920460	41.9	1534975.2	2310611.9	20335941	31540768.8
Note: PDR Costs = Total of (Production + Distribution + Recovery (refurbishing)) Costs								

Table 3.7: Mean and standard deviation of OFV for Network-1 (3*5*7*2) under uncertain demand

S. N.	Model	ρ	Scenario and OFV				Mean	SD
1	ROM	0.2	7369010.87	7225491.81	6710791.13	6418871.71	6931041.38	383844.456
		0.4	9004641.46	9195048.56	7805216.97	7190450.76	8298839.43	832696.8
		0.6	9824382.53	8957183.63	7742796.83	7189246.12	8428402.28	1028826.2
		0.8	11564512.63	10367585.57	9190864.61	7871975.53	9748734.58	1370535.46
2	Deterministic	0.2	7525491.81	7378925.13	6839873.19	6494068.8	7059589.73	414466.26
		0.4	10096319.17	10806342.89	9322160.88	7991107.45	9553982.6	1043893.58
		0.6	12587342.75	12312028.25	9455774.49	8851651.44	10801699.2	1664618.29
		0.8	15538079.17	13607093.2	11943528.5	10967639.6	13014085.1	1736104.47

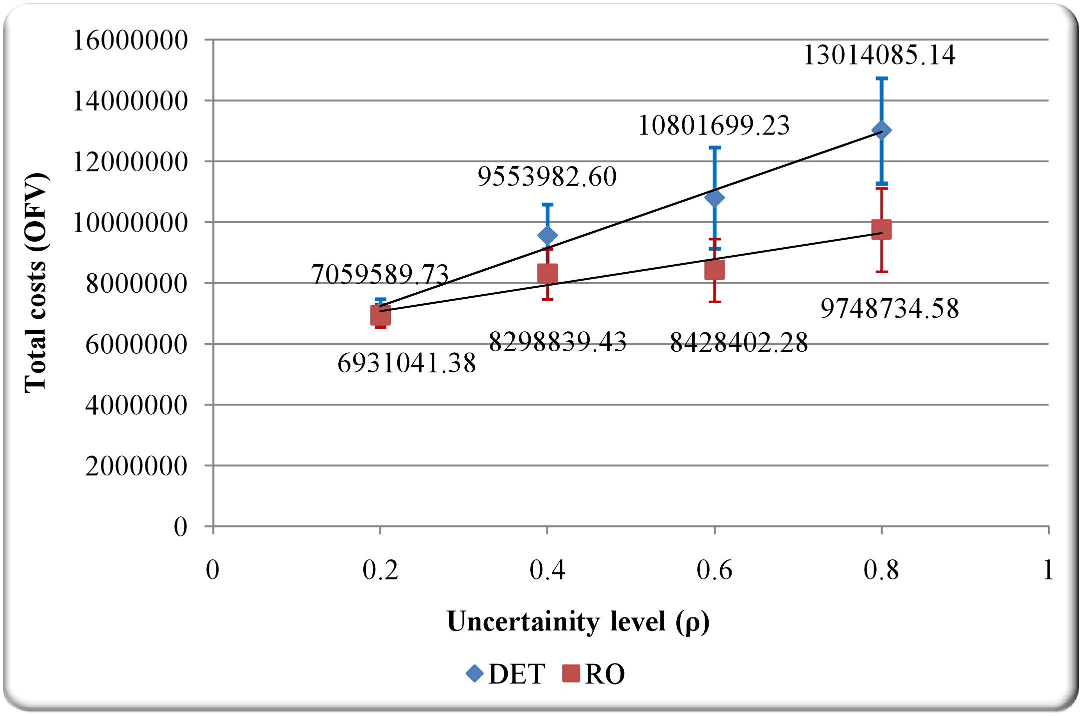


Figure 3.5: Mean and standard deviation of objective function values for Network-1 (3*5*7*2) under uncertain demand

3.4.3 Validation

The validation of results is an essential step in simulation and modeling studies to substantiate if the model provides a truthful representation of the system under study (Law, 2006; Adenso-diaz et al., 2012). The validation of this work has two aspects, namely, model validation and validation of solution approach. There are several methods used in literature for the validation of supply chain network simulations (Adenso-diaz et al., 2012). The rigorous validation can be conducted by the practitioners, academicians, engineers and scientists having the domain expertise (Adenso-diaz et al., 2012; Law, 2006). The model validation and verification ensures that the model behaviors are in accordance with the actual system i.e. the model have the ability to mimic the real system. A practical case study is used in our work to map these requirements of model validation and presented in the later part of this chapter. The network developed and used in this work is inspired by literature (Figure 1.1) and vetted by experts from academia and industry to accommodate the e-commerce dimension.

Sargent (2007) said, "*Operational validation is determining whether the simulation model's output behavior has the accuracy required for the model's intended purpose, over the domain of the model's intended applicability*." In the present study, a broad set of NPIs is devised so that the system performance can be captured rationally. It is possible to estimate the various NPIs (e.g. OFV, service level, realized profits, operational costs, the flow of quantities, etc.) which provide sufficient insights into SCND aspects and evaluate the network configuration. Hence, the real values of the system performance parameters can be reasonably estimated by comparing the output of numerical tests and simulations in final experimentation. However, Quade (1980) highlighted that the primary purpose of model testing is to build confidence in the model and no model can be a "*fully-validated model*". The other aspect of validation theory is validation of solution approach which is discussed below in detail.

Validation of solution approach

The validation of solution approach can be achieved by substituting the modeling method with other equally capable technique. For example, one can change the method of dealing with uncertainty i.e. adopting a two-stage stochastic programming in place of RO. Another approach can be adopting the meta-heuristic approaches in place of heuristics. In literature, Peidro (2010) has replaced solution approach by benchmarking the results and thus validating them. On the similar lines, in this study has used another method to capturing the uncertainty in SCND modeling. This substituted method is based on Bertsimas and Sim (2003, 2004) and a different RC is obtained for the deterministic model given in Equations 3.1 to Equations 3.20. This Bertsimas and Sim (2003, 2004) based approach were adopted by Hatefi and Jolai (2014) to model the SCND problem under demand uncertainty in his study. In the methodology, a parameter Γ^i which is called the *budget of uncertainty* is used to address the robustness. The parameter Γ^i can vary in the continuous interval [0, 1] and it adjusts the robustness against the level of conservatism of the solution. The particular case of interest is when the budget of uncertainty is highest i.e. $\Gamma^i = 1$, which is signifies maximum robustness allowed. This condition is very similar to RO method of Ben-Tal and Nemirovski (2000) and Ben-Tal et al. (2009) (Hatefi and Jolai, 2014; Pishvaee et al., 2011, Bertismas et al., 2007).

In other words, for Equations 3.22 and 3.21, the budget of uncertainty is associated with the right-hand side of constraint and takes a value in [0, 1]. Thus, $\Gamma^i = 0$ and $\Gamma^i = 1$ address the cases where there is no protection against uncertainty and there is a complete protection. In the range, $\Gamma^i \in (0, 1)$ the supply chain decision maker can adjust the robustness of constraint i against the level of conservatism of the solution. It is worthy to add that the robust formulation obtained under these state of affairs will be is similar to that obtained by the RO introduced by Ben-Tal and Nemirovski (2000) and Ben-Tal et al. (2009). This RO approach based on Bertsimas and Sim approach (refer article by Bertsimas and Sim approach 2003, 2004) is termed as "ROBS" and successfully implemented in this study and some numerical tests are performed. The readers are referred to Bertsimas and Sim (2003, 2004), Hatefi and Jolai (2014) and Pishvaee et al. (2011) for in detail treatment of the subject and exploring the fundamentals and finding more detailed about RC formulation. However, the AIMMS© code for ROBS approach is also given in Appendix-II, which provides sufficient insight.

The comparison of results obtained from of RO and ROBS is carried out. The SCND results are assimilated for NPIs such as OFV, supply chain costs (transportation costs, production costs, distribution costs etc.) the number of facilities open or close and flow of quantities. The Network-4 is used for this purpose because of ease of benchmarking the new NPI values from ROBS with previous RO results. Table 3.8 provides the summary of the results obtained from ROBS approach for Network-4. Table 3.9 illustrates the network configuration obtained from ROBS approach for Network-4. Similarly, Figure 3.6 shows the behavior of the mean and standard deviation of OFV obtained from ROBS approach for problem Network-4.

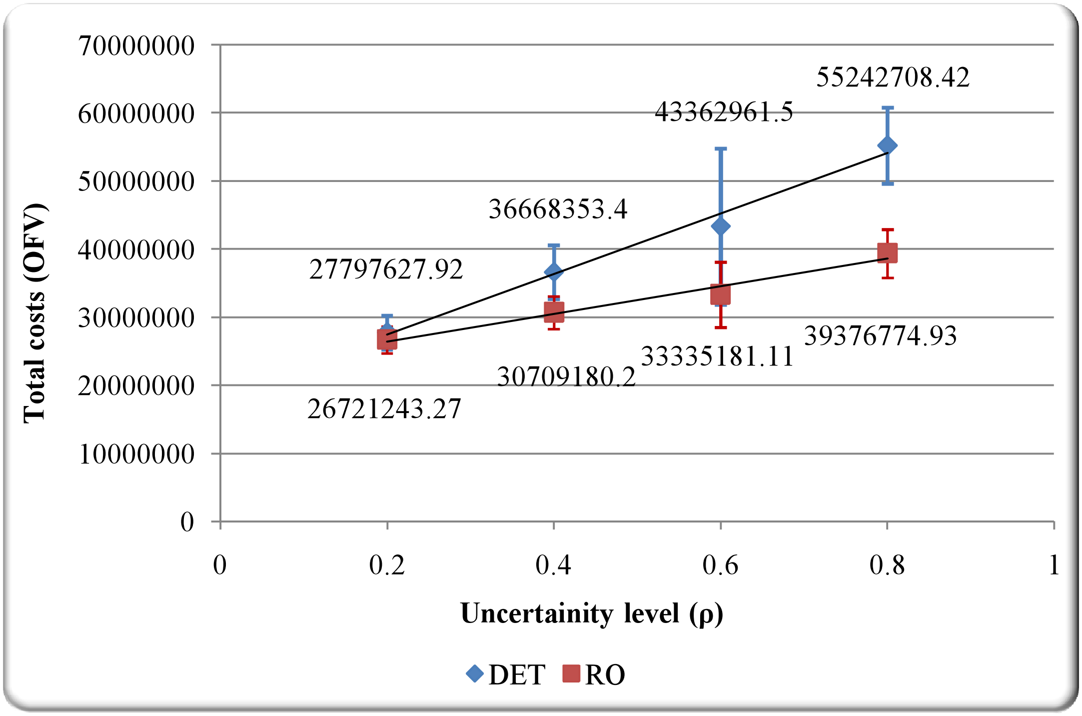


Figure 3.6: Mean and standard deviation of OFV obtained from ROBS approach for problem Network-4

The NPI results and network configuration obtained indicates that the trends for ROBS and their NPIs are similar to RO with values near to the previous solutions. It can be seen in Figure 3.6 that the mean and standard deviation of OFV of ROBS approach for Network-4 that solutions obtained from ROBS model is stable and producing superior results.

The variation in the values of NPIs for RO and ROBS models results can be attributed to the fact that the input values are randomly generated. These findings clearly suggest that RO based SCND is capable of giving robust supply chain topology which will provide optimal results to the firms in the worst case of demand uncertainty. It should be made clear that this study focused on presenting modeling methods for robust and reliable SCND. Hence, any further comparative analysis of RO with other uncertainty handling method is not pursued. However, it can be a great opportunity for future research.

Table 3.8: Summary of the results obtained from ROBS approach for Network-4

S. N.	ρ	Observed values of NPI under four random cases of realization for 8*20*28*3							
		Objective function values		Service level (%)		Stock out rate (%)		Unsatisfied demand	
		DWC	ROMBS	DWC	ROMBS	DWC	ROMBS	DWC	ROMBS
1	0.2	30621332.15	29185999.83	86.60	90.42	13.3	9.5	2048	1464
		28411622.04	27052379.49	92.48	96.41	7.5	3.5	1076	513
		27614385.61	26248962.62	94.93	98.98	5.06	1.0	706	142
		24543171.86	24397631.14	99.13	100	0.86	0	112	0
	Mean	27797627.92	26721243.27						
	SD	2514978.883	1983842.941						
2	0.4	41411755.05	33902629.46	74.8	96.9	25.1	3.08	4461	536
		37549663.06	30739856.76	82.4	100	17.5	0	2829	0
		35898631.69	30067856.08	84.3	100	15.6	0	2467	0
		31813363.79	28126378.5	89.4	92.8	10.5	7.1	1569	985
	Mean	36668353.4	30709180.2						
	SD	3976596.6	2400084.754						
3	0.6	53829414.52	37675051.78	67.6	100	32.3	0	6351	0
		50751737.49	36455740.19	69.8	100	30.1	0	5706	0
		40407879.29	32099805.2	78.7	98.4	21.2	1.5	3585	265
		28462814.68	27110127.25	92.3	96.2	7.6	3.7	1102	539
	Mean	43362961.5	33335181.11						
	SD	11472976.01	4790609.41						
4	0.8	60837841.58	43232879.75	59.645	89.78	40.9	10.2	8960	2268
		58821461.51	41431284.92	61.92	93.21	38.07	6.78	8144	1452
		52639779.94	37203052.39	68.51	100	31.48	0	6095	0
		48671750.64	35639882.67	71.63	100	28.36	0	5251	0
	Mean	55242708.42	39376774.93						
	SD	5599574.733	3548708.175						

Note: DWC = Deterministic Worst Case; DM = Deterministic Model; ROMBS= ROBS Model; SD = Standard Deviation

Table 3.9: Network configuration obtained from ROBS approach for Network-4

<table>
<tr><th>S. N.</th><th>ρ</th><th colspan="2">PCR Open</th><th colspan="2">DC Open</th><th colspan="2">Disposal Center</th><th colspan="2">Total Facility Cost</th></tr>
<tr><th colspan="2"></th><th>DWC</th><th>ROMBS</th><th>DWC</th><th>ROMBS</th><th>DWC</th><th>ROMBS</th><th>DWC</th><th>ROMBS</th></tr>
<tr><td>1</td><td>0.2</td><td rowspan="4">2,3,4,5</td><td>2,3,5,7</td><td rowspan="4">2,3,7,10,11,13,14,15,18,20</td><td>2,3,5,7,9,11,13,14,15,18,20</td><td rowspan="4">2</td><td>2</td><td rowspan="4">2858237</td><td>2942213</td></tr>
<tr><td>2</td><td>0.4</td><td>2,3,5,6,7</td><td>2,3,5,7,8,9,11,13,14,15,18,20</td><td>2</td><td>3611889</td></tr>
<tr><td>3</td><td>0.6</td><td>2,3,4,5,6,7</td><td>2,3,5,7,8,9,10,11,13,14,15,18,20</td><td>2</td><td>4214285</td></tr>
<tr><td>4</td><td>0.8</td><td>2,3,4,5,6,7,8</td><td>1,2,3,4,5,7,8,9,10,11,13,14,15,17,18,20</td><td>2</td><td>4985874</td></tr>
</table>

3.5 Chapter summary

In this chapter, a closed-loop supply chain network design and planning problem with uncertain demand is addressed, formulated and solved. In the starting, a CLSC network is developed. This aspect of CLSC is one of the important practical aspects of many modern supply chains and this enables the companies to handle product returns. The proposed CLSC also captures direct shipments of products from PCR termed as 'DSP' as well as the delivery of the products through DC termed as 'SDC' simultaneously. The deterministic modeling of this model is presented in Section 3.2. As highlighted by Hamta et al. (2015), the uncertainty in the supply chain is one of the contemporary issues. Thus, this deterministic model is modified to address the demand uncertainty. Hence, the RO approached based on Ben-Tal and Nemirovski (2000) and Ben-Tal et al. (2009) is used for modeling the parameter uncertainty for SCND and robust counterpart (RC) is generated. The RC is numerically tested and solved for a set of test problems of different network sizes.

The computational results show that the network configuration obtained from RO based model is capable of handling higher level of demand variations as compared to network structure defined by deterministic modeling. The total supply chain cost of the deterministic worst case was found to be higher than RO model. Hence, it can be argued that the solution provided by RO approach is superior than deterministic model for the worst case data realization for uncertain parameters. The high service level can be achieved by RO modeling. The configurations obtained from RO models also ensure the low stockout rate which in turn also improves the responsiveness. Additionally, the company revenue, brand image, customer experience, stock value etc. will get better. In RO model, there are more quantities shipped directly to the customers as compared to deterministic model which shows that the network topology achieved through RO model is more capable of engaged in DSP to benefit more. Thus, this research advocates the adoption of RO methods to counter the effect of parameter uncertainty and argued that the supply chain configuration obtained from RO will be not only superior but also optimal too.

These RO based SCND methods help in formulating strategies, obtaining managerial insights for prioritizing the location-allocation decisions under uncertainty environment. In this manner, the second objective of the study is achieved. The RO based modeling approaches provide efficient tool which empowers managers and strategists to make SCND decisions to counter the uncertainties. The resulted modeling methods help managers in decisions making regarding opening and closing of facilities, locating and selecting facilities, demand management, production capacity allocation, and supply chain planning. One major drawback of the RO based modeling is their over conservatism of solutions which can be an exciting avenue for future research. The RO approach can also be useful for nonlinear optimization problem such as method adopted by Houska and Diehl (2013) for nonlinear robust optimization via sequential convex bilevel programming. The model can also be extended to accommodate the multiobjective formulation in future. The proposed CLSC network can be extended to make it multi-stage, multi-product, the multi-planing horizon in future studies. Additionally, the models presented in this chapter do not include the operational issues of supply chain and their associated risks. This risk modeling in SCND is very essential and addressed in detail in next chapter.

CHAPTER 4
ROBUST SUPPLY CHAIN DESIGN UNDER RISK AND UNCERTAINTY

Chapter 4
Robust Supply Chain Design under Risk and Uncertainty

4.1 Introduction

The contemporary firms can differentiate themselves from each other by decreasing operational cost while considering sustainability through embracing CLSC practices Özkır and Başlıgil (2013). The supply chain network considered in this study has some distinctive features such as, plants which acts as hybrid facilities that do production as well as collect returned products, the network simultaneously ships the products from plants to DC as well as directly to customers, returned products are refurbished and introduced in system accordingly. The previous chapter presented mathematical model for CLSC design under demand uncertainty. In this formulation, operational and tactical level risk are not considered. However, apart from demand uncertainty in SCND, the tactical and operational level challenges must be included to obtain not only a robust network topology but also reliable functioning (Peng et al., 2011). As we have highlighted in the previous chapter that the SCND is the strategic scheme to determine the optimized supply chain configuration and the network configuration achieved in such manner has a significant effect on firm performance (Pazhani et al., 2013). Hence, in this Chapter 4, attempts are made to reformulate the CLSC network design presented in Chapter 3 again to improve network reliability under some identified risks keeping its robust behavior intact.

This chapter aims at achieving the third objective of this study i.e. presenting the mathematical modeling and analysis to obtain the robust, reliable and optimal supply chain configuration for the selected CLSC network under uncertainty and risks. In other words, a method is proposed for robust and reliable supply chain design and optimization under supply risk, logistics risks and demand uncertainty for a single product, single period, and multi-echelon supply chain network. The subsequent section provides the background of risk modeling in supply chain context. In Section 4.3, some important mathematical procedures for embedding risks in SCND are illustrated. Section 4.4 presents the integration of supply risk; logistics risks model with RO modeling to define the robust and reliable RC. The numerical tests, results and their analysis are provided in Section 4.5. The chapter culminates by proposing an integrated approach for SCND under uncertainty and risk to determine robust and reliable network configuration.

4.2 Risk considerations in supply chain network design and modeling

4.2.1 Background and overview

The risk in supply chains can be defined as the potential deviations from profitability and subsequent decrease in value added activities for the firm (Christopher and Peck, 2004); Tang, 2006). Typically, the supply chain comprises of multiple partner organizations/firms, which may be subjected to numerous risks. The detailed treatment of risk and uncertainty in supply chain literature is provided in Chapter 3. In review studies, some of the important risk classification are given by Christopher and Peck (2004), Tang (2006), Manuj and Mentzer (2008), Kumar et al. (2010) and Samvedi et al. (2013).

In the context of supply chain risk typology, the risk classification scheme by Christopher and Peck (2004) emphasized on five types of risks in the supply chain. These risks are classified as process risk, control risk, demand risk, supply risk and environment risk. These risks may be caused by factors external or internal to supply chain. The authors argued that operational risks be created in the supply chain due to its inability of managing supply chain actions internally. The unsatisfied demand, issues in production, and supply shortage are a few examples of these situations. The external risks are those risk factors which arise due to the negative impact of the external environment on the supply chain. For example, terrorist attacks, earthquake, natural disasters, etc. The internal and external risk factors generate inefficiency and vulnerability within the company. On the lines of Owen and Daskin (1998); Simchi-Levi et al. (2003); Farahani et al., (2014) the SCND activities which involves the strategic decisions for deciding the number of facilities, distribution centers, number of suppliers, channel of transportation, and method of product recovery should keep internal or external, or both risk factors in SCND.

In the SCND and risk management context, Kumar et al. (2010) said, "*The consequence of the risks occurring in the contemporary supply chain is the addition to the cost of operation, and therefore a reduction in profits. Hence, for an efficient operation of the supply chain, an optimum policy, which minimizes the overall risks* *and associated cost, should be adopted*". The literature review presented in this Section 2.3 revealed that both uncertainties and risks affect the modern supply chain. Thus, there is need of addressing both issues simultaneously. For example, some of the critical risk issues in the supply chain are demand uncertainty, disruption in supply, supplier side issues, transportation issues, process risk, etc.

The supply chain management literature abounds with mathematical approaches and models proposed for portraying supply chain cost minimization under various risks. However, in most of the SCND problems the network design parameters considered are of deterministic nature (Amin and Zhang, 2013a). Additionally, only a few number of studies have considered two or more types of risks at a time while formulating the network design problems (Amin and Zhang, 2013a). Thus, it is desirable that supply chain should not only be reliable but robust as well.

Table 4.1 provides a review of some select studies which deals with CLSC network design under risks. In the context of the modeling the supply chain risks, in most of the cases, the objective function of the mathematical model is to minimize the total supply chain costs. The methods of modeling include linear programming, mixed-integer linear programming, dynamic programming, stochastic programming, chance-constraint programming, etc. Most of the models are solved using resources such as IBM ILOG CPLEX®, LINGO, LINDO, C++ etc. (Owen and Daskin, 1998; Ambrosino and Grazia Scutellà, 2005; Snyder, 2006, Melo et al., 2009; Klibi et al., 2010; Özceylan et al., 2014).

Apart from above solution methods, the meta-heuristic optimization algorithms for example genetic algorithm (Ko and Evans, 2007; Kumar et al., 2010; Soleimani and Kannan, 2014; Wang and Yin, 2013), particle swarm optimization (Prasannavenkatesan and Kumanan, 2012; Soleimani and Kannan, 2014) are also used by researchers in this context.

Table 4.1 Review of studies which deals with CLSC network design under risks

S.N.	Author	Comment	Risk aspect
1	Amin and Zhang, (2013a)	A three-stage model for CLSC configuration under uncertainty.	Fuzzy sets theory is used to overcome the uncertainty in the decision-making related to suppliers, remanufacturing subcontractors, and refurbishing sites.
2	Amin and Zhang, (2013b)	A multi-objective facility location model for CLSC network under uncertain demand and return.	CLSC network is investigated. Also, the impact of demand and return uncertainties on the network configuration analyzed by stochastic programming.
3	Benyoucef et al., (2013)	SCND with unreliable suppliers: a Lagrangian relaxation-based approach.	This paper deals with the integrated facility location and supplier selection decisions for the design of supply chain network with reliable and unreliable suppliers.
4	Cardoso et al., (2012)	Designing and planning of CLSC for risk and economical optimization.	In this paper, MILP formulation is developed for the design and planning of CLSC with the goal of maximizing the expected Net Present Value (NPV) and simultaneously minimize the risk, under products demand uncertainty.
5	Kenné et al., (2012)	Production planning of a hybrid manufacturing–remanufacturing system under uncertainty.	Production planning and control of a single product supply chain involving combined manufacturing and remanufacturing operations within a CLSC with machines failures and repairs.
6	Lieckens and Vandaele, (2012)	Multi-level reverse logistics network design under uncertainty.	It takes into account stochastic delays due to the collection, production, and transportation, disturbances due to various sources of variability like uncertain supply, uncertain process times, unknown quality, breakdowns, etc.
7	Peng et al., (2011)	Reliable logistics networks design with facility disruptions.	This paper studies a strategic supply chain management problem to design reliable networks under disruptions strike, the objective is to minimize the nominal cost while reducing the disruption risk.
8	Ramezani et al., (2014)	Closed-loop supply chain network design under a fuzzy environment.	It addresses the application of fuzzy sets to design a multi-product, multi-period, closed-loop supply chain network in uncertainty.
9	Soleimani et al., (2014)	Incorporating risk measures in the closed-loop supply chain network design.	This paper considers a location-allocation problem in a CLSC with demand and prices of new and return products uncertain.
10	Subulan et al., (2014)	A case study of a lead/acid battery CLSC network design under risk and uncertainty.	Considered financial and collection risks. Different risk measures such as “variability index”, “downside risk” and “conditional value at risk” are integrated in themodel.
11	Vahdani et al., (2013)	Reliable design of CLSC networks under uncertainty.	Demand risk, supply risk, uncertain environment for CLSC design.
12	Zeballos et al., (2014)	Multi-period design and planning of CLSC.	Risk of uncertain supply and demand in multi-period CLSC problem.

The detailed analysis of literature shows that the large-scale supply chain networks are subject to several operational risks, which hamper firm's relationship and functioning with other echelon members. An important observation is that SCND and planning may yield sub-optimal results in risk environment. However, the exact mode of network failure, cause of failure, risks elements in supply chain network are hard to quantify. The review of studies on CLSC network design under various supply chain risk reveal that inclusion of risk and uncertainty in SCND modeling is very limited. Most of the studies in Table 4.1 are focusing on only risk modeling. Vahdani et al. (2013), Zeballos et al. (2014) and Lieckens and Vandaele (2012) uses the CLSC modeling to create more reliable supply chain operations but simultaneous shipments, return management of refurbished products is not focused much. The robust optimization of network under risk or uncertainty is also not attempted much. There was a visible gap regarding devising the robust and reliable SCND procedures in CLSC system. The remaining sections of this chapter attempts embedding risks in SCND and modeling process. The supply chain configuration achieved after adopting such approach will not only be robust but also optimal too.

4.3 Supply chain modeling for supply and logistics risk

Recently, Kumar et al. (2010) and Singh et al. (2012) presented the design of global supply chain network under operational risks factors, but the authors have not analysed the CLSC aspects. Soleimani et al. (2014) attempted to archive a robust supply chain network design through incorporating risk measures in design and these risk measures are modelled for forward supply chain network. Hence, still, there is a need for carry out the investigation on robust SCND for a CLSC network under risk and uncertainty.

The mathematical formulations given in Equation 3.1 to Equation 3.40 are modified for accommodating some prevalent supply chain risks. The inclusion of risks in mathematical models has added few more cost parameters. However, similar to the previous chapter, the objective is to achieve the optimal supply chain configuration with minimum total supply chain cost. Two types of risk namely, supply and logistics risks are embedded in the RO model. The supply risk is defined as a possible scenario of shortage in supplies due to lack of consistency in material quality at the plant which further increases the overall production costs. While the logistics risk is the variability of lead time of transporting the products from one supply chain stage to other which causes a delay in deliveries. As a result, the companies have to spend more on transportation to match the deadline.

4.3.1 Embedding the risks in mathematical modeling

The presence of supply risk and logistics risk in the network affects various costs functions such as production cost, distribution cost, transportation cost, etc. In mathematical formulation, the supply risks are embedded in cost elements which are affected by supply disruption i.e. production and distribution costs at PCRs and DCs. It is noting that risk at each echelon of the supply chain is dependent on the functioning of previous echelons, for example, the manufacturing of correct product depends on upon the supply of the raw material. Hence, Equation 3.2 and Equation 3.3 can be rewritten as follows:

$$\sum_{i \in I} m(i) * [Ni/(\sum_{\emptyset} p(\theta) * \theta]) \quad (4.1)$$

$$\sum_{\substack{j \in J \\ k \in K}} n(j) * [Y(j,k)/(\sum_{\partial} p(\omega) * \omega]) \quad (4.2)$$

The physical interpretation of the above equation is that these equation captures the extra cost of including risk in SCND modelling. Where, $\emptyset$ is the set of all scenarios for supplier (i.e. plants to DC), comprising the reliability of availability and quality of supplies regarding percentage of total supply; and $p(\theta)$ denotes the probability of scenario θ, where$\theta \in \emptyset$, such that $\sum_{\emptyset} p\ (\theta) = 1$. Failure of supply can lead to loss of production and associated profit. Similarly, ∂ is the set of all scenarios for DC, 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 ϖ $\in \partial$, such that $\sum_{\partial} p(\omega) = 1$. The supply risk has been calculated in terms of additional requirement of finished product at some additional cost (Kumar et al., 2010; Singh et al., 2012).

The next major risk is identified in shipments. Figure 3.1 shows the transportation arcs of the CLSC network considered here. The shipment of products is happening among PCR to DC, PRC to CZ, DC to CZ, CZ to PCR, and PCR to DIC. Hence, these arcs of the network will be affected by logistics risk and results in higher expenditure. However, it is worth to note that the late delivery of returned products will not impact the customers at all. Thus, the only forward flow of network i.e. the transportation costs of PCR to DC, PRC to CZ, DC to CZ are affected by logistics risks. The modifications in cost elements for capturing the above phenomenon are presented as follows.

$$\sum_{\substack{i \in I \\ j \in J}} \sum_{t \geq \min LTij}^{\max LTij} p\ (€(i,j)) * a(i,j)(t) * X\ (i,j) \tag{4.3}$$

$$\sum_{\substack{i \in I \\ k \in K}} \sum_{t \geq \min LTik}^{\max LTik} p\ (¥(i,k)) * e(i,k)(t) * T(i,k) \tag{4.4}$$

$$\sum_{\substack{j \in J \\ k \in K}} \sum_{t \geq \min LTjk}^{\max LTjk} p\ (£(j,k)) * b(j,k)(t) * Y(j,k) \tag{4.5}$$

Here, min LT_{ij} is the minimum lead time required for PCR i to deliver products to DC j; max LT_{ij} is the maximum allowed lead time for PCR i to provide products to DC$_j$; $€(i,j)$ is the set of all scenarios of lead times with probability p ($€(i,j)$) for delivering product from PCR i to DC$_j$. Similarly, min LT_{ik} is the minimum lead time required for PCR i to deliver products directly to CZ$_k$; max LT_{ik} is the maximum allowed lead time; $¥(i,k)$ is the set of all scenarios of lead times with probability p ($¥(i,k)$) for delivering product from PCR i to CZ$_j$. And, min LT_{jk} is the minimum lead time required for DC j to deliver products to CZ$_k$; max LT_{jk} is the maximum allowed lead time for DC$_j$ to provide products to CZ$_k$; (j,k) is the set of all scenarios of lead times with probability p $((j,k))$for delivering product from DC$_j$ to CZ$_k$.

Furthermore, due to PCR failure, it falls short to deliver the supplies to next stage within the maximum allowed lead time. This result in an additional cost (penalty cost) function given as follows:

$$\sum_{\substack{i \in I \\ j \in J}} a\ (i,j) * X(i,j) * [1 - \sum_{t \geq \min LTij}^{\max LTij} p\ (€(i,j))] * PC\ (i,j)(t) \tag{4.6}$$

$$\sum_{\substack{i \in I \\ k \in K}} e(i,k) * T(i,k) * [1 - \sum_{t \geq \min LTik}^{\max LTik} p\ (¥(i,k))] * PC\ (i,k)(t) \tag{4.7}$$

$$\sum_{\substack{j \in J \\ k \in K}} b(j,k) * Y(j,k) * [1 - \sum_{t \geq \min LTjk}^{\max LTjk} p\ ((j,k))] * PC\ (j,k)(t) \tag{4.8}$$

Where $PC_{i,j}$ (t) is the penalty cost function per shipment per unit of product supplied from PCR i to DC j after maximum lead time. Similarly, $PC_{i,k}$ (t) is the penalty cost function per shipment per unit of product supplied from PCR i to CZ k after maximum lead time and $PC_{j,k}$ (t) is the penalty cost function per shipment per unit of product supplied from DC j to CZ k after maximum lead time. The above formulation follows Singh et al.(2012) and Kumar et al.(2010) to incorporate the risk in supply chain modeling. It is a mixed-integer linear programming (MILP) problem. The above changes must be reflected in new objective function. It is important to note that no constaint is altered in this modification processs. The new objective function is given as-

Min Total Cost (TC'*)*

$$
\begin{aligned}
TC' = {} & \sum_{i\in I} f(i)U(i) + \sum_{j\in J} g(j)V(j) + \sum_{l\in L} h(l)W(l) + \sum_{i \in I} m(i) * [Ni/(\sum_{\emptyset} p(\theta) * \\
& \theta]) + \sum_{\substack{j\in J \\ k\in K}} n(j) * [Y(j,k)/(\sum_{\partial} p(\omega) * \omega]) + \sum_{i\in I}\sum_{j\in J}[a(i,j)]\, Q(i,j) + \\
& \sum_{i\in I}\sum_{k\in K}[e(i,k)]\, B(i,k) + \sum_{\substack{i\in I \\ j\in J}} \sum_{t\geq \min LTij}^{\max LTij} p\,(\text{€}(i,j)) * a(i,j)(t) * \\
& X\,(i,j) + \sum_{\substack{i\in I \\ k\in K}} \sum_{t\geq \min LTik}^{\max LTik} p\,(\text{¥}(i,k)) * e(i,k)(t) * \\
& T(i,k) + \sum_{\substack{j\in J \\ k\in K}} \sum_{t\geq \min LTjk}^{\max LTjk} p\,((j,k)) * b(j,k)(t) * Y(j,k) + \sum_{\substack{i\in I \\ j\in J}} a\,(i,j) * X(i,j) * \\
& [1 - \sum_{t \geq \min LTij}^{\max LTij} p\,(\text{€}(i,j))] * PC\,(i,j)(t) + \sum_{\substack{i\in I \\ k\in K}} \overset{e(i,k) * T(i,k) *}{[1 - \sum_{t \geq \min LTik}^{\max LTik} p\,(\text{¥}(i,k))]} * \\
& PC\,(i,k)(t) + \sum_{\substack{j\in J \\ k\in K}} b(j,k) * Y(j,k) * [1 - \sum_{t \geq \min LTjk}^{\max LTjk} p\,((j,k))] * \\
& PC\,(j,k)(t) + \sum_{k\in K}\sum_{i\in I}[p(k,i)]\, Z(k,i) + \sum_{i\in I}\sum_{l\in L}[q(i,l)]\, S(i,l) + \sum_{i\in I}[r(i) * \\
& M(i)] + \sum_{k\in K}\sum_{i\in I}[c(i)]\, Z(k,i) + \sum_{i\in I}\sum_{l\in L}[s(l)]\, S(i,l) + \sum_{k\in K}\mu(k)\alpha(k)
\end{aligned}
\tag{4.9}
$$

4.4 Robust supply chain design and optimization under supply risk, logistics risks and demand uncertainty

The objective function given in Equation 4.9 captures the impact of risks and increases the reliability of the CLSC. The integration of this reliable model with robust formulation is carried out in this section. Thus, the RO based reliable supply chain model for SCND under risk and uncertainty (called as RORU model) is proposed. The robust counterpart is generated by the similar procedure given in Section 3.3. The RORU formulation is given below:

$$\min z' \tag{4.10}$$

Subjected to-

$$TC' \leq z' \tag{4.11}$$

$$M(i) = \sum_{j\in J} Q(i,j) + \sum_{k\in K} B(i,k), \forall i \in I \tag{4.12}$$

$$N(i) = \sum_{j\in J} X(i,j) + \sum_{k\in K} T(i,k), \forall i \in I \tag{4.13}$$

$$\sum_{i\in I} T(i,k) + \sum_{i\in I} B(i,k) + \sum_{i\in I} Y(j,k) + \alpha(k) \geq d(k) + \rho^{d} G^{d}(k), \forall k \in K \tag{4.14}$$

$$\sum_{i\in I} Z(k,i) = rr(k)[\, d(k) - \alpha(k)] + [rr(k)\, d(k)\, \rho^{d} G^{d}(k)], \forall k \in K \tag{4.15}$$

$$\sum_{i\in I} X(i,j) + \sum_{i\in I} R(i,j) = \sum_{k\in K} Y(j,k), \forall j \in J \tag{4.16}$$

$$\sum_{l\in L} S(i,l) = df * \sum_{k\in K} Z(k,i), \forall i \in I \tag{4.17}$$

$$M(i) = [1 - df] * \sum_{k\in K} Z(k,i), \forall i \in I \tag{4.18}$$

$$N(i) \leq pc(i) * U(i), \forall i \in I \tag{4.19}$$

$$\sum_{k\in K} Y(j,k) \leq dc(j) * V(j), \forall j \in J \tag{4.20}$$

$$\sum_{k\in K} Z(k,i) \leq cc(i) * U(i), \forall i \in I \tag{4.21}$$

$$\sum_{i\in I} S(i,l) \leq sc(l) * W(l), \forall l \in L \tag{4.22}$$

$$U_i, V_j, W_l \in \{0,1\}, \forall i \in I, \forall j \in J, \forall k \in K \tag{4.23}$$

$$M_i, B_{ik}, Q_{ij}, N_i, X_{ij}, T_{ik}, Y_{jk}, Z_{ki}, S_{il}, \alpha_k \geq 0, \forall i \in I, \forall j \in J, \forall k \in K, \forall l \in L \tag{4.24}$$

This is the RC of the CLSC model under risk and uncertainty and termed as RORU model. To assess the performance of this model, on the lines of Section 3.4, a number of numerical experiments are performed and results are reported in subsequent sections.

4.5 Numerical tests

4.5.1 Input data sets

To solve the RORU model, input data given in Table 3.1 is used along with some additional inputs. As the RORU model has introduced number of new parameters into the new RC, thus their respective input values are generated in the similar fashion as Section 3.4.1. Table 4.2 provides the required input values of additional parameters used in RORU model. The solution procedure of this new RC is also similar to that in Chapter 3 i.e. programmed in AIMMS© and solved with

CPLEX®. The results obtained for RORU model (i.e. NPIs) are compared with deterministic, robust and deterministic worst case (OFVs).

Table 4.2: Input values of additional parameters used in RORU model

S. N.	Parameter input value (Additional to Table 3.1)
1	p(θ) = (0.80 to .99)
2	p(ω) = (0.80 to .99)
3	p (€(i, j))= (0.01 to .2)
4	p (¥(i, k))= (0.01 to .2)
5	p (£(j, k))= (0.01 to .2)
6	Production reliability of PCR (i) = (.89 to .99)
7	Distribution reliability of DC (j) = (.89 to .99)
8	Maximum lead time (days) = Minimum lead time (days) + Delay* Where, Delay = (2-5) days
9	High TC = Low TC + PTC* *PTC = ((.15 to .30)*Low TC)

4.5.2 Test results and discussion

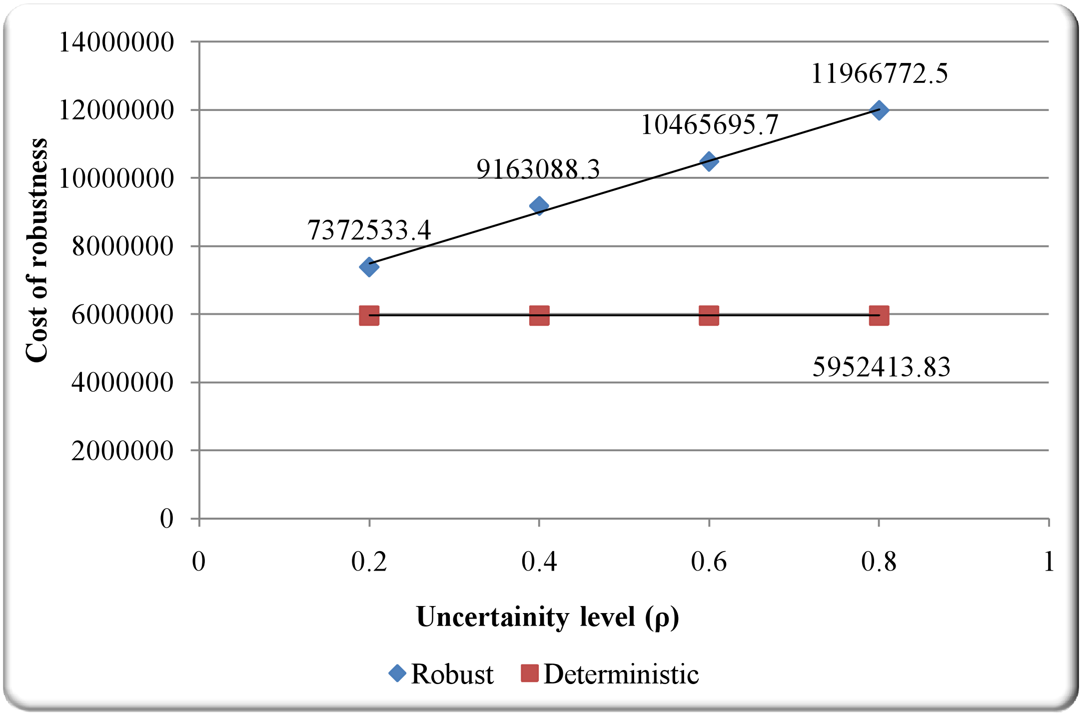
In this section, the results obtained from numerical tests are evaluated using the NPIs defined in Chapter 3. Similar to the previous observations, the total supply chain cost or OFV of RORU and deterministic models are compared. This benchmarking of results yielded the information about most efficient network configuration of the network. Table 4.3 provides the summary of the results of NPIs under demand uncertainty and risks for all four networks. Additionally, for Table 4.3, the solution obtained (all sixteen instances) in AIMMS are presented in Appendix-II as screenshots for reference purpose.

The test results exhibit that the OFV from RORU model increases as the size of network increases. For example, Network-1 at $\rho = 0.2$ has OFV equal to 7372533.40 while, for Network-2 it is 17350226.45 at same level of uncertainty (in only RO case it was 14165797). In the similar manner, for a particular network the total supply chain cost always increases with the increase in level of uncertainty. Figure 4.1 shows total supply chain cost variations for RORU and deterministic models under demand uncertainty, supply and logistics risks for all four test networks sizes. Figure 4.2 shows behavior of cost of robustness under demand uncertainty, supply and logistics risks for all four network sizes. It can be observed that the behavior of Network-2 is different from Figure 3.3 (RO case) and it is more costly in RORU case to accommodate both risk and uncertainty. The small size network is showing high variation is total supply chain costs for RORU models.

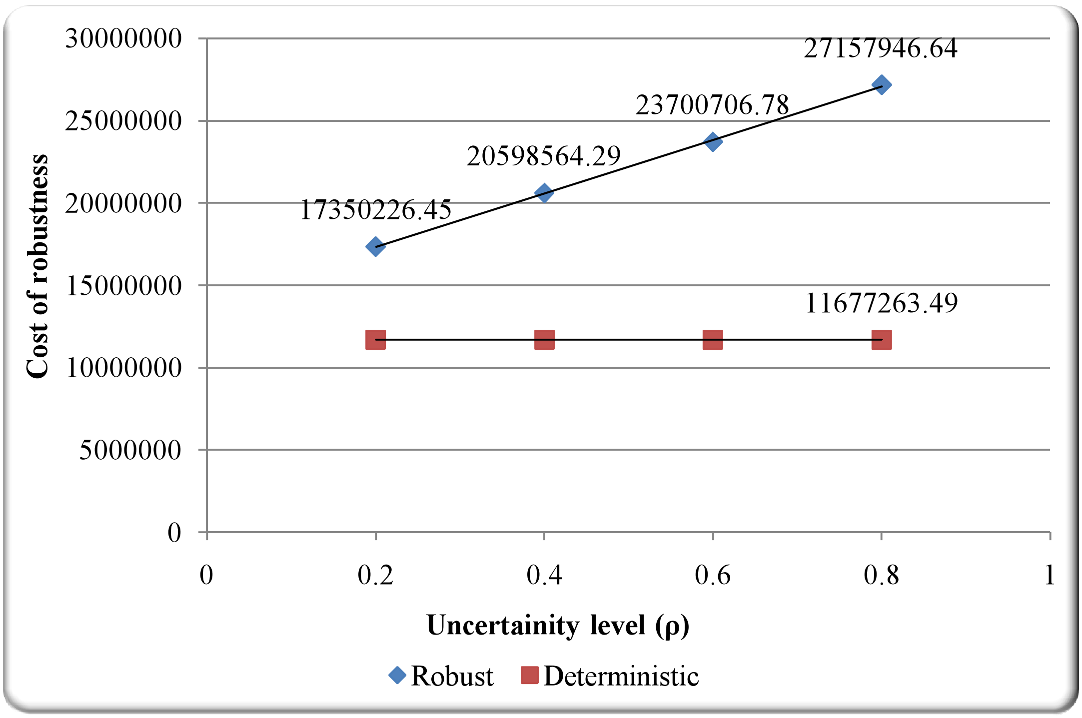
Table 4.3: Summary of the results of NPIs under demand uncertainty and risks for all four networks

Problem size	ρ	Total supply chain cost (OFV)		Computational time	Constraints	Variables	Non-zero	Integer	Iterations	Gap
i * j * k * l		RORU	Deterministic	(sec)						(%)
3*5*7*2	0.2	7372533.4	5952413.83	0.26	77	176	606	157	617	0
	0.4	9163088.3		1.99					1622	0
	0.6	10465695.7		0.27					772	0
	0.8	11966772.5		0.28					918	0
4*8*14*2	0.2	17350226.45	11677263.49	49.29	131	413	1223	388	6373	0
	0.4	20598564.29		41.13					7598	0.02
	0.6	23700706.78		51.6					8072	0
	0.8	27157946.64		40.84					8217	0
6*14*22*2	0.2	22735818.41	18055166.96	82.1	203	989	3693	940	9313	0
	0.4	27218354.75		110.7					11301	0.06
	0.6	31716852.84		89.3					13303	0
	0.8	36516180.04		99.5					14315	0
8*20*28*3	0.2	29656466.61	23412801.22	120.78	264	1712	6451	1651	17020	0.07
	0.4	35555138.24		101.41					21091	0
	0.6	41462475.69		141.03					110139	0.03
	0.8	47411596.17		184.01					112830	0.05

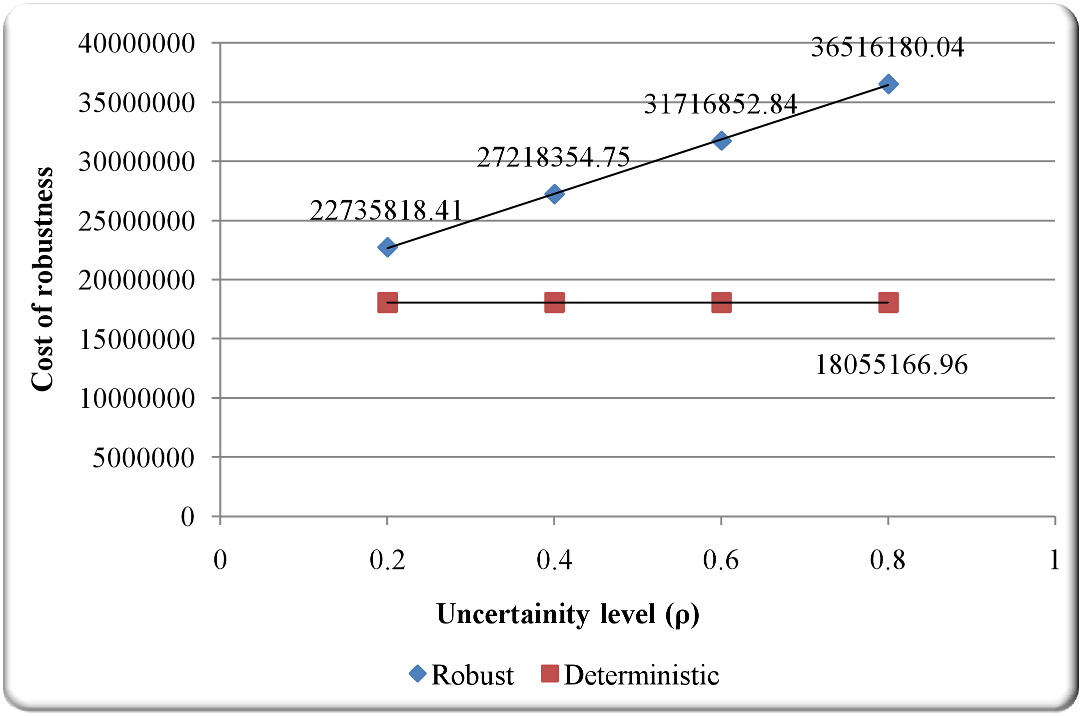
In context of solution and model performance, the RORU formulation does not introduced any additional constraint in the modified model; hence, the model statistics related NPIs such as the total numbers of constraints, variables are similar to RO model of Chapter 3. Apart from it, NPIs such as non-zero entities have reduced in number, and a total number of iterations required for solving the model has increased. The smaller size network is solved with less variation in solution time while large size network case has noticeable variation in solution time with respect to uncertainty level changes. Figure 4.3 shows the model solution time for RO and RORU models for all four network sizes.



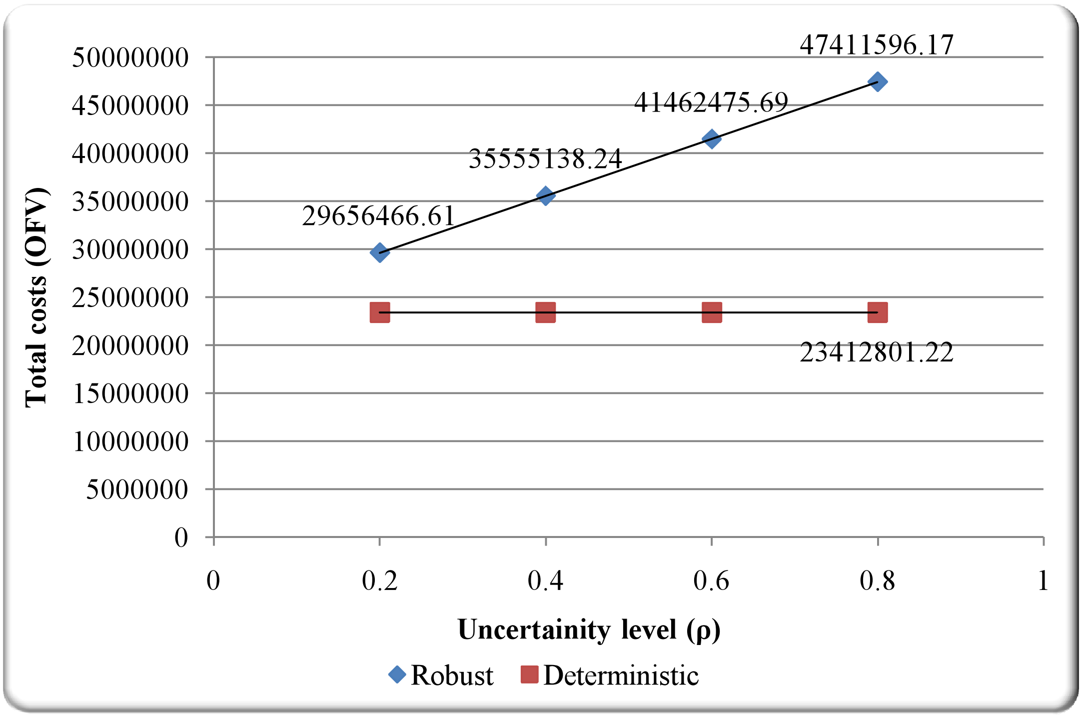
(a) OFV For the Network-1 of size 3*5*7*2



(b) OFV For the Network-2 of size 4*8*14*2



(c) OFV For the Network-3 of size 6*14*22*2



(d) OFV For the Network-4 of size 8*20*28*3

Figure 4.1: Total supply chain cost variations for RORU and deterministic models under demand uncertainty, supply and logistics risks for all four test networks sizes

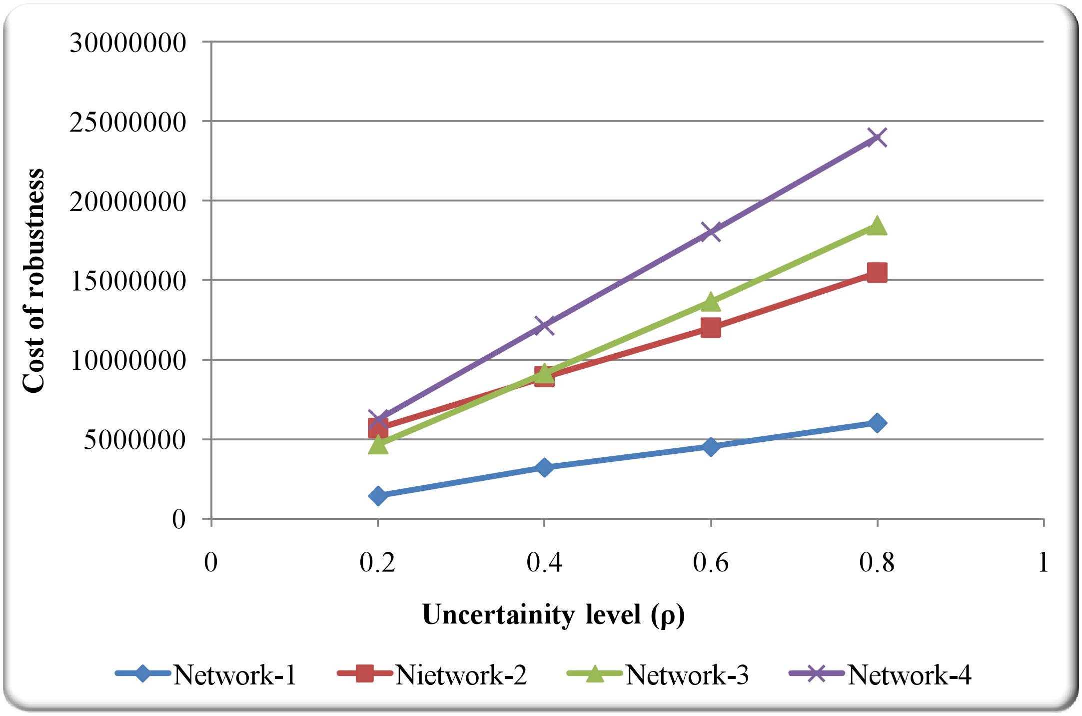


Figure 4.2: Behavior of cost of robustness under demand uncertainty, supply and logistics risks for all four network sizes

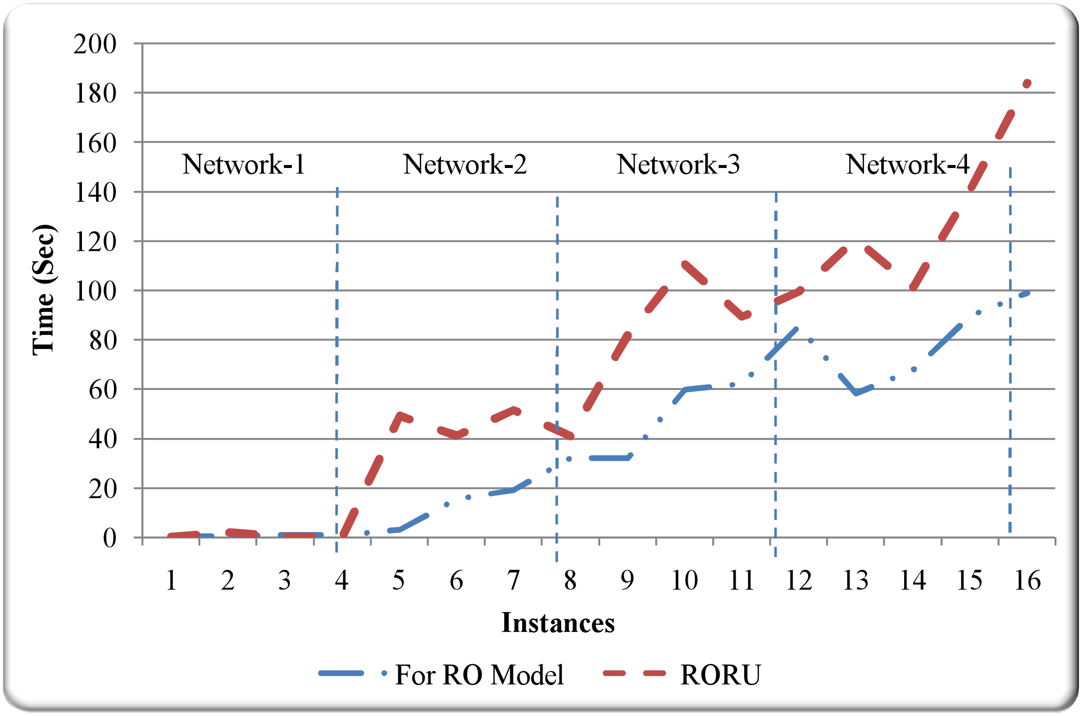


Figure 4.3: Model solution time for RO and RORU models for all four network sizes

Till this point, it is observed that supply chain configuration obtained through RORU model has high cost as compared to the network topology obtained from pure deterministic case. As highlighted in Section 3.4.2, this comparison is incomplete without benchmarking the solutions with worst case of uncertainty and risks. Hence, the deterministic worst case is again re-calculated for realized network configurations obtained from RORU and deterministic models. This exercise is done for Network-4 in a similar manner as Chapter 3.

Table 4.4 presents the summary of test results and NPIs values under uncertain demands and risks for Network-4 and Table 4.5 presents the summary of supply chain network configuration of deterministic and RORU model for Network-4 under risk and uncertainty. The configuration obtained from Table 4.5 is used to calculate the facility costs, transportation costs and PDR costs for the network. Table 4.6 provides the comparison of facility cost, transportation costs and PDR costs for network configurations obtained using deterministic and RORU model for network-4 under risks and uncertainty. The deterministic network structure obtained is having PCR={2,3,4,5}, DC={2,3,7,10,11,13,14,15,18,20}and DIC = {2}. This network has lower facility cost, transportation cost, etc. but, it is also not capable handling higher demands. This fact can be observed from quantities shipped through the DS and SDC mode in RORU model and DWC model in Table 4.6. Additionally, high use of SDC and DSP shipments in RORU models ensure that the network facilities are optimally utilized. Table 4.7 shows the comparison of OFV for deterministic, RO and RORU model for Network-4 under risks and uncertainty.

Table 4.4: Summary of test results and NPIs values under uncertain demand and risks for Network-4

S. N.	ρ	Observed values of network performance parameters under four random cases of realization for 8*20*28*3								
		Objective function values		Service level		Stock out rate		Unsatisfied demand		Realized Profit
		DWC	RORU	DWC	RORO	DWC	RORU	DWC	RORU	RORU
1	0.2	30191953	30095802	89.36	90.5	10.63	9.49	1576	1407	96150.71
		29407251	29432590	91.2	92	8.79	7.98	1277	1160	-25339.87
		27376384	27461575	97.05	97.65	2.94	2.34	401	320	-85190.6
		26831901	26811807	99.1	100	0.89	0	117	0	20094.33
	Mean	27851107	28450444							
	SD	1289970	1563629							
2	0.4	40777783	35029815	76.56	93.93	23.43	6.06	4059	1051	5747968.4
		41852223	33635952	79.45	97.47	20.54	2.52	3429	421	8216270.5
		37055053	31321234	84.76	100	15.23	0	2380	0	5733818.7
		34179809	29936411	88.36	91.35	11.63	8.64	1744	1296	4243397.7
	Mean	38466217	32480853							
	SD	3520087.7	2284028.6							
3	0.6	49611314	41255635	65.90	82.47	34.09	17.52	6851	3522	8355679.1
		45548841	38025170	70.95	87.18	29.04	12.81	5421	2392	7523670.9
		41451051	34132833	78.39	96.17	21.60	3.82	3655	647	7318218.1
		21150995	28883622	91.24	94.33	8.750	5.66	1270	822	-7732627
	Mean	39440550	35574315							
	SD	12639958	5326891.6							
4	0.8	61951037	46177378	59.14	86.43	40.85	13.56	9261	3076	15773658
		55456478	40140479	69.05	98.27	30.94	1.72	6551	366	15316000
		55101581	39915434	67.37	98.67	32.62	1.32	6424	260	15186148
		49188145	36862093	72.52	100	27.47	0	5024	0	12326052
	Mean	55424310	40773846							
	SD	5215141.4	3900341.6							
Note: DWC = Deterministic Worst Case; DM = Deterministic Model; RORU= Robust Optimization Model; SD = Standard Deviation										

Table 4.5: Summary of supply chain network configuration of deterministic and RORU model for Network-4 under risks and uncertainty

<table>
<tr><th colspan="2"></th><th colspan="2">Plant Open</th><th colspan="2">DC Open</th><th colspan="2">Disposal Center</th><th colspan="4">Quantity Shipped</th></tr>
<tr><th>S. N.</th><th>ρ</th><th>DWC</th><th>RORU</th><th>DWC</th><th>RORU</th><th>DWC</th><th>RORU</th><th>DS (DET)</th><th>DS (RORU)</th><th>SDC (DET)</th><th>SDC (RORU)</th></tr>
<tr><td>1</td><td>0.2</td><td rowspan="4">2,3,4,5</td><td>1,2,3,4,5</td><td rowspan="4">2,3,7,10,11,13,14,15,18,20</td><td>2,3,5,7,10,11,13,14,15,18,20</td><td rowspan="4">2</td><td>3</td><td rowspan="4">1617</td><td>2738</td><td rowspan="4">10541</td><td>11679</td></tr>
<tr><td>2</td><td>0.4</td><td>2,3,4,5,6</td><td>2,3,5,7,10,11,13,14,15,18,20</td><td>3</td><td>3875</td><td>11679</td></tr>
<tr><td>3</td><td>0.6</td><td>1,2,3,4,5,6</td><td>2,3,5,7,9,10,11,13,14,15,18,20</td><td>3</td><td>5725</td><td>12696</td></tr>
<tr><td>4</td><td>0.8</td><td>1,2,3,4,5,6,7</td><td>2,3,4,5,7,8,9,10,11,13,14,15,18,20</td><td>3</td><td>7171</td><td>14255</td></tr>
<tr><td colspan="12">Note: DS (DET) = Quantity of products in direct shipping for deterministic case; DS (RORU) = Quantity of products in direct shipping for RORU model; SDC (DET) = Quantity of products in shipped through DC for deterministic case; SDC (RORU) = Quantity of products in shipped through DC for RORU model</td></tr>
</table>

Table 4.6: Comparison of facility cost, transportation costs and PDR costs for network configurations obtained using deterministic and RORU model for Network-4 under risks and uncertainty

<table>
<tr><th></th><th></th><th colspan="2">Total Facility Cost</th><th colspan="2">Transportation Costs</th><th colspan="2">PDR Cost</th></tr>
<tr><th>S. N.</th><th>ρ</th><th>Deterministic</th><th>RORU</th><th>Deterministic</th><th>RORU</th><th>Deterministic</th><th>RORU</th></tr>
<tr><td>1</td><td>0.2</td><td rowspan="4">2858237</td><td>3530643</td><td>1533416.4</td><td>1671219.9</td><td>20336438</td><td>21663742</td></tr>
<tr><td>2</td><td>0.4</td><td>3574374</td><td>1560258.8</td><td>2077173.5</td><td>20340206</td><td>27831487</td></tr>
<tr><td>3</td><td>0.6</td><td>4394645</td><td>1541896.3</td><td>2321976.8</td><td>20335735</td><td>32498879</td></tr>
<tr><td>4</td><td>0.8</td><td>5088817</td><td>1534975.2</td><td>2488805.5</td><td>20335941</td><td>34051739</td></tr>
<tr><td colspan="8">Note: PDR Costs = Total of (Production + Distribution + Recovery (refurbishing)) Costs</td></tr>
</table>

Table 4.7: Comparison of OFV for deterministic, RO and RORU model for Network-4 under risks and uncertainty

Network Size	ρ	Total Supply Chain Costs (OFV)			Solution Time (Sec)		No. of Iterations	
		RO	RORU	Det.	RO	RORU	RO	RORU
Network-1 3*5*7*2	0.2	7372311	7372533.4	5952414	0.45	0.26	310	617
	0.4	9014747	9163088.3		0.55	1.99	378	1622
	0.6	10224383	10465695.7		0.85	0.27	458	772
	0.8	11498209	11966772.5		0.92	0.28	572	918
Network-2 4*8*14*2	0.2	14165797	17350226.45	11677263	3.12	49.29	410	6373
	0.4	17097589	20598564.29		15.52	41.13	603	7598
	0.6	19755537	23700706.78		19.23	51.6	738	8072
	0.8	23087306	27157946.64		31.98	40.84	878	8217
Network-3 6*14*22*2	0.2	22445176	22735818.41	18055167	32.2	82.1	372	9313
	0.4	26675143	27218354.75		59.83	110.7	627	11301
	0.6	31014787	31716852.84		62.12	89.3	751	13303
	0.8	35869587	36516180.04		85.4	99.5	1054	14315
Network-4 8*20*28*3	0.2	29085690	29656466.61	23412801	58.25	120.78	954	17020
	0.4	34727810	35555138.24		67.77	101.41	1046	21091
	0.6	40370735	41462475.69		89.73	141.03	3047	110139
	0.8	46377225	47411596.17		110.97	184.01	5309	112830

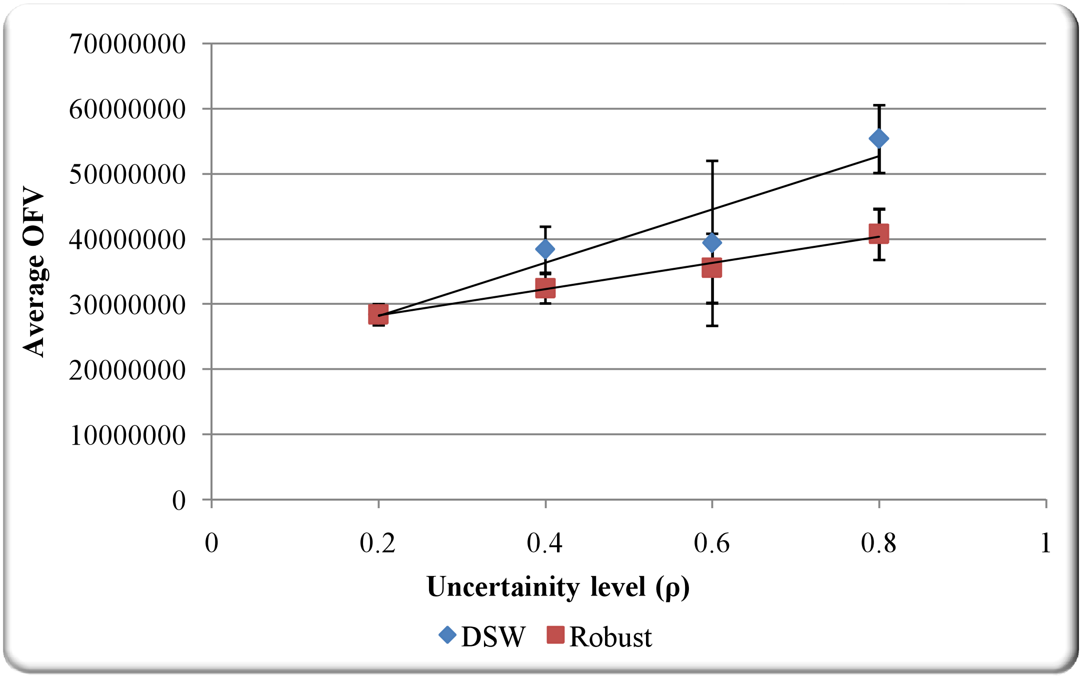


Figure 4.4: Mean and standard deviation of OFV of RORU model for Network-4 under uncertain demand and risks

Figure 4.4 presents the mean and standard deviation of OFVs of RORU model for Network-4 under uncertain demand and risks. It is also clear from Figure 4.4 that the RORU model has the solutions (i.e. OFV) with both higher quality and lower standard deviations than the deterministic model which is a similar observation as RO model of Chapter 3. Similar to the RO model, in case of RORU formulations, the solution obtained are superior to deterministic model under the worst cases of uncertain and risky parameters.

4.6 The integrated approach for SCND under uncertainty and risk to determine robust and reliable network topology

The research presented in this study so far has focused on strategic and tactical decision making under uncertain and risky environment for CLSC network design. It is expected that these decisions are to be used by the firms for achieving RSCO. The models proposed in this study considered the uncertainty in facility location (strategic decisions), network configuration (strategic-tactical decisions) and risks in supply and logistics activities (tactical-operational decisions). The specific mathematical formulation for attaining these objectives is also elaborated in detail. In this section, on the basis of the work done so far, a unified approach for supply chain risk and uncertainty management is proposed.

This section presents an integrated approach for SCND under uncertainty and risk to establish a robust and reliable network topology. The proposed approach integrates the procedure of previous chapters in a cohesive manner such that the supply chain manager can easily follow and implement them in their organizations. Figure 4.5 shows the integrated approach for SCND under uncertainty and risk to determine robust and reliable network configuration. The framework shown in Figure 4.5 illustrate the data needed for each model, the decisions made and the output expected at each stage.

This proposed integrated approach framework has two stages. The stage -1 kept focus on devising the strategic models. For example, the mathematical modeling carried out in Section 3.2 can be used to design robust CLSC network. The strategic model gives emphasis on prioritization of facility locations and uncertainty and risk handling at the strategic level. There are a number of methodologies available to prioritize the locations for establishing facilities. Typically, all multiple-criteria decision-making (MCDM) approach can be used for this purpose, but if prioritization has to be carried out with some uncertain data itself, then it becomes challenging. Within this context, a study is carried out separately study to demonstrate such prioritization methodology.

A grey based MCDM method can be used to identify the best location for plants while considering risks related to candidate locations and uncertainty of risk evaluation process. The full details of the method can be found in (Prakash et al., 2015). Once the decision maker has the ultimate set of possible locations with priority, these candidate locations can be used to establish the final supply chain configuration under design parameter uncertainty. The manager has the choice to stop here before going for identifying the operational risks and include them in a robust model of Stage -1.

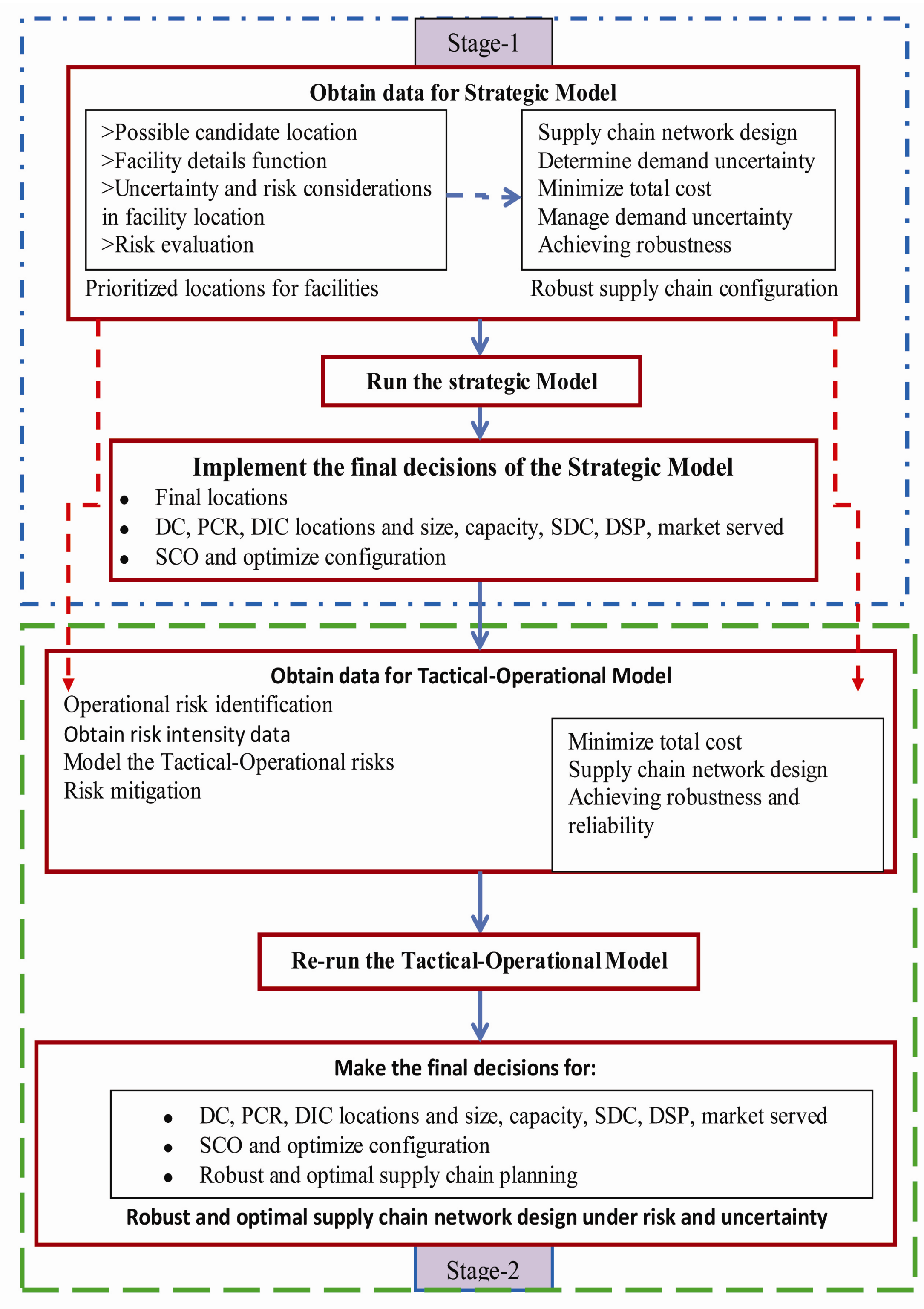


Figure 4.5: The integrated approach for SCND under uncertainty and risk to determine robust and reliable network configuration

The stage-2 provides the opportunity to include the tactical-operational risk in SCND. In this step, the operational risks are identified, and Stage-1 actions are repeated. The ultimate aim is in not only achieving RSCO but also devising risk mitigation. The mathematical formulations of this chapter can be an example of this step. However, the Stage-2 is not only limited to RSCO and it focuses on enhancing reliable operations of the firm. The results obtained from Stage-2 may be vital for devising the comprehensive risk mitigation policies for the organization. One such example of demonstrating the risk mitigation strategy formulation after risks identification was carried out by us in another separate study. An interpretive structural modeling (ISM) methodology is used to find most effective risk mitigation strategies in for a case organization. Presenting the full detail of this method will divert the focus of this section; hence readers are advised to refer (Prakash et al., 2016). Thus, adopting and implementing this proposed methodology will result in robust and reliable SCO.

4.7 Chapter summary

In this chapter, the SCND problem for CLSC structure is conceptualized, formulated and mathematically modeled under risk and uncertainty. Specifically, effect of disruption in supply i.e. supply risk and delay in product delivery i.e. logistics risks is analyzed on supply chain topology or network design. The numerical tests are performed as per the scheme of Chapter 3 and results are presented. The test results revealed that risk consideration in SCND is essential and the network structure obtained is capable of handling number of risk and uncertainty issues efficiently.

In the numerical tests, for a particular network size, the total supply chain cost always increases with the increase in level of uncertainty under demand uncertainty, supply and logistics risks for all four test networks sizes. It is also more costly to design the network under both risk and uncertainty cases and the small size network is showing high variation in total supply chain costs but, the network cost for worst cases of situations is found less along with better values of various NPIs. The network configuration obtained through the modeling not only optimized but also perform well in worst case of parameter uncertainty when the network encountered the risks and uncertainties both.

The main contribution of this chapter is that the models proposed here consider the uncertainty in facility location (strategic decisions), network configuration (strategic-tactical decisions) and risks in supply and logistics activities (tactical-operational decisions). The specific mathematical formulation for attaining these objectives is also elaborated in detail. On the basis of the formulation and insights obtained from test results, a unified approach for supply chain risk and uncertainty management is also proposed. This integrated approach for SCND under uncertainty and risk can be a very useful tool to establish a robust and reliable network topology. The proposed approach integrates the procedure of previous chapters in a cohesive manner such that the supply chain manager can easily follow and implement them in their organizations. The model and integrated approach given here are applied to a case company and in-depth analysis is presented in Chapter 5.

CHAPTER 5
CASE STUDY

Chapter 5
Case Study

5.1 Introduction

In this chapter, all the steps of the proposed integrated approach for supply chain uncertainty and risk management in SCND are illustrated in detail with the help of a case study. A case of an Indian e-retailer which manufactures and sells furniture is presented to demonstrate the reliable and robust SCND aspects. In the starting of the chapter, fundamentals and basic description of e-commerce business and the CLSC network perspectives in this environment are discussed. Then the RO and RORU models are applied to SCND for the case company. The mechanism and mathematical formalism involved are implemented using AIMMS© and CPLEX®, similar to Chapter 3 and Chapter 4. The SCND models are developed and used for generating RSCO strategies and topology for the case company. In the end, relevant recommendations derived from the case results are discussed.

5.2 Background

In the e-commerce context, e-marketplace methods can be used by firms to acquire inputs (e.g. demand of products), and sell outputs (e.g. finished products), electronically, thereby minimizing operational costs (Combe, 2006). Most of the products bought and sold in this manner require management of transportation, inventory management, automated transactions, etc. It was observed that e-marketplaces have been the catalyst for many changes in traditional industries too. The existing traditional industries also got benefited from the network integration that e-commerce exchanges have brought about. The information exchange and services have been simplified to a great extent by the growth of e-commerce. Figure 5.1 provides a framework for buy-side and sell-side dynamics of e-marketplace exchanges.

Business-to-Consumer (B2C) business model has been the most high profile of the e-business markets, principally because of the global brand awareness of firms such as Amazon.com and e-Bay among others. This B2C e-commerce has lately entered in the Indian economy, but it has started gaining growth and popularity in recent years. A recent report by leading industry consultancy firm PwC (www.pwc.in) revealed that e-commerce market in India has grown by 34% since 2009 to touch 16.4 billion USD in 2014, and the sector is expected to be in the range of 22 billion USD in 2015 (PwC, 2015). It is worth noting that most of the e-commerce firms have CLSC structure with the capacity to handle the returned products in same or another firm.

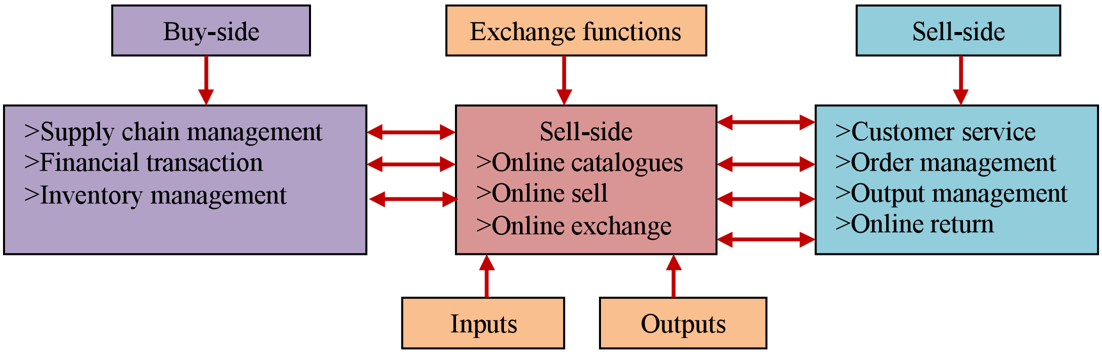


Figure 5.1: Framework for buy-side and sell-side dynamics of e-marketplace exchanges (Adopted from Combe, 2006)

Figure 5.2 shows some of the important characteristics and activities of a typical e-commerce supply chain. There is an industry, and product specific system exists in e-commerce CLSC of the firms but in general, the products bought electronically (online) undergo a number of processes before they finally delivered to the end customers. In the first mile logistics, the picking up of products from the sellers or plants happens. The products are then transported to the e-commerce firm's warehouse to assign barcodes, perform quality checks and packaging. The activities of last mile delivery involve dispatching the items to customers. It is worth noting that the returned products are sent back into the inventory after necessary refurbishing, repackaging and relisted as new items. These returned products increase the overall cost of the supply chain. These returns comprise about 15% to 20% of forward shipments and out of which 4% to 6% being credited to logistics failure (Atroley et al., 2015).

The uncertain demand of products also impacts the CLSC structure of firms in a significant manner because the demand variation impacts the return as well. Thus, SCND decisions for CLSC network are not only vital but also essential too. The remaining sections of the study illustrate the case of an Indian e-commerce B2C company which has CLSC network structure and facing demand uncertainty and logistics risks.

Figure 5.2: Overview of a typical e-commerce retail supply chain (Adopted from Atroley et al., 2015)

5.3 The case company and issues

The XYZ is India's leading furniture and home products e-retailer firm from southwest region (company name is concealed to keep confidentiality). The company offers more than 45000 products across categories like furniture, home decor, lamps, lighting, kitchen, home appliances and house-keeping, etc. The firm sells these products through its web portal and provides shipping in all parts of India. The web portal of XYZ has branded furniture items from market leaders as well as XYZ's product range. Presently, the company possesses few numbers of manufacturing facilities (MFs) and mostly relies on external suppliers (ESs) to fulfill the demand. Being a market leader, XYZ maintains a large product portfolio, which helps it in attracting a large number of customers and achieves high sales, but it forces the company to have an excessive dependency on the ESs.

Moreover, sourcing the products from the ESs is not cost-effective; rather, company concluded that it may increase its profit if it fulfills the demand from its own MFs. There is another challenge faced by the company that the demand of products is quite uncertain. The festive sessions, fashion trends, innovative designs are some of the reason for this demand uncertainty. Hence, the company is set to redesign its supply chain by opening or closing more facilities at some strategic locations. Our proposed model was employed to address the above issues for XYZ.

It is worth noting that the firm has typical CLSC network and features like DSP, SDC, and the return of products are practiced. The furniture products are usually bulky. Thus, the logistics arm of the firm delivers them in the form of modules and sub-assemblies. The product is finally assembled at customer's doorstep. If an item does not meet the customer expectations, it is returned by customers to MFs or ESs through online return request. These return products are routed back to the MFs or ESs accordingly. Handling the return products is an issue for the case company because the furniture items are usually delicate and bulky which attracts high transportation costs with a greater risk of damage in transit.

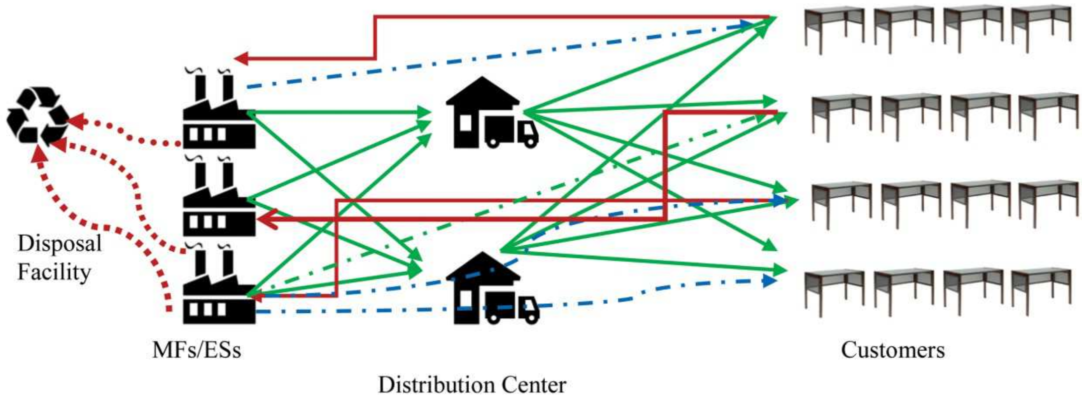


Figure 5.3: Closed-loop supply chain structure for the furniture case company

Recovered products fulfill some portion of the total demand after doing the necessary refurbishing and repackaging etc. At present, used products and their recycling is not practiced by the organization. Figure 5.3 illustrates the CLSC structure for the furniture case company. A number of brainstorming sessions were conducted with manager level executives of XYZ to understand the features, issues and challenges of its supply chain. Finally, the required inputs for modeling of its supply chain are assimilated. The case data is gathered in discussion with company supply chain managers. Table 5.1 lists the input values of SCND parameters of the case study (amounts are in INR). This data is for single product i.e. tables; the largest selling product of the company.

Table 5.1: Input values of SCND parameters of the case study

S. N.	Parameters	Case data	S.N.	Parameters	Case data
1	d_k	(1500,2000)	12	n_j	(50,80)
2	rr_k	(0.1, 0.2)	13	a_{ij}	(80,150)
3	pc_i	(10000,15000)	14	b_{jk}	(120,200)
4	dc_j	(8000,12000)	15	e_{ik}	(100,1000)
5	cc_i	(2000,5000)	16	c_i	(40,60)
6	sc_l	(500,1000)	17	s_l	(40,60)
7	d_f	(0.1,0.2)	18	r_i	(40,60)
8	f_i	(700000,900000)	19	p_{ki}	(150,200)
9	g_j	(20000,50000)	20	q_{il}	(150,200)
10	h_l	(100000,200000)	21	μ_k	(4200,6200)
11	m_i	(2500,6000)			
Note: The parameters have meaning as given in Table Section 3.2.3					

5.3.1 Implementation of proposed integrated approach for the case study

The proposed integrated approach is adopted as an implementation framework to determine the optimized supply chain configuration of the case company under given circumstances. First, for the Stage-1, the strategic model inputs and parameters are identified, and robust optimization model is created for handling demand uncertainty. The Stage-2 activities are also accordingly devised, and logistics risk and supply risk parameters are incorporated to obtain the optimized network for XYZ. The supply risk and logistics risks are found to be dominant in XYZ business environment because the production and distribution are integrated activities for XYZ and prone to disturbances. Figure 5.4 presents the implementation steps of proposed integrated approach for the case study.

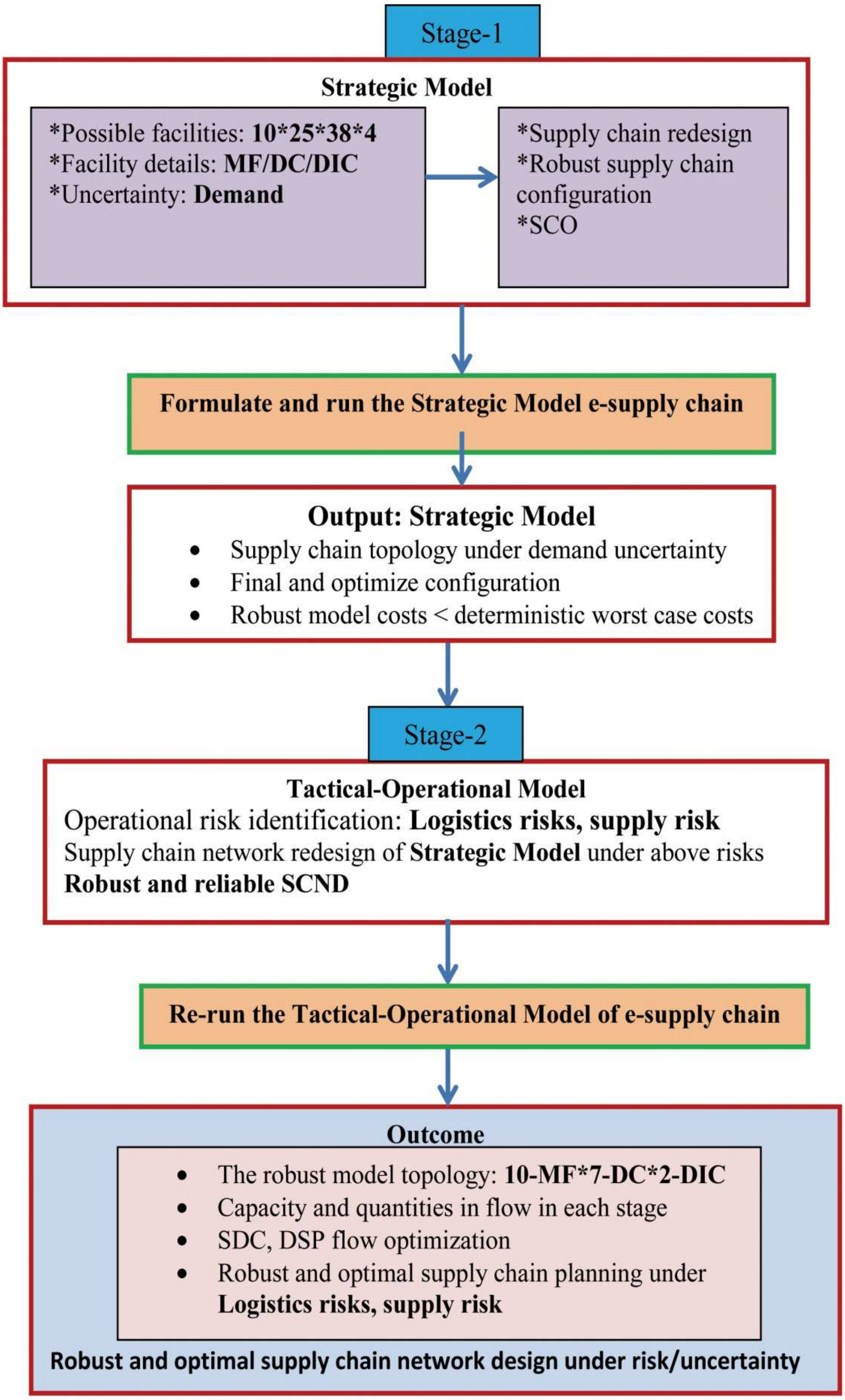


Figure 5.4: Implementation of proposed integrated approach for the case study

5.4 Case study results and discussion

The product category *table* has a line of products such as computer tables, dressing tables, coffee tables, office tables, corner tables, center tables, console tables, etc. The firm has to set up 10 MFs, 25 DCs, and 4 DIC to serve 38 market zones spread across 29 states of India. The SCND is based on deterministic modeling of the supply chain as well as creating a robust and reliable plan as per the approach which is given in Figure 5.4.

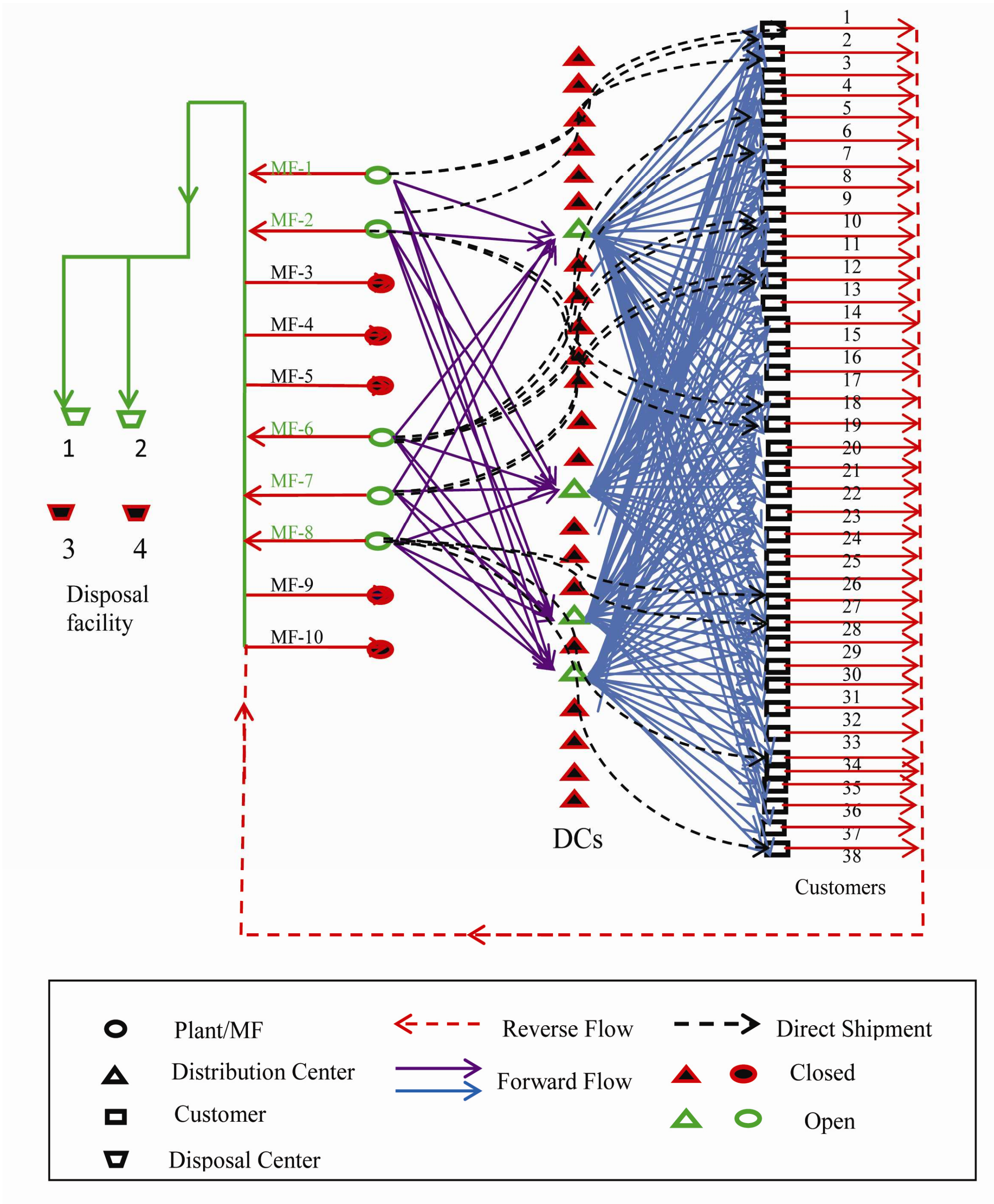


Figure 5.5: Initial configuration of supply chain of case company without risk under deterministic parameter values

The modeling is formulated using robust optimization for addressing uncertainty as discussed in Section 3.3. Total 12 instances are generated for modeling uncertainty with four levels of uncertainty i.e. ρ = 0.2, 0.4, 0.6 and 0.8 and three bands of return rate, *rr* = {(0.03-0.06), (0.07-0.1) and (0.1-0.2)}. Figure 5.5 shows the initial configuration of supply chain of case company without risk under deterministic parameter values. In the case of results reporting, solution robustness, as well as model robustness, are useful for NPIs identification (Wang and Huang, 2013). Hence, a detailed configuration of model statistics as well as NPIs such as total supply chain cost, investment for robustness, flow quantity DSP and SDC, facility open-close decisions, etc. are recorded for case study network. Table 5.2 presents the total supply chain cost, investment for robustness and model statistics of the case the company and Table 5.3 provides the values of the quantity of product flow in SDC and DSP, facility open-close decisions for the case company. It can be observed from Figure 5.5 that the realized network size is 5*3*38*2.

Table 5.2: Total supply chain cost, investment for robustness and model statistics

Case (10*25*38*4)	***ρ***	**Total supply chain cost for case company**		**Investment for robustness**	**Computational time (sec)**	**No. of constraints**	**No. of variables**	**No. of integer**	**No. of iterations**
		Det.	**RO**	**(Det.- RO)**	**For RO model**				
rr= (0.03-0.06)	0.2	233070784.9	291409092	58338307.1	60.01	347	2808	2727	52693
	0.4		352992277.8	119921492.9	55.16				42728
	0.6		418216039.7	185145254.8	56.35				34737
	0.8		490672028.1	257601243.2	55.8				24299
rr= (0.07-0.1)	0.2	223959950.8	283636041.6	59676090.8	60.01				34597
	0.4		347173118.8	123213168	41.95				29194
	0.6		414436799.3	190476848.5	60.01				40274
	0.8		489761638	265801687.2	43.14				28074
rr= (0.1-0.2)	0.2	213528865.2	274509482.9	60980617.7	60.01				45377
	0.4		339783498.9	126254633.7	60.02				38342
	0.6		409440135.1	195911269.9	60.01				34599
	0.8		487737072.8	274208207.6	38.55				23454

Table 5.3: Values of quantity of product flow in SDC and DSP, facility open-close decisions of case company

Case (10*25*38*4)	ρ	Quantity shipped in DSP		Quantity shipped in SDC		Plant		DC		Disposal Center	
		Det.	RO	Det.	RO	Det.	RO	Det.	RO	Det.	RO
rr= (0.03-0.06)	0.2	43610	59219	20955	19197	1,2,6,7,8	1,2,3,6,7,8	7,15,19,21	3,7,15,19,21	1	1
	0.4		68755		19639		1,2,3,6,7,8,9		3,15,19,21,22	1	1
	0.6		86307		15380		1,2,3,4,6,7,8,9		3,19,21,22	1	1
	0.8		94728		14293		1,2,3,4,6,7,8,9		3,5,21,22	1,2	1,2
rr= (0.07-0.1)	0.2	39245	57187	22737	19197	1,2,6,7,8	1,2,3,6,7,8	7,15,19,21	3,7,15,19,21	1	1
	0.4		70611		19639		1,2,3,6,7,8,9		3,19,21,22	1	1
	0.6		88656		14017		1,2,3,4,6,7,8,9		3,19,21,22	1	1
	0.8		98884		13873		1,2,3,4,6,7,8,9,10		3,19,21,22	1,2	1,2
rr= (0.1-0.2)	0.2	33811	54870	25099	20654	1,2,6,7,8	1,2,3,6,7,8	7,15,19,21	3,7,15,19,21	1	1
	0.4		69358		19639		1,2,3,6,7,8,9		3,15,19,21,22	1	1
	0.6		88861		13942		1,2,3,4,6,7,8,9		3,19,21,22	1	1
	0.8		101956		13222		1,2,3,4,6,7,8,9,10		3,19,21,22	1,2	1,2

RO = Demand uncertainty taken for case company in model, Det.= Deterministic; RO = Robust Optimization

The result of the model statistics (see Table 5.2) shows the intricacy of the network XYZ. In the context of production facilities location, it is very much essential to find out the status of how many facilities have to be established and how they will handle demand and its uncertainty, shipped quantities in DSP, SDC and returns in order to optimize the total costs. The initial configuration (the deterministic case) has five production facility locations (MF-1, MF-2, MF-6, MF-7 and MF-8), four DCs (DC7, DC15, DC19 and DC21) and two disposal centeres (DIC 1 and DIC 2) to fulfill the nominal demand of all 38 market zones. Hence, to incorporate the demand uncertainty, robust optimization based modeling is followed and then production capacity management decisions are suggested.

The total supply chain costs for the RO model increases as the demand uncertainty in the network become higher (see Figure 5.6). Figure 5.6 presents a variation of total supply chain cost with demand uncertainty. However, it will become insignificant in case of realization of uncertainty in future, and the RO based supply chain network will yield more benefits. Table 5.2 and Table 5.3 show that model is successful to incorporate the uncertainty in demand while providing optimal solutions for network decisions. The RO model results show that the firm can take the advantage of DSP over the SDC as more products have started following DSP route for reducing the costs. There was no significant effect of demand uncertainty on opening and closing of DIC for the case company. As highlighted in Section 5.2, these returned items in e-commerce comprise about 15% to 20% of forward shipments and out of which 4% to 6% being credited to logistics failure (Atroley et al., 2015). Similar to the numerical tests, the effect of supply risks from MFs or ESs and logistics failures on the SCND for XYZ is also evaluated using robust and reliable modeling and results are analyzed in subsequent Section.

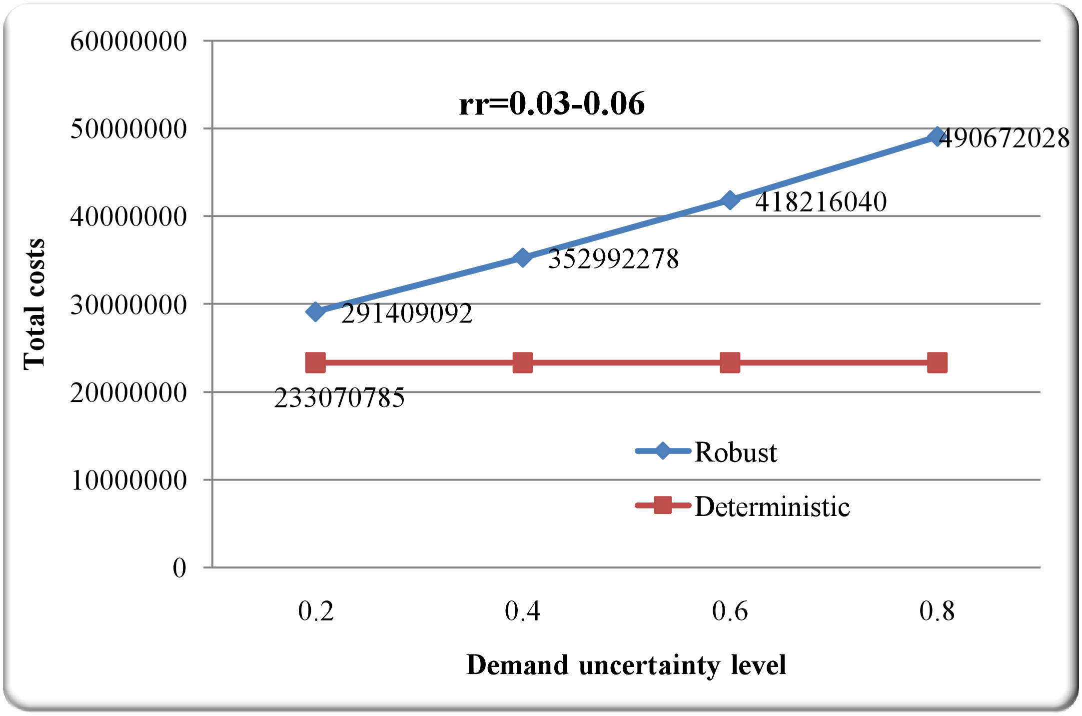


Figure 5.6: Variation of total supply chain cost with demand uncertainty

As it was highlighted previously that return rate is a very important aspect of e-commerce supply chain, hence its impact on SCND is evaluated. If the return rate is low, i.e. 0.03-0.06, the cost of robustness appears stable for all uncertainty levels (for example, 291409092 for =0.2). It can be recommended that impact variation of return rate on RO network will be very limited even worst case of demand realized. Additionally, on lower return volume, the company has to spend more (special arrangements for few customers) to manage it but, it is recommended that company must target low *rr* as low value of *rr* reflects high customer satisfaction in business. For RO network configuration, it can be observed from Table 5.3 that when the return rate is 0.1-0.2 and ρ = 0.2, the DCs required are DC3, DC7, DC15, DC19 and DC 21, which are more in number as compared to the case at ρ = 0.8. Moreover, the percentage increase in total supply chain cost of RO model for different *rr* and ρ levels shows that about 50% rise in total supply chain cost can accommodate ρ = 0.4 without being impacted much by level of return rate. It is an important insight for managers for deciding the network structure and facilities for case company to operate under uncertainty with product return variability. One more insight from this analysis is that for designing the robust CLSC network, firms have to consider worst demand realizations.

Effect of risk

The robust model is modified to accommodate the variations in supply due to quality issues at MFs and missed deliveries dates with variable lead time (high transportation costs). The managers of XYZ are consulted to assign the probabilities, transportation costs to capture the impact of supply risk and logistics risks. To make the simple case for demonstration, the parameters are taken as {p(θ) = p(ω) =0.99}, {p(€(i,j)) = p (¥(i,k)) = p (£(j,k)) = 0.1}, { availability of MFs and DCs = 0.95}, {30% premium on transportation cost if deadline missed by shipment in consultation with experts in the company. Table 5.4 presents the network configuration of XYZ under uncertain demand, return rate and supply/logistics risks.

The total supply chain cost increases about 4 to 12% as compared to RO values to accommodate the risks. The total numbers of MFs open in RORU model for XYZ are almost similar to RO model which implies that there are very few incidents of supply disruptions in the company. The main impact is on the total number of DCs in the final configuration. To accommodate the lead time variation, model proposes to open more DCs as compared to RO model. Similar to the RO model, the disposal center DIC 1 and DIC 2 are part of the final configuration. Figure 5.7 presents the robust and reliable supply chain network configuration obtained for case company for worst case of uncertainty (level of uncertainty = 0.8 and *rr*=0.2).

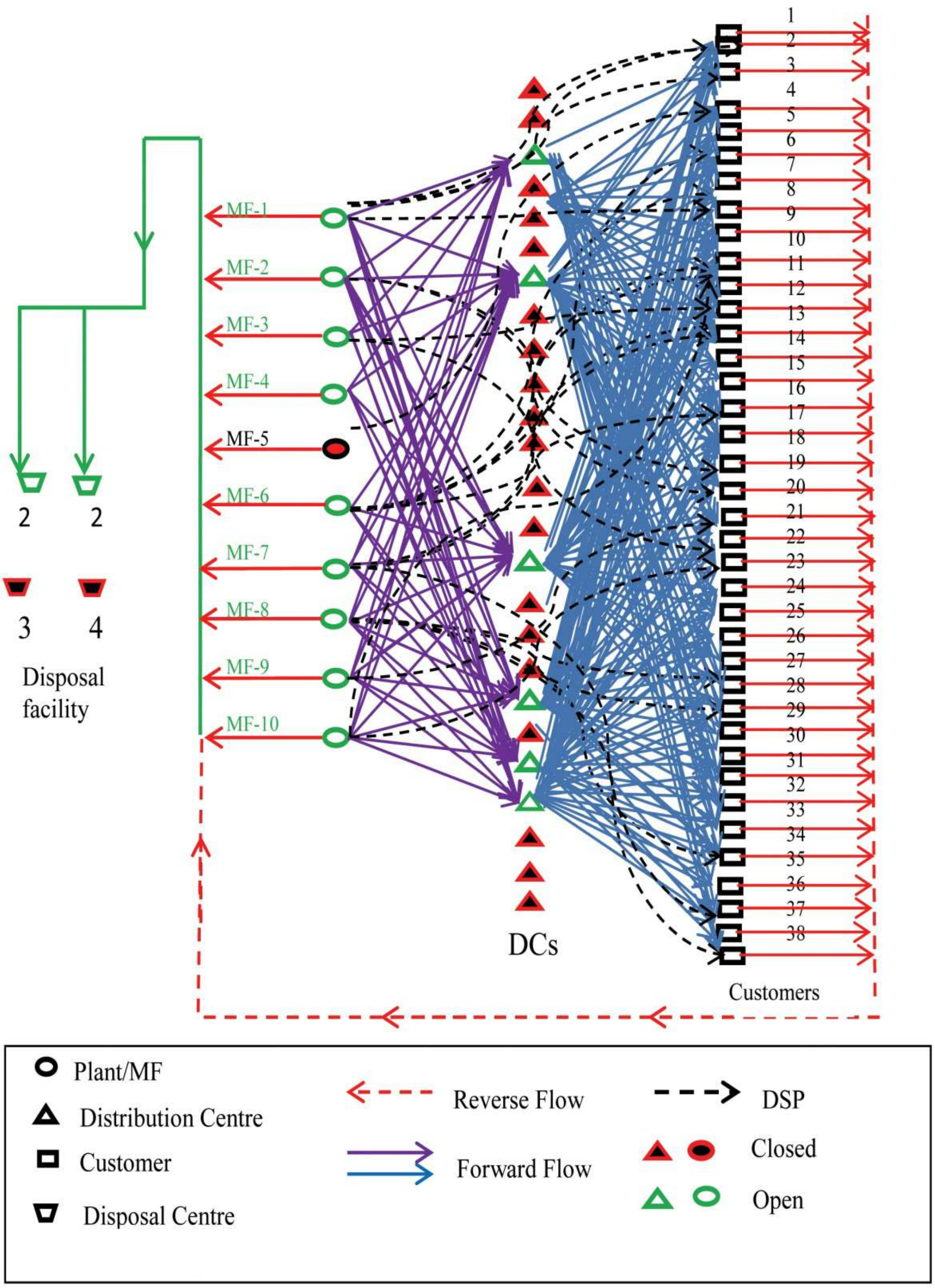


Figure 5.7: The robust and reliable supply chain network configuration obtained for case company for worst case of uncertainty (level of uncertainty = 0.8 and rr=0.2)

Table 5.4: Network configuration of case company under uncertain demand, return rate and supply and logistics risks

Case	LOU	Total supply chain cost		Plant open (MFs)		DC open	
		RORU	Deterministic	Deterministic	RORU	Deterministic	RORU
10*25*38*4 and rr= (0.03-0.06)	0.2	305913979.6	233070784.9	1,2,6,7,8	1,2,3,6,7,8	7,15,19,21	3,7,11,15,19,21
	0.4	368246662.6			1,2,3,6,7,8,9		3,7,15,19,21,22
	0.6	445681735.7			1,2,3,4,6,7,8,9		3,7,19,21,22
	0.8	527263403.9			1,2,3,4,6,7,8,9,10		3,5,19,21,22
10*25*38*4 and rr= (0.07-0.1)	0.2	292144101.8	223959950.8		1,2,3,6,7,8		3,7,11,15,19,21
	0.4	369392198.4			1,2,3,6,7,8,9		3,7,19,21,22
	0.6	438430203.4			1,2,3,4,6,7,8,9		3,7,19,21,22
	0.8	531727299.8			1,2,3,4,6,7,8,9,10		3,7,19,21,22
10*25*38*4 and rr= (0.1-0.2)	0.2	290641307.2	213528865.2		1,2,3,6,7,8		3,11,15,19,21
	0.4	369942682.3			1,2,3,6,7,8,9		3,7,15,19,21,22
	0.6	453041415.1			1,2,3,4,6,7,8,9		3,17,19,21,22
	0.8	550362512.9			1,2,3,4,6,7,8,9,10		3,7,15,19,21,22
LOU = Level of Uncertainty, RORU = RO based reliable supply chain model for SCND under risk and uncertainty							

5.5 Chapter summary

In this chapter, the integrated approach proposed in previous chapter was illustrated in detail with the help of a case study. The study of an Indian e-retailer which manufactures and sells online the furniture items is carried out. The study aims at demonstrating the reliable and robust SCND aspects for the case company under demand uncertainty and select risks. In the starting of the chapter, fundamentals and basic description of e-commerce business and the CLSC network perspectives in this environment are provided. Then, the RO and RORU models are applied to SCND for the case company. The SCND models are developed and used for generating RSCO strategies and topology for the case company. In the end, relevant recommendations derived from the case results are discussed.

Initial configuration of supply chain of case company without risk under deterministic parameter values is compared with the robust and reliable supply chain network configuration obtained for case company for worst case of uncertainty. The study also highlighted the network configuration of case company under uncertain demand, return rate and supply and logistics risks and total costs are benchmarked with deterministic cases. The result shows that the case firm must opt RO based SCND process to counter the risk and uncertainties and achieve robust and reliable supply chain configuration.

CHAPTER 6
CONCLUSION

Chapter 6
Conclusion

6.1 Introduction

The final chapter presents the conclusion of the thesis. The emphasis is on how this research has contributed to the body of research in SCND considering risk and uncertainties. This chapter also presents the limitations of this study and potential areas for future studies.

Section 6.2 provides a detailed discussion and conclusion on the findings of this study. Section 6.3 illustrates the limitations of the present study and the section ends with highlighting the future research opportunities.

6.1.1 Managerial implications

In this dissertation, a new supply chain modelling approach based on RO, consisting of incorporation of the supply chain risk and uncertainty in network design modelling, was presented and explained. There are number of managerial implications in the different phases of the robust supply chain network design process: firstly, during risk identification, the proposed SLR method enables the firms to have clear focus of the major risks and specific causal areas. The prioritized risk, based on SLR and the risk identification, is a good tool to combine a creative risk and uncertainty management approaches. The test network considered in this research is practical in the sense that it not only includes SDC but at the same time enables the firms to take the advantage of DSP which is mostly followed in present time for example medical equipment manufacturer, fast moving consumer goods, white goods etc. This study attempts the integration of risk and uncertainty in a single model for achieving robust configuration which makes the applicability of the proposed model valid for many sectors of economy and products. The study proposes an integrated approach for SCND under risk and uncertainty in CLSC aspect. The robust supply chain network obtained after considering risk and uncertainty will impact the overall robustness of the supply chain system in a positive manner. This aspect of the thesis will help supply chain engineers to take decisions which not only be less risky but also optimal too and aligned with long term strategy of the firm. In this regard, some more implication can be derived from Section 6.2 which outlines some of the major contributions of this research.

6.2 Concluding comments and discussion

Management of risk and related uncertainties in supply chain network has become an integral part of a holistic SCM philosophy (Samvedi et al. 2013). The literature review revealed that there are a number of issues that gives rise to risks in the supply chain. The contemporary risk management approaches involve the generation and deliberation of alternative scenarios and solutions. In SCRM, judging the methods, identifying their respective merits, decide on appropriate solutions and undertaking the execution is more implicit in the SCRM literature (Samvedi et al. 2013). This study employed a SLR based approach to synthesize the state of the art in SCRAUM content. A comprehensive literature review was conducted for a critical analysis of 347 articles from SCM domain. The primary keywords used for searching the relevant articles includes supply chain risk, uncertainty, robustness, reliable, crisis, catastrophe, etc. The content coding and stratification are carried out by creating the categories and extracting information about supply chain issue, industry, demographic, methodological, research design, and type of risk and causes of risk. Various research gaps were identified which also helped in setting the thesis objectives.

There are two ways to handle the risks and uncertainties, ex-post and ex-ante approaches. The ex-post (reactive) methods are more useful for managing operational risks to counter the risk than ex-ante. However, ex-ante (planning in advance) scenario, risk and uncertainty considerations in some strategic SCND are practiced. The objective of both the philosophies is to keep the performance of supply chain at an acceptable level during disruptions. Some companies do so in reactive fashion i.e. responding to risks as they appear, while others are proactive or planning in advance the risks or uncertainties that they wish to assume and how they can best manage them.

It was also observed that handling risk and uncertainties are critical issues, and this field is now getting more attention of researchers. However, most of the research is in a nascent stage and contributing mostly to theory building. As a result, the large numbers of articles published are of desk-based research. The SCRM related issues from a business domain such as e-commerce, perishable food, FMCG, logistics service providing, etc., are less reported. Persistence of demand uncertainty, supply chain uncertainty, supplier side issues, and disruptions are some of the foremost causes of risks in the supply chain. Additionally, it was observed that there is a need for addressing operational level risks such as process risk, security issues, inventory issues, enterprise issues, outsourcing activities in a holistic manner so that supply chain can have the minimum impact on risk and uncertain events.

It can be argued that the supply chains of the modern era are vulnerable to many external as well as internal risk factors. The distinctive absence of specific risk management practices which aim at robust supply chain behavior that performs under an uncertain environment with high reliability under risks and uncertainties is also noticed. Hence, keeping in mind the above observation, some of the key research agendas are set, and research gaps are identified and listed below.

- The nature of research being carried out for SCRM is predominantly qualitative having a focus on risk management theories. Thus, there is a high need for more empirical research (case studies, action research, etc.) in SCRAUM area.
- There is the notable absence of research related to CLSC network design while addressing the risks ex-ante by incorporating SCRAUM philosophies. This is an important activity because by addressing the issues related to supply side and demand side risks or uncertainty, effective SCRM can be achieved.
- Analysis of literature also revealed that parameters used in SCND are often deterministic, and even if the parameter uncertainty is addressed utilizing probability theories, still the estimation and application of underlying probability distributions are practically very difficult.
- It is found that unification of reverse supply chain practices in supply chain modeling is and indispensable, however there are very few studies which capture the CLSC context and practice simultaneous shipping (i.e. to follow DSC and DSP).

- A substantial part of the available literature deals with proposing mathematical models for a particular type of risk or uncertainty. The joint treatment of both (risk and uncertainty) is not investigated much. Thus, there is a requirement of a comprehensive and unified approach to obtain robust and reliable supply chain topology so as to achieve robust supply chain optimization.
- There is a lack of modeling approach for embedding risks in robust supply chain design in a CLSC context to achieve robust supply chain optimization, and analyze the effect of risks and uncertainty on optimal supply chain configuration.

This thesis is an effort to address some of these research lacunas mentioned above. The emphasis of this study was to advance the area of SCND under uncertainty and risk in a CLSC context. Robust optimization (RO) approach based on Ben-Tal et al. (2004), Ben-Tal and Nemirovski (1999), Ben-Tal et al. (2009), and Ben-Tal and Nemirovski (2000, 2002) is used to model the uncertainty. First, a mathematical model for CLSC network with simultaneous shipping using deterministic design parameters is developed. In next step, using RO approach, MILP based mathematical models are formulated to obtain the robust and optimal supply chain network configuration under demand uncertainty. The RO based modeling is further extended to include the supply risks and logistics risks. All models are programmed in AIMMS© and solved with CPLEX® and analysis of results is presented. The major contributions of this research are:

- The network considered in this research is novel in the sense that it not only includes SDC but at the same time enables the firms to take the advantage of DSP. The proposed mathematical model successfully captured this phenomenon which is further demonstrated by numerical simulations and yielded that the robust models are more efficient under such circumstances.
- There are number of studies available on CLSC modeling under uncertainty but using RO in the context of SDC and DSP is not investigated much. Hence, this study contributes to the body of research in SCND in a significant manner.

- On the lines of Hatefi and Jolai (2014), this study attempts the integration of risk and uncertainty and in a single model for achieving robust configuration which makes the research contribution of this study eminent.
- In this study, a large number of numerical tests (four network sizes and four levels of uncertainty for deterministic, RO and RORU) are performed with a sufficient number of instances to demonstrate the modeling for various network sizes which provides the most general results.
- The RO based approach of Ben-Tal and Nemirovski (1999) used for modeling the uncertainty and the trends of results obtained are validated by another similar approach of Bertsimas and Sim (2003, 2004).
- The network configurations obtained from numerical simulation of deterministic RO and RORU are compared using a large set of performance indicator which includes total supply chain costs (i.e. total objective function value), network flow related costs (i.e. transportation, production, distribution etc.), number of facilities open or close (i.e. PCR, DC and DIC), amount of products flowing through supply chain echelon etc.
- The thesis presents a case study of an Indian furniture manufacturer firm which practices CLSC, DSP and DSP and wants to redesign its supply chain for variable and uncertain demand, considering supply risk and logistics risks simultaneously. The case study results show that network configuration obtained from proposed models are more robust and reliable and perform well under worst case of demand.
- The study proposes an integrated approach for SCND under risk and uncertainty in CLSC aspect (see Figure 4.5). The robust supply chain network obtained after considering risk and uncertainty will impact the overall robustness of the supply chain system in a positive manner. The Integrated approach proposed in this work will be in a position to help supply chain managers to refine risk management strategies to handle risk events.
- When facing trouble, an established robust supply chain strategy would enable a company to deploy the allied contingency plan effectively and efficiently. Tang (2006) highlighted that robust strategies should help a firm to sustain its operation during major disruptions, and it should enable the

firm to manage regular fluctuations efficiently under normal circumstances regardless of the occurrence of major disruptions. This study helps in this direction and enables companies to mitigate risks ex-ante. As we can see that service level in RO and RORU based models is higher than standard deterministic cases, thus practicing robust SCND will surely help supply chain strategists to archive robust and reliable operations.

6.3 Limitations and future scope

This study contains many unique mathematical models, concepts and procedures for SCND under risks and uncertainty which have significant potential for application in modern industry. Any such research aimed at meeting the academic requirements is bound to suffer from certain limitations. This study is not an exception as well. While deliberating various issues related to the study reported in this thesis, a few points were noticed which could be identified as the limitations of the present work, some of which are as follows.

The integrated approach put forward in this work is based on logic followed in mathematical procedures, and it should be empirically tested and validated so that more generic cross-industry applicability can be achieved. This study has attempted to make a considerable contribution for enhancing knowledge about robust and reliable SCND considering the risk and uncertainties. However, for the generalization of findings of this case study, further empirical studies are needed. The input data used for the study is representation of the real data from published research papers. Other sources of data have not been considered here. A limited set of NPIs have been considered for numerical tests and simulation experiments. There are many other which can also be tested for the realized network configuration such as return on investment, cash flow, flexibility, quality etc. focusing on different industries.

Future research

In essence, this research has resulted in systematic and practical approaches for dealing with different problems in SCRM, SCND and optimization of supply chain configuration. Practically, it has attempted to address the problem of demand uncertainty, supply risk and logistics risk that are of significant importance to the industry and also bridges the gaps identified from the literature. It is envisaged that this would open avenues for many more research studies in future. Considering the aspects such as multi-product, multi-stage, value of discarded products etc. can be investigated in mathematical modeling.

Considering multi-product, multi-stage aspects in mathematical modeling of the RO and RORU model is a logical extension of this work. In future, research can be carried out by applying some contemporary simulation and modeling techniques for introducing some more types of risks and uncertainties. Salvage value of the scraped products can be considered in the

In the context of solution method adopted, future studies can use unconventional approaches such as meta-heuristic optimization for solving the SCND under risk and uncertainty. It was also observed that these problems are NP-hard which can be effectively solved by such tools. In the case of heuristic solution methodologies, to overcome both the over precise nature of stochastic programming and the conservative nature of RO, a new variant of optimization scheme, which includes distributions in robust optimization approach, can be investigated in future studies. In such type of robust optimization, the probability distribution can be treated itself be uncertain. Therefore, further research is required to test that which risk or uncertainty can be included in the proposed integrated approach for making it more useful for the industries of diverse nature. We argued that this proposed approach should be empirically tested and validated so that more generic cross-industry applicability can be achieved.

This empirical investigation of risk and uncertainty will provide insight into the procedure and process followed by firms to achieve robustness. More empirical studies must be carried out to understand the effect of individual risk and uncertainty handling methods. This could be investigated through conducting case studies, action research, surveys, etc. by capturing the following facts:

- How companies are managing supply chain risk and uncertainties at the strategic level?
- What methods, approaches, and tools do companies use to counter risk and uncertainties in their supply chains at SCND level?

- How do they attempt to achieve robust supply chain?
- How do companies benchmark their supply chain risk and uncertainty management procedures against those of industry norms?

Thus, progressing from this understanding is the need to devise robust and well-grounded models of SCRAUM, which should incorporate new theories, methodologies, tools, and techniques.

The future scope of the research can be summarized as follows.

- More generic cross-industry applicability can be achieved by conducting empirical studies, case studies, action research etc.
- Applying some contemporary simulation and modelling techniques for introducing some more risks and uncertainties in the modelling.
- Use of meta-heuristic optimization for solving RO model.
- Investigating the effect of individual risk and uncertainty on robust design.
- Extending the mathematical modelling for multi-product, multi-stage, multiple planning horizon.
- Investigating the effect of back ordering, bullwhip effect, salvage value in RO based modelling for SCND.
- The network can be extended to include the external suppliers in the modelling.

REFERENCES

Adenso-diaz, B., Mena, C., Garcıa-Carbajal, S., Liechty, M., García-Carbajal, S. and Liechty, M. (2012), "The impact of supply network characteristics on reliability", Supply Chain Management: An International Journal, Vol. 17 No. 3, pp. 263–276.

Adhitya, A., Srinivasan, R. and Karimi, I. A. (2007), "A model-based rescheduling framework for managing abnormal supply chain events", Computers & Chemical Engineering, Vol. 31 No. 5, pp. 496–518.

Ahsan, D.A. (2011), "Farmers' motivations, risk perceptions and risk management strategies in a developing economy: Bangladesh experience", Journal of Risk Research, Vol. 14 No. 3, pp. 325–349.

Al-E-Hashem, S.M.J., Malekly, H. and Aryanezhad, M.B. (2011), "A multi-objective robust optimization model for multi-product multi-site aggregate production planning in a supply chain under uncertainty", International Journal of Production Economics, Vol. 134 No. 1, pp. 28–42.

Aliev, R.A., Fazlollahi, B., Guirimov, B.G. and Aliev, R.R. (2007), "Fuzzy-genetic approach to aggregate production-distribution planning in supply chain management", Information Sciences, Vol. 177 No. 20, pp. 4241–4255.

Aloini, D., Dulmin, R., Mininno, V. and Ponticelli, S. (2012), "Supply chain management: a review of implementation risks in the construction industry", Business Process Management Journal, Vol. 18 No. 5, pp. 735–761.

Ambrosino, D. and Grazia Scutellà, M. (2005), "Distribution network design: new problems and related models", European Journal of Operational Research, Vol. 165 No. 3, pp. 610–624.

Amin, S.H. and Zhang, G. (2013), "A multi-objective facility location model for closed-loop supply chain network under uncertain demand and return", Applied Mathematical Modelling, Vol. 37 No. 6, pp. 4165–4176.

Amin, S.H. and Zhang, G. (2013), "A three-stage model for closed-loop supply chain configuration under uncertainty", International Journal of Production Research, Vol. 51 No. 5, pp. 1405–1425.

Aras, N., Aksen, D. and Gönül Tanuğur, A. (2008), "Locating collection centers for incentive-dependent returns under a pick-up policy with capacitated vehicles", European Journal of Operational Research, Vol. 191 No. 3, pp. 1223–1240.

Archie, L.III. (2011), "Benchmarking supplier risks using Bayesian networks", Benchmarking: An International Journal, Vol. 18 No. 3, pp. 409–427.

Ashayeri, J., Ma, N. and Sotirov, R. (2014), "Supply chain downsizing under bankruptcy: A robust optimization approach", International Journal of Production Economics, Vol. 154, pp. 1–15.

Atroley, N., Ghosh, J. and Tanwar, P. (2015), India's E-Commerce Retail Logistics Growth Story, available at: KPMG.com/in., https://www.kpmg.com/E-commerce-retail-logistics-in-India.pdf (accessed on 04 March 2016).

Baghalian, A., Rezapour, S. and Farahani, R.Z. (2013), "Robust supply chain network design with service level against disruptions and demand uncertainties: A real-life case", European Journal of Operational Research, Vol. 227 No. 1, pp. 199–215.

Ballou, R.H. (2003), "Business logistics: Supply chain management", 5th edition. Prentice Hall, USA.

Bandaly, D., Shanker, L., Kahyaoglu, Y. and Satir, A. (2013), "Supply chain risk management — II: A review of operational, financial and integrated approaches", Risk Management, Vol. 15 No. 1, pp. 1–31.

Ben-Tal, A., Chung, B. Do, Mandala, S.R. and Yao, T. (2011), "Robust optimization for emergency logistics planning: Risk mitigation in humanitarian relief supply chains", Transportation Research Part B: Methodological, Vol. 45 No. 8, pp. 1177–1189.

Ben-Tal, A., Ghaoui, L. El and Nemirovski, A. (2009), "Robust Optimization", Princeton University Press, USA.

Ben-Tal, A., Goryashko, A., Guslitzer, E. and Nemirovski, A. (2004), "Adjustable robust solutions of uncertain linear programs", Mathematical Programming, Vol. 99 No. 2, pp. 351–376.

Ben-Tal, A. and Nemirovski, A. (1999), “Robust solutions of uncertain linear programs”, Operations Research Letters, Vol. 25 No. 1, pp. 1–13.

Ben-Tal, A. and Nemirovski, A. (2000), “Robust solutions of linear programming problems contaminated with uncertain data”, Mathematical Programming, Vol. 88 No. 3, pp. 411–424.

Ben-Tal, A. and Nemirovski, A. (2002), “Robust optimization□? methodology and applications”, Mathematical Programming, Vol. 92 No. 3, pp. 453–480.

Benyoucef, L.., Xie, X. C. and Tanonkou, G.A.. (2013), “Supply chain network design with unreliable suppliers: A Lagrangian relaxation-based approach”, International Journal of Production Research, Vol. 51 No. 21, pp. 6435–6454.

Bertsimas, D., Brown, D.B. and Caramanis, C. (2007), “Theory and applications of robust optimization”, pp. 1–34., SIAM review, Vol. 53 No. 3, pp.464-501.

Bertsimas, D. and Sim, M. (2003), “Robust discrete optimization and network flows”, Mathematical Programming, Vol. 98 No. 1-3, pp. 49–71.

Bertsimas, D. and Sim, M. (2004), “The price of robustness”, Operations Research, Vol. 52 No. 1, pp. 35–53.

Blackhurst, J. V., Scheibe, K.P. and Johnson, D.J. (2008), “Supplier risk assessment and monitoring for the automotive industry”, International Journal of Physical Distribution & Logistics Management, Vol. 38 No. 2, pp. 143–165.

Blackhursta, J., Wub, T. and O’gradyc, P. (2007), “A network-based decision tool to model uncertainty in supply chain operations”, Production Planning & Control, Vol. 18 No. 6, pp. 526–535.

Burgess, K., Singh, P.J. and Koroglu, R. (2006), “Supply chain management: a structured literature review and implications for future research”, International Journal of Operations & Production Management, Vol. 26 No. 7, pp. 703–729.

Cagliano, A.C., De Marco, A., Grimaldi, S. and Rafele, C., (2012), “An integrated approach to supply chain risk analysis”, Journal of Risk Research, Vol. 15 No. 7, pp. 817–840.

Cagliano, A.C., Marco, A. De, Rafele, C. and Arese, M. (2012), “A decision-making approach for investigating the potential effects of near sourcing on supply chain”, Strategic Outsourcing: An International Journal, Vol. 5 No. 2, pp. 100–120.

Cannon, A.R., Reyes, P.M., Frazier, G. V. and Prater, E.L. (2008), “RFID in the contemporary supply chain: multiple perspectives on its benefits and risks”, International Journal of Operations & Production Management, Vol. 28 No. 5, pp. 433–454.

Cardoso, S.R., Barbosa-Póvoa, A.P.F.D. and Relvas, S. (2012), “Designing and planning of closed-loop supply chains for risk and economical optimization”, Proceedings of the 22nd European Symposium on Computer Aided Process Engineering, London, UK. Vol. 30, pp. 447–451.

Carlsson, D., Flisberg, P. and Rönnqvist, M. (2014), “Using robust optimization for distribution and inventory planning for a large pulp producer”, Computers and Operations Research, Vol. 44, pp. 214–225.

Carter, C.R. and Rogers, D.S. (2008), “A framework of sustainable supply chain management: moving toward new theory”, International Journal of Physical Distribution & Logistics Management, Vol. 38 No. 5, pp. 360–387.

Chen, A., Kim, J., Lee, S. and Kim, Y. (2010), “Stochastic multi-objective models for network design problem”, Expert Systems with Applications, Vol. 37 No. 2, pp. 1608–1619.

Cheng, S.K. and Kam, B.H. (2008), “A conceptual framework for analysing risk in supply networks”, Journal of Enterprise Information Management, Vol. 21 No. 4, pp. 345–360.

Chiu, C.-H., Choi, T.-M. and Li, X. (2011), “Supply chain coordination with risk sensitive retailer under target sales rebate”, Automatica, Vol. 47 No. 8, pp. 1617–1625.

Chopra, S. and Sodhi, M.S. (2004), “Managing risk to avoid supply-chain breakdown”, MIT Sloan Management Review, Vol. 46 No 1, pp. 53.

Chopra, S. and Meindl, P. (2001), "Supply Chain Management: Strategy, Planning, and Operation", Prentice Hall, USA.

Chowdhury, N.B. (2015), "A new robust scenario approach to supply chain optimization under bounded uncertainty", Queen's University, Ontario, Canada, https://hdl.handle.net/1974/13836 (accessed on 8-June 2016).

Christopher, M. and Peck, H. (2004), "Building the resilient supply chain", International Journal of Logistics Management, Vol. 15 No. 2, pp. 1–14.

Cintron, A.L. (2010), "Optimizing an integrated supply chain, The Pennsylvania state university", https://etda.libraries.psu.edu/paper/11332/6664 (accessed on 06 April 2016)

Colicchia, C. and Strozzi, F. (2012), "Supply chain risk management: a new methodology for a systematic literature review", Supply Chain Management: An International Journal, Vol. 17 No. 4, pp. 403–418.

Combe, C. (2006), "Introduction to e-business: Management and strategy: Management and Strategy", First edition. Elsevier Ltd., Oxford.

Croom, S., Romano, P. and Giannakis, M. (2000), "Supply chain management: an analytical framework for critical literature review", European Journal of Purchasing & Supply Management. Vol. 6 No. 1, pp. 67–83.

Cucchiella, F. and Gastaldi, M. (2006), "Risk management in supply chain: a real option approach", Journal of Manufacturing Technology Management, Vol. 17 No. 6, pp. 700–720.

Dabbene, F., Gay, P. and Sacco, N. (2008), "Optimisation of fresh-food supply chains in uncertain environments, Part II: A case study", Biosystems Engineering, Vol. 99 No. 3, pp. 360–371.

Dai, Z. and Zheng, X. (2015), "Design of close-loop supply chain network under uncertainty using hybrid genetic algorithm: a fuzzy and chance-constrained programming model", Computers & Industrial Engineering, Vol. 88, pp. 444–457.

Demirkan, H. and Cheng, H.K. (2008), "The risk and information sharing of application services supply chain", European Journal of Operational Research, Vol. 187 No. 3, pp. 765–784.

Diabat, A., Govindan, K. and Panicker, V. V. (2012), "Supply chain risk management and its mitigation in a food industry", International Journal of Production Research, Vol. 50 No. 11, pp. 3039–3050.

Elleuch, H., Hachicha, W. and Chabchoub, H. (2013), "A combined approach for supply chain risk management: description and application to a real hospital pharmaceutical case study", Journal of Risk Research, Vol. 17 No. 5, pp. 641-663.

Eslamipoor, R., Fakhrzad, M.B. and Zare Mehrjerdi, Y. (2014), "A new robust optimization model under uncertainty for new and remanufactured products", International Journal of Management Science and Engineering Management, Vol. 10 No. 2, pp. 137–143.

Faisal, M.N., Banwet, D.K. and Shankar, R. (2007), "Information risks management in supply chains: an assessment and mitigation framework", Journal of Enterprise Information Management, Vol. 20 No. 6, pp. 677–699.

Fallah-Tafti, A., Sahraeian, R., Tavakkoli-Moghaddam, R. and Moeinipour, M. (2014), "An interactive possibilistic programming approach for a multi-objective closed-loop supply chain network under uncertainty", International Journal of Systems Science, Vol. 45 No. 3, pp. 283–299.

Farahani, R.Z., Rezapour, S., Drezner, T. and Fallah, S. (2014), "Competitive supply chain network design: An overview of classifications, models, solution techniques and applications", Omega, Vol. 45, pp. 92–118.

Farooq, S. and O'Brien, C. (2009), "Risk calculations in the manufacturing technology selection process", Journal of Manufacturing Technology Management, Vol. 21 No. 1, pp. 28–49.

Feng, Y. and Viswanathan, S. (2006), "Impact of demand uncertainty on coordinating supply chain inventories through common replenishment epochs", Journal of the Operational Research Society, Vol. 58 No. 7, pp. 964–971.

Finch, P. (2004), "Supply chain risk management", Supply Chain Management: An International Journal, Vol. 9 No. 2, pp. 183–196.

Fleischmann, B., Meyr, H. and Wagner, M. (2002), “Advanced planning”, in Stadtler, Hartmut, Kilger, C. (Eds), Supply Chain Management and Advanced Planning, Springer, pp. 81–106.

Fleischmann, M., Beullens, P., Bloemhof-Ruwaard, J.M. and Wassenhove, L.N. (2001), “The impact of product recovery on logistics network design”, Production and Operations Management, Vol. 10 No. 2, pp. 156–173.

Fleischmann, M., Bloemhof-Ruwaard, J. M., Dekker, R., Van der Laan, E., Van Nunen, J. A., & Van Wassenhove, L. N (1997), “Quantitative models for reverse logistics: A review”, European Journal of Operational Research, Vol. 103 No. 1, pp. 1–17.

Gabrel, V., Murat, C. and Thiele, A. (2014), “Recent advances in robust optimization: An overview”, European Journal of Operational Research, Vol. 235 No. 3, pp. 471–483.

Ganguly, K.K. and Guin, K.K. (2013), “A fuzzy AHP approach for inbound supply risk assessment”, Benchmarking: An International Journal, Vol. 20 No. 1, pp. 129–146.

Georgiadis, M.C., Tsiakis, P., Longinidis, P. and Sofioglou, M.K. (2011), “Optimal design of supply chain networks under uncertain transient demand variations”, Omega, Vol. 39 No. 3, pp. 254–272.

Ghadge, A., Dani, S. and Kalawsky, R. (2012), “Supply chain risk management: present and future scope”, International Journal of Logistics Management, Vol. 23 No. 3, pp. 313–339.

Giannakis, M. and Louis, M. (2011), “A multi-agent based framework for supply chain risk management”, Journal of Purchasing and Supply Management, Vol. 17 No. 1, pp. 23–31.

Golicic, S.L. and Smith, C.D. (2013), “A meta-analysis of environmentally sustainable supply chain management practices and firm performance”, Journal of Supply Chain Management Activities, Vol. 49 No. 2, pp. 78–95.

Gosling, J. and Naim, M.M. (2009), “Engineer-to-order supply chain management: a literature review and research agenda.”, International Journal of Production Economics, Vol. 122 No. 2, pp. 741–754.

Govindan, K., Soleimani, H. and Kannan, D. (2014), "Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future", European Journal of Operational Research, Vol. 240 No. 3, pp. 603–626.

Greening, P. and Rutherford, C. (2011), "Disruptions and supply networks: a multi-level, multi-theoretical relational perspective", The International Journal of Logistics Management, Vol. 22 No. 1, pp. 104–126.

Gümüs, A. T. and Güneri, A. F. (2007), "Multi-echelon inventory management in supply chains with uncertain demand and lead times: literature review from an operational research perspective", Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 221 No. 10, pp. 1553–1570.

Guo, L. (2008), "Perspective: An analysis of 22 years of research in JPIM", Journal of Product Innovation Management, Vol. 25 No. 3, pp. 249–260.

Hamta, N., Shirazi, M. A. and Ghomi, S.F. (2015), "A bi-level programming model for supply chain network optimization with assembly line balancing and push-pull strategy", Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture available at: http://doi.org/10.1177/0954405414564406, (Accessed on 26-March 2016).

Hasani, A., Zegordi, S.H. and Nikbakhsh, E. (2012), "Robust closed-loop supply chain network design for perishable goods in agile manufacturing under uncertainty", International Journal of Production Research. Vol. 50 No. 16, pp. 4649–4669.

Hasani, A., Zegordi, S.H. and Nikbakhsh, E. (2014), "Robust closed-loop global supply chain network design under uncertainty: the case of the medical device industry", International Journal of Production Research, Vol. 53 No. 5, pp. 1596–1624.

Hatefi, S.M.M. and Jolai, F. (2014), "Robust and reliable forward-reverse logistics network design under demand uncertainty and facility disruptions", Applied Mathematical Modelling. Vol. 38 No. 9, pp. 2630–2647.

He, Y. and Zhao, X. (2012), "Coordination in multi-echelon supply chain under supply and demand uncertainty", International Journal of Production Economics. Vol. 139 No. 1, pp. 106–115.

Heckmann, I., Comes, T. and Nickel, S. (2015), "A critical review on supply chain risk – Definition, measure and modeling", Omega. Vol. 52, pp. 119–132.

Hetland, P.W. (2003), "Uncertainty Management in Appraisal", Risk and Uncertainty, edited by N. J. Smith, Thomas Telford, London, UK.

Ho, W., Zheng, T., Yildiz, H. and Talluri, S. (2015), "Supply chain risk management: a literature review", International Journal of Production Research, Vol.53 No. 16, pp. 5031-5069.

Hollmann, D. (2011), "Supply chain network design under uncertainty and risk", Brunel University, available at: http://v-scheiner.brunel.ac.uk/handle/2438/6407, (accessed on 20 March 2016).

Houska, B., Moritz D., (2013), "Nonlinear robust optimization via sequential convex bilevel programming." Mathematical Programming, Vol. 142 No. 1-2, PP. 539-577.

Hsu, C. and Li, H. (2011), "Reliability evaluation and adjustment of supply chain network design with demand fluctuations", International Journal of Production Economics. Vol. 132 No. 1, pp. 131–145.

Hung, K.-T. and Ryu, S. (2008), "Changing risk preferences in supply chain inventory decisions", Production Planning & Control, Vol. 19 No. 8, pp. 770–780.

Hung, S.-J. (2011), "Activity-based divergent supply chain planning for competitive advantage in the risky global environment: A DEMATEL-ANP fuzzy goal programming approach", Expert Systems with Applications. Vol. 38 No. 8, pp. 9053–9062.

Jia, X. and Cui, L. (2012), "Reliability Research of k -out-of- n□: G Supply chain system based on copula", Communications in Statistics - Theory and Methods, Vol. 41 No. 21, pp. 4023–4033.

Jindal, A. and Sangwan, K.S. (2014), "Closed loop supply chain network design and optimisation using fuzzy mixed integer linear programming model", International Journal of Production Research. Vol. 52 No.14, pp. 4156-4173.

Jüttner, U. and Maklan, S. (2011), “Supply chain resilience in the global financial crisis: an empirical study”, Supply Chain Management: An International Journal, Vol. 16 No. 4, pp. 246–259.

Jüttner, U., Peck, H. and Christopher, M. (2003), “An agenda for future research supply chain risk management: Outlining an agenda for future research”, International Journal of Logistics Research and Applications. Vol. 6 No. 4, pp. 197–210.

Kam, B.H., Chen, L. and Wilding, R. (2011), “Managing production outsourcing risks in China’s apparel industry: a case study of two apparel retailers”, Supply Chain Management: An International Journal, Vol. 16 No. 6, pp. 428–445.

Kang, J.-H. and Kim, Y.-D. (2012), “Inventory control in a two-level supply chain with risk pooling effect”, International Journal of Production Economics. Vol. 135 No. 1, pp. 116–124.

Kenné, J.-P., Dejax, P. and Gharbi, A. (2012), “Production planning of a hybrid manufacturing–remanufacturing system under uncertainty within a closed-loop supply chain”, International Journal of Production Economics, Vol. 135 No. 1, pp. 81–93.

Kern, D., Moser, R., Hartmann, E. and Moder, M. (2012), “Supply risk management: model development and empirical analysis”, International Journal of Physical Distribution & Logistics Management, Vol. 42 No. 1, pp. 60–82.

Khan, O. and Burnes, B. (2007), “Risk and supply chain management: creating a research agenda”, The International Journal of Logistics Management, Vol. 18 No. 2, pp. 197–216.

Klibi, W., Martel, A. and Guitouni, A. (2010), “The design of robust value-creating supply chain networks: A critical review”, European Journal of Operational Research, Vol. 203 No. 2, pp. 283–293.

Klimov, R. and Merkuryev, Y. (2008), “Simulation model for supply chain reliability evaluation”, Technological and Economic Development of Economy, Vol. 14 No. 3, pp. 300–311.

Ko, H.J. and Evans, G.W. (2007), "A genetic algorithm-based heuristic for the dynamic integrated forward/reverse logistics network for 3PLs", Computers and Operations Research, Vol. 34 No. 2, pp. 346–366.

Kumar, S.K., Tiwari, M.K. and Babiceanu, R.F. (2010), "Minimisation of supply chain cost with embedded risk using computational intelligence approaches", International Journal of Production Research, Vol. 48 No. 13, pp. 3717–3739.

Law, A.M. (2006), "Simulation modeling and analysis", McGraw-Hill, New York, NY. Available at: http://www.mheducation.com/highered/product/simulation-modeling-analysis-law/M0073401323.html, (Accessed on 11 April 2016).

Lee, C.K.M., Yeung, Y.C. and Hong, Z. (2012), "An integrated framework for outsourcing risk management", Industrial Management & Data Systems, Vol. 112 No. 4, pp. 541–558.

Lee, D. H. and Dong, M. (2008), "A heuristic approach to logistics network design for end-of-lease computer products recovery", Transportation Research Part E: Logistics and Transportation Review, Vol. 44 No. 3, pp. 455–474.

Li, H. and Amini, M. (2012), "A hybrid optimisation approach to configure a supply chain for new product diffusion: a case study of multiple-sourcing strategy", International Journal of Production Research, Vol. 50 No. 11, pp. 3152–3171.

Lieckens, K. and Vandaele, N. (2012), "Multi-level reverse logistics network design under uncertainty", International Journal of Production Research, Vol. 50 No. 1, pp. 23–40.

Lin, Y. and Zhou, L. (2011), "The impacts of product design changes on supply chain risk: a case study", International Journal of Physical Distribution & Logistics Management, Vol. 41 No. 2, pp. 162–186.

Lin, Y.-K., Yeh, C.-T. and Huang, C.-F. (2013), "Reliability evaluation of a stochastic-flow distribution network with delivery spoilage", Computers & Industrial Engineering, Vol. 66 No. 2, pp. 252–259.

Listeş, O. (2007), "A generic stochastic model for supply-and-return network design", Computers & Operations Research, Vol. 34 No. 2, pp. 417–442.

Lockamy, A. and McCormack, K. (2010), "Analysing risks in supply networks to facilitate outsourcing decisions", International Journal of Production Research, Vol. 48 No. 2, pp. 593–611.

Lundin, J.F. (2012), "Redesigning a closed-loop supply chain exposed to risks", International Journal of Production Economics, Vol. 140 No. 2, pp. 596–603.

Mahnam, M., Yadollahpour, M.R., Famil-Dardashti, V. and Hejazi, S.R. (2009), "Supply chain modeling in uncertain environment with bi-objective approach", Computers & Industrial Engineering, Vol. 56 No. 4, pp. 1535–1544.

Manuj, I. and Mentzer, J.T. (2008), "Global supply chain risk management strategies", International Journal of Physical Distribution & Logistics Management, Vol. 38 No. 3, pp. 192–223.

Melnyk, S. A., Narasimhan, R. and DeCampos, H. A. (2014), "Supply chain design: issues, challenges, frameworks and solutions", International Journal of Production Research, Vol. 52 No. 7, pp. 1887–1896.

Melo, M.T., Nickel, S. and Saldanha-da-Gama, F. (2009), "Facility location and supply chain management – a review", European Journal of Operational Research, Vol. 196 No. 2, pp. 401–412.

Mentzer, J.T., DeWitt, W., Keebler, J.S., Min, S., Nix, N.W., Smith, C.D. and Zacharia, Z.G. (2001), "Defining supply chain management", Journal of Business Logistics, Vol. 22 No. 2, pp. 1–25.

Merschmann, U. and Thonemann, U.W. (2011), "Supply chain flexibility, uncertainty and firm performance: An empirical analysis of German manufacturing firms", International Journal of Production Economics, Vol. 130 No. 1, pp. 43–53.

Minoux, M. (2009), "On robust maximum flow with polyhedral uncertainty sets", Optimization Letters, Vol. 3 No. 3, pp. 367–376.

Muchen, T. (2014), “Linear programming based models for resilient supply systems design, national university of Singapore”, Available at: http://scholarbank. nus.edu.sg/ handle/10635/118196, (Accessed on 26 March 2016).

Mulvey, J.M., Vanderbei, R.J. and Zenios, S.A. (1995), “Robust optimization of large-scale systems”, Operations Research, Vol. 43 No. 2, pp. 264–281.

Musa, S.N. (2012), “Supply Chain Risk Management: Identification , Evaluation and Mitigation Techniques”, available at: http://www.diva-portal.org/smash/ record.jsf?pid=diva2:535627, (Accessed on 15 April 2016).

Nagurney, A., Cruz, J., Dong, J. and Zhang, D. (2005), “Supply chain networks, electronic commerce, and supply side and demand side risk”, European Journal of Operational Research, Vol. 164 No. 1, pp. 120–142.

Nagurney, A. and Qiang, Q. (2012), “Fragile networks: identifying vulnerabilities and synergies in an uncertain age”, International Transactions in Operational Research, Vol. 19 No. 1-2, pp. 123–160.

Natarajarathinam, M., Capar, I. and Narayanan, A. (2009), “Managing supply chains in times of crisis: a review of literature and insights”, International Journal of Physical Distribution & Logistics Management, Vol. 39 No. 7, pp. 535–573.

Nepal, B. and Yadav, O.P. (2015), “Bayesian belief network-based framework for sourcing risk analysis during supplier selection”, International Journal of Production Research, Vol. 53 No.20, pp.6114-6135.

Oke, A. and Gopalakrishnan, M. (2009), “Managing disruptions in supply chains: A case study of a retail supply chain”, International Journal of Production Economics, Vol. 118 No. 1, pp. 168–174.

Oliveira, F., Grossmann, I.E. and Hamacher, S. (2014), “Accelerating benders stochastic decomposition for the optimization under uncertainty of the petroleum product supply chain”, Computers and Operations Research, Vol. 49, pp. 47–58.

Olson, D.L. and Wu, D.D. (2010), “A review of enterprise risk management in supply chain”, Kybernetes, Vol. 39 No. 5, pp. 694–706.

Owen, S.H. and Daskin, M.S. (1998), “Strategic facility location□: a review”, European Journal of Operational Research, Vol. 111 No. 3, pp. 423–447.

Özceylan, E., Paksoy, T. and Bektaş, T. (2014), “Modeling and optimizing the integrated problem of closed-loop supply chain network design and disassembly line balancing”, Transportation Research Part E: Logistics and Transportation Review, Vol. 61, pp. 142–164.

Özkır, V. and Başlıgil, H. (2013), “Multi-objective optimization of closed-loop supply chains in uncertain environment”, Journal of Cleaner Production, Vol. 41, pp. 114–125.

Pantaleo, A.M., Giarola, S., Bauen, A. and Shah, N. (2014), “Integration of biomass into urban energy systems for heat and power. Part I: An MILP based spatial optimization methodology”, Energy Conversion and Management, Vol. 83, pp. 347–361.

Papadakis, I.S. (2006), “Financial performance of supply chains after disruptions: an event study”, Supply Chain Management: An International Journal, Vol. 11 No. 1, pp. 25–33.

Pazhani, S.., Ramkumar, N.., Narendran, T.T.. and Ganesh, K.. (2013), “A bi-objective network design model for multi-period, multi-product closed-loop supply chain”, Journal of Industrial and Production Engineering, Vol. 30 No. 4, pp. 264–280.

Peck, H. (2005), “Drivers of supply chain vulnerability: an integrated framework”, International Journal of Physical Distribution & Logistics Management, Vol. 35 No. 4, pp. 210–232.

Peidro, D., Mula, J., Jiménez, M. and del Mar Botella, M. (2010), “A fuzzy linear programming based approach for tactical supply chain planning in an uncertainty environment”, European Journal of Operational Research, Vol. 205 No. 1, pp. 65–80.

Peng, P., Snyder, L. V., Lim, A. and Liu, Z. (2011), “Reliable logistics networks design with facility disruptions”, Transportation Research Part B: Methodological, Vol. 45 No. 8, pp. 1190–1211.

Pfohl, H.-C., Gallus, P. and Thomas, D. (2011), "Interpretive structural modeling of supply chain risks", International Journal of Physical Distribution & Logistics Management, Vol. 41 No. 9, pp. 839–859.

Piekkari, R., Plakoyiannaki, E. and Welch, C. (2010), "'Good' case research in industrial marketing: Insights from research practice", Industrial Marketing Management, Vol. 39 No. 1, pp. 109–117.

Pishvaee, M.S., Jolai, F. and Razmi, J. (2009), "A stochastic optimization model for integrated forward/reverse logistics network design", Journal of Manufacturing Systems, Vol. 28 No. 4, pp. 107–114.

Pishvaee, M.S., Rabbani, M. and Torabi, S.A. (2011), "A robust optimization approach to closed-loop supply chain network design under uncertainty", Applied Mathematical Modelling, Vol. 35 No. 2, pp. 637–649.

Pishvaee, M.S. and Torabi, S. a. (2010), "A possibilistic programming approach for closed-loop supply chain network design under uncertainty", Fuzzy Sets and Systems, Vol. 161 No. 20, pp. 2668–2683.

Prakash, S., Soni, G. and Rathore, A.P.S. (2015), "A grey based approach for assessment of risk associated with facility location in global supply chain", Grey Systems: Theory and Application, Vol. 5 No. 3, pp. 419 – 43.

Prakash, S., Soni, G. and Rathore, A.P.S. (2015), "Mitigating risk in perishable food supply chain using interpretive structural modeling (ISM)", Benchmarking: An International Journal, Vol. 24 No. 1, In press.

Prasannavenkatesan, S. and Kumanan, S. (2012), "Multi-objective supply chain sourcing strategy design under risk using PSO and simulation", International Journal of Advanced Manufacturing Technology, Vol. 61 No. 1-4, pp. 325–337.

Prater, E. (2005), "A framework for understanding the interaction of uncertainty and information systems on supply chains", International Journal of Physical Distribution & Logistics Management, Vol. 35 No. 7, pp. 524–539.

Punniyamoorthy, M., Thamaraiselvan, N. and Manikandan, L. (2013), "Assessment of supply chain risk: scale development and validation", Benchmarking: An International Journal, Vol. 20 No. 1, pp. 79–105.

Qiang, Q., Ke, K., Anderson, T. and Dong, J. (2013), "The closed-loop supply chain network with competition, distribution channel investment, and uncertainties", Omega, Vol. 41 No. 2, pp. 186–194.

Quade, E. S. and Majone, G. (1980), "Pitfalls in formulation and modeling", In Pitfalls of analysis, Wiley John, New York, pp. 23-43, Retrieved from Sandbox on April 9, 2016.

Rahmani, D., Ramezanian, R., Fattahi, P. and Heydari, M. (2013), "A robust optimization model for multi-product two-stage capacitated production planning under uncertainty", Applied Mathematical Modelling, Vol. 37 No. 20, pp. 8957–8971.

Ramanathan, R. (2010), "The moderating roles of risk and efficiency on the relationship between logistics performance and customer loyalty in e-commerce", Transportation Research Part E: Logistics and Transportation Review, Vol. 46 No. 6, pp. 950–962.

Ramanathan, U., Gunasekaran, A. and Subramanian, N. (2011), "Supply chain collaboration performance metrics: a conceptual framework", Benchmarking: An International Journal, Vol. 18 No. 6, pp. 856 – 872.

Ramezani, M., Kimiagari, A.M. and Karimi, B. (2014), "Closed-loop supply chain network design: a financial approach", Applied Mathematical Modelling, Vol. 38 No. 15, pp. 4099–4119.

Ramezani, M., Kimiagari, A.M., Karimi, B. and Hejazi, T.H. (2014), "Closed-loop supply chain network design under a fuzzy environment", Knowledge-Based Systems, Vol. 59, pp. 108–120.

Rao, S. and Goldsby, T.J. (2009), "Supply chain risks: a review and typology", The International Journal of Logistics Management, Vol. 20 No. 1, pp. 97–123.

Ratnasingam, P. (2006), "Perceived risks in supply chain management e-collaboration", Journal of Internet Commerce, Vol. 5 No. 4, pp. 105–124.

Ritchie, B. and Brindley, C. (2007), "Supply chain risk management and performance: A guiding framework for future development", International Journal of Operations & Production Management, Vol. 27 No. 3, pp. 303–322.

Ritchie, B. and Brindley, C. (2007), “An emergent framework for supply chain risk management and performance measurement”, Operational Research Society, Vol. 58 No. 11, pp. 1398–1411.

Rodrigues, V.S., Stantchev, D., Potter, A., Naim, M. and Whiteing, A. (2008), “Establishing a transport operation focused uncertainty model for the supply chain”, International Journal of Physical Distribution & Logistics Management, Vol. 38 No. 5, pp. 388–411.

Rusman, M. (2013), “Multistage logistic network optimization under disruption risk”, Hasanuddin university, Indonesia. available at: http://repository.unhas.ac.id/handle/123456789/4516, (Accessed on 02 April 2016).

Salema, M.I.G., Barbosa-Povoa, A.P. and Novais, A.Q. (2007), “An optimization model for the design of a capacitated multi-product reverse logistics network with uncertainty”, European Journal of Operational Research, Vol. 179 No. 3, pp. 1063–1077.

Samvedi, A., Jain, V. and Chan, F.T.S. (2013), “Quantifying risks in a supply chain through integration of fuzzy AHP and fuzzy TOPSIS”, International Journal of Production Research, Vol. 51 No. 8, pp. 2433–2442.

Sanchez-Rodrigues, V., Potter, A. and Naim, M.M. (2010), “The impact of logistics uncertainty on sustainable transport operations”, International Journal of Physical Distribution & Logistics Management, Vol. 40 No. 1, pp. 61–83.

Santoso, T., Ahmed, S., Goetschalckx, M. and Shapiro, A. (2005), “A stochastic programming approach for supply chain network design under uncertainty”, European Journal of Operational Research, Vol. 167 No. 1, pp. 96–115.

Sargent, R. G. (2007), “Verification and validation of simulation models”, In R. R. (Eds) Handerson, S. G., Biller, B., Hsieh, M. H., Shortle, J., Tew, J. D. and Barton (Ed.), Proceedings of the 2007 Winter simulation conference, USA.

Setlhaolo, D., Xia, X. and Zhang, J. (2014), “Optimal scheduling of household appliances for demand response”, Electric Power Systems Research, Vol. 116, pp. 24–28.

Shabani, N., Sowlati, T., Ouhimmou, M. and Rönnqvist, M. (2014), "Tactical supply chain planning for a forest biomass power plant under supply uncertainty", Energy, Vol. 78, pp. 346–355.

Shapiro., J.F. (2007), "Modelling the supply chain", 2nd ed., cengage learning, USA.

Shi, J., Zhang, G. and Sha, J. (2011), "Optimal production planning for a multi-product closed loop system with uncertain demand and return", Computers & Operations Research, Vol. 38 No. 3, pp. 641–650.

Shimizu, T., Park, Y.W. and Hong, P. (2012), "Project managers for risk management: case for Japan", Benchmarking: An International Journal, Vol. 19 No. 4-5, pp. 532–547.

Shukla, A., Lalit, V.A. and Venkatasubramanian, V. (2011), "Optimizing efficiency-robustness trade-offs in supply chain design under uncertainty due to disruptions", International Journal of Physical Distribution & Logistics Management, Vol. 41 No. 6, pp. 623–647.

Simangunsong, E.S., Hendry, L. and Stevenson, M. (2012), "Supply chain uncertainty: a review and theoretical foundation for future research", International Journal of Production Research, Vol. 50 No. 16, pp. 4493–4523.

Simchi-Levi, D. (2005), "The Logic of Logistics - Theory and Algorithms", 2nd ed., Springer, available at: http://www.springer.com/us/book/9781461491484 (accessed on 28 May 2016).

Simchi-Levi, D., Kaminsky, P. and Simchi-Levi, E. (2003), "Managing the supply chain: The definitive guide for the business professional", McGraw Hill Professional, http://books.google.co.in/books/about/Managing_the_Supply_Chain.html?id=dUKGHB_YjFQC&pgis=1, (accessed on 4 February 2015).

Singh, A.R., Mishra, P.K., Jain, R. and Khurana, M.K. (2012), "Design of global supply chain network with operational risks", International Journal of Advanced Manufacturing Technology, Vol. 60 No. 1-4, pp. 273–290.

Snyder, L. V. (2006), "Facility location under uncertainty: A review", IIE Transactions, Vol. 38 No. 7, pp. 547–564.

Snyder, L. V. and Daskin, M.S. (2006), “Stochastic p-robust location problems”, IIE Transactions, Vol. 38 No. 11, pp. 971–985.

Sofyalıoğlu, Ç. and Kartal, B. (2012), “The selection of global supply chain risk management strategies by using fuzzy analytical hierarchy process – a case from Turkey”, Procedia - Social and Behavioral Sciences, Vol. 58, pp. 1448–1457.

Soleimani, H. and Kannan, G. (2014), “A hybrid particle swarm optimization and genetic algorithm for closed-loop supply chain network design in large-scale networks”, Applied Mathematical Modelling, Vol. 39 No.14, pp. 3990-4012.

Soleimani, H.., Seyyed-Esfahani, M.. and Kannan, G.. (2014), “Incorporating risk measures in closed-loop supply chain network design”, International Journal of Production Research, Vol. 52 No. 6, pp. 1843–1867.

Solo, C.J. (2009), “Multi-objective, integrated supply chain design and operation under uncertainty”, the Pennsylvania state university. Available at: https://etda.libraries.psu.edu/catalog/9709, (accessed on 18 March 2016).

Soni, G. and Kodali, R. (2011), “A critical analysis of supply chain management content in empirical research”, Business Process Management Journal, Vol. 17 No. 2, pp. 238–266.

Soni, G. and Kodali, R. (2013), “A critical review of supply chain management frameworks: proposed framework”, benchmarking: An International Journal, Vol. 20 No. 2, pp. 263-298.

Soyster, A.L. (1973), “Technical Note—Convex programming with set-inclusive constraints and applications to inexact linear programming”, Operations Research, Vol. 21 No. 5, pp. 1154-1157.

Stonebraker, P.W., Goldhar, J. and Nassos, G. (2009), “Weak links in the supply chain: measuring fragility and sustainability”, Journal of Manufacturing Technology Management, Vol. 20 No. 2, pp. 161–177.

Subulan, K., Baykasoğlu, A., Özsoydan, F.B., Taşan, a. S. and Selim, H. (2014), “A case-oriented approach to a lead/acid battery closed-loop supply chain network design under risk and uncertainty”, Journal of Manufacturing Systems, available at: http://doi.org/10.1016/j.jmsy. (Accessed on 19 March 2016).

Tabrizi, B.H. and Razmi, J. (2013), "Introducing a mixed-integer non-linear fuzzy model for risk management in designing supply chain networks", Journal of Manufacturing Systems, Vol. 32 No. 2, pp. 295–307.

Talluri, S., Narasimhan, R. and Chung, W. (2010), "Manufacturer cooperation in supplier development under risk", European Journal of Operational Research, Vol. 207 No. 1, pp. 165–173.

Tang, C.S. (2006), "Perspectives in supply chain risk management", International Journal of Production Economics, Vol. 103 No. 2, pp. 451–488.

Tang, C.S. (2006), "Robust strategies for mitigating supply chain disruptions", International Journal of Logistics Research and Applications, Vol. 9 No. 1, pp. 33–45.

Tang, O. and Musa, S.N. (2011), "Identifying risk issues and research advancements in supply chain risk management", International Journal of Production Economics, Vol. 133 No. 1, pp. 25–34.

Taylor, P., Chaudhuri, A., Mohanty, B. K., and Singh, K. N. (2013), "Supply chain risk assessment during new product development: A group decision making approach using numeric and linguistic data", International Journal of Production Research, Vol. 51 No. 10, pp. 2790–2804.

Tranfield, D.R., Denyer, D. and Smart, P. (2003), "Towards a methodology for developing evidence-informed management knowledge by means of systematic review", British Journal of Management, Vol. 14 No.3, pp. 207–222.

Tse, Y.K. and Tan, K.H. (2011), "Managing product quality risk in a multi-tier global supply chain", International Journal of Production Research, Vol. 49 No. 1, pp. 139–158.

Tummala, R. and Schoenherr, T. (2011), "Assessing and managing risks using the supply chain risk management process (SCRMP)", Supply Chain Management: An International Journal, Vol. 16 No. 6, pp. 474–483.

Tuncel, G. and Alpan, G. (2010), "Risk assessment and management for supply chain networks: A case study", Computers in Industry, Vol. 61 No. 3, pp. 250–259.

Vahdani, B., Tavakkoli-moghaddam, R., Jolai, F. and Baboli, A. (2013), "Reliable design of a closed loop supply chain network under uncertainty: An interval fuzzy possibilistic chance- constrained model", Engineering Optimization, Vol. 45 No. 6, pp. 745–765.

Vahdani, B., Tavakkoli-moghaddam, R., Modarres, M. and Baboli, A. (2012), "Reliable design of a forward / reverse logistics network under uncertainty: A robust-M / M / c queuing model", Transportation Research Part E: Logistics and Transportation Review, Vol. 48 No. 6, pp. 1152–1168.

Vilko, J.P.P. and Hallikas, J.M. (2012), "Risk assessment in multimodal supply chains", International Journal of Production Economics, Vol. 140 No. 2, pp. 586–595.

Wagner, S.M. and Bode, C. (2008), "An empirical examination of supply chain performance along several dimensions of risk", Journal of Business Logistics, Vol. 29 No. 1, pp. 307–325.

Wagner, S.M., Mizgier, K.J. and Arnez, P. (2014), "Disruptions in tightly coupled supply chain networks: the case of the US offshore oil industry", Production Planning & Control, Vol. 25 No. 6, pp. 494–508.

Wagner, S.M. and Neshat, N. (2010), "Assessing the vulnerability of supply chains using graph theory", International Journal of Production Economics, Vol. 126 No. 1, pp. 121–129.

Wang, H.-F. and Hsu, H.-W. (2010), "Resolution of an uncertain closed-loop logistics model: an application to fuzzy linear programs with risk analysis.", Journal of Environmental Management, Vol. 91 No. 11, pp. 2148–2162.

Wang, H.-F. and Huang, Y.-S. (2013), "A two-stage robust programming approach to demand-driven disassembly planning for a closed-loop supply chain system", International Journal of Production Research, Vol. 51 No. 8, pp. 2414–2432.

Wang, Q., Chu, B., Wang, J. and Kumakiri, Y. (2012), "Risk analysis of supply contract with call options for buyers", International Journal of Production Economics, Vol. 139 No. 1, pp. 97–105.

Wang, X., Li, D. and Shi, X. (2012), “A fuzzy model for aggregative food safety risk assessment in food supply chains”, Production Planning & Control. Vol. 23 No. 5, pp. 377–395.

Wang, Y.M. and Yin, H.L. (2013), “Integrated optimization for supply chain with facility disruption”, 2013 IEEE International Conference on Mechatronics and Automation, IEEE ICMA 2013, pp. 1625–1629.

Waters, C.D.J. (2007), “Supply chain risk management: Vulnerability and resilience in logistics”, Kogan page publishers, available at: https://books.google.co.in/books/about/Supply_Chain_Risk_Management.html?id=HhVveSOyKwQC&pgis=1 (accessed on 11 August 2015).

Watson, M., Lewis, S., Cacioppi, P. and Jayaraman, J. (2013), “Supply chain network design”, pearson education, inc., upper saddle river, New Jersey, USA.

Webster, J. and Watson, R.T. (2002), “Analyzing the past to prepare for the future: Writing a literature review.”, MIS Quarterly, Vol. 26 No. 2, pp.13-23.

Williams, Z., Lueg, J.E. and LeMay, S. A. (2008), “Supply chain security: an overview and research agenda”, The International Journal of Logistics Management, Vol. 19 No. 2, pp. 254–281.

Wu, D. and Olson, D.L. (2008), “Supply chain risk, simulation, and vendor selection”, International Journal of Production Economics, Vol. 114 No. 2, pp. 646–655.

Wu, D.D., Zhang, Y., Wu, D. and Olson, D.L. (2010), “Fuzzy multi-objective programming for supplier selection and risk modeling: A possibility approach”, European Journal of Operational Research, Vol. 200 No. 3, pp. 774–787.

Wu, T., Blackhurst, J. and Chidambaram, V. (2006), “A model for inbound supply risk analysis”, Computers in Industry, Vol. 57 No. 4, pp. 350–365.

www.pwc.in. (2015), “eCommerce in India accelerating growth”, India, PwC. available at: http://www.pwc.in/assets/pdfs/publications/2015/ecommerce-in-india-accelerating-growth.pdf (accessed on 19 April 2016).

Xanthopoulos, A., Vlachos, D. and Iakovou, E. (2012), "Optimal newsvendor policies for dual-sourcing supply chains: A disruption risk management framework", Computers & Operations Research, Vol. 39 No. 2, pp. 350–357.

Yang, B. and Yang, Y. (2010), "Postponement in supply chain risk management: a complexity perspective", International Journal of Production Research, Vol. 48 No. 7, pp. 1901–1912.

Yao, J.M. (2013), "Scheduling optimisation of co-operator selection and task allocation in mass customisation supply chain based on collaborative benefits and risks", International Journal of Production Research, Vol. 51 No. 8, pp. 2219-2239.

Yin, S. and Nishi, T. (2012), "Game theoretic approach for global manufacturing planning under risk and uncertainty", Procedia CIRP, Vol. 3, pp. 251–256.

Zeballos, L.J., Méndez, C. a., Barbosa-Povoa, A.P. and Novais, A.Q. (2014), "Multi-period design and planning of closed-loop supply chains with uncertain supply and demand", Computers & Chemical Engineering, Vol. 66, pp. 151–164.

Zeballos, L.J., Gomes, M. I., Barbosa-Povoa, A.P. and Novais, A.Q. (2012), "Addressing the uncertain quality and quantity of returns in closed-loop supply chains", Computers & Chemical Engineering, Vol. 47, pp. 237–247.

Zhang, M., Huang, J. and Zhu, J. (2012), "Reliable facility location problem considering facility failure scenarios", Kybernetes, Vol. 41 No. 10, pp. 1440–1461.

Zsidisin, G. A., Ellram, L.M., Carter, J.R. and Cavinato, J.L. (2004), "An analysis of supply risk assessment techniques", International Journal of Physical Distribution & Logistics Management, Vol. 34 No. 5, pp. 397–413.

ANNEXURES

Appendix I: List of 347 articles used for review

1. Lodree, E. J., and Taskin, S. (2008), "An insurance risk framework for management disaster relief and supply chain disruption inventory planning", The Journal of the Operational Research Society, Vol. 59 No. 5, pp. 674–684.

2. Poojari, C. A., Lucas, C., and Mitra, G. (2008), "Robust solutions and risk measures for a supply chain planning problem uncertainty", The Journal of the Operational Research Society, Vol. 59 No. 1, pp. 2–12.

3. Tapiero, C. S., and Kogan, K. (2007), "Risk and quality control in a supply chain: Competitive and collaborative approaches", The Journal of the Operational Research Society, Vol. 58 No. 11, pp. 1440–1448.

4. Ritchie, B, and Brindley, C. (2013), "An emergent framework for supply chain risk management and performance measurement", Journal of the Operational Research Society, Vol. 58 No. 11, pp. 1398–1411.

5. Tomlin, B. (2006), "On the value of mitigation and contingency strategies for managing supply chain disruption risks", Management Science, Vol. 52 No. 5, pp. 639–657.

6. Ho, C., Chi, Y., and Tai, Y. (2005), "A structural approach to measuring uncertainty in supply chains", International Journal of Electronic Commerce, Vol. 9 No. 3, pp. 91–114.

7. Feng, Y., and Viswanathan, S. (2007), "Impact uncertainty chain supply through replenishment epochs", The Journal of the Operational Research Society, Vol. 58 No. 7, pp. 964–971.

8. Natarajarathinam, M., Capar, I., and Narayanan, A. (2009), "Managing supply chains in times of crisis: a review of literature and insights", International Journal of Physical Distribution and Logistics Management, Vol. 39 No. 7, pp. 535 – 573.

9. Ghadge, A., Dani, S., and Kalawsky, R. (2012), "Supply chain risk management: Present and future scope", The International Journal of Logistics Management, Vol. 23 No. 3, pp. 313–339.

10. Finch, P. (2004), "Supply chain risk management", Supply Chain Management: An International Journal, Vol. 9 No. 2, pp. 183 – 196.

11. Colicchia, C., and Strozzi, F. (2012), "Supply chain risk management: A new methodology for a systematic literature review", Supply Chain Management: An International Journal, Vol. 17 No. 4, pp. 403–418.

12. Cheng, S. K. (2008), "A conceptual framework for analysing risk in supply networks", Journal of Enterprise Information Management, Vol. 22 No. 4, pp. 345–360.

13. Soni, G., and Kodali, R. (2013), "A decision framework for assessment of risk associated with global supply chain", Journal of Modelling in Management, Vol. 8 No. 1, pp. 25–53.

14. Prater, E. (2005), "A framework for understanding the interaction of uncertainty and information systems on supply chains", International Journal of Physical Distribution and Logistics Management, Vol. 35 No. 7, pp. 524–539.

15. Ganguly, K. K., and Guin, K. K. (2013), "A fuzzyF AHP approach for inbound supply risk assessment", Benchmarking: An International Journal, Vol. 20 No. 1, pp. 129–146.

16. Olson, D. L., and Wu, D. (2010), "A review of enterprise risk management in supply chain", Kybernetes, Vol. 39 No. 5, pp. 694–706.

17. Bai, C., Sarkis, J., and Wei, X. (2010), "Addressing key sustainable supply chain management issues using rough set methodology", Management Research Review, Vol. 33 No. 12, pp. 1113–1127.

18. Zsidisin, G. A., Ellram, L. M., Carter, J. R., and Cavinato, J. L. (2004), "An analysis of supply risk assessment techniques", International Journal of Physical Distribution and Logistics Management, Vol. 34 No. 5, pp. 397 – 413.

19. Lee, C. K. M., Yeung, Y. C., and Hong, Z. (2012), "An integrated framework for outsourcing risk management", Industrial Management and Data Systems, Vol. 112 No. 4, pp. 541–558.

20. Chapman, P., Bernon, M., andHaggett, P. (2011), "Applying selected quality management techniques to diagnose delivery time variability", International Journal of Quality and Reliability Management, Vol. 28 No. 9, pp. 1019–1040.

21. Christopher, M., Mena, C., Khan, O., and Yurt, O. (2011), "Approaches to managing global sourcing risk", Supply Chain Management: An International Journal, Vol. 16 No. 2, pp. 67 – 81.

22. Tummala, R., and Schoenherr, T. (2011), "Assessing and managing risks using the supply chain risk management process (SCRMP)", Supply Chain Management: An International Journal, Vol. 16 No. 6, pp. 474 – 483.

23. Murugesan, P., and Natarajan, T. (2013), "Assessment of Supply Chain Risk: Scale development and validation", Benchmarking: An International Journal, Vol. 20 No. 1, pp. 79-105.

24. Lockamy, A. (2011), "Benchmarking supplier risks using Bayesian networks", Benchmarking: An International Journal, Vol. 18 No. 3, pp. 409–427.

25. Dey, A., Laguardia, P., and Srinivasan, M. (2011), "Building sustainability in logistics operations: a research agenda", Management Research Review, Vol. 34 No. 11, pp. 1237 – 1259.

26. Bandaly, D., Shanker, L., Kahyaoglu, Y. and Satir, A. (2013), "Supply chain risk management — II: a review of operational, financial and integrated approaches", Risk Management, Vol. 15 No. 1, pp. 1–31.

27. Wieland, A., and Wallenburg, C. M. (2012), "Dealing with supply chain risks linking risk management practices and strategies to performance", International Journal of Physical Distribution and Logistics Management, Vol. 42 No. 10, pp. 887–905.

28. Hittle, B., and Leonard, K. M. (2011), "Decision making in advance of a supply chain crisis", Management Decision, Vol. 49 No. 7, pp. 1182–1193.

29. Caldwell, N., Harland, C., Powell, P. and Zheng, J. (2013), “Impact of e-business on perceived supply chain risks”, Journal of Small Business and Enterprise Development, Vol. 20 No. 4, pp. 688–715.

30. Greening, P., and Rutherford, C. (2011), “Disruptions and supply networks: A multi-level, multi-theoretical relational perspective”, The International Journal of Logistics Management, Vol. 22 No. 1, pp. 104–126.

31. Peck, H. (2005), “Drivers of supply chain vulnerability: An integrated framework”, International Journal of Physical Distribution and Logistics Management, Vol. 35 No. 4, pp. 210–232.

32. Diehl, D. and Spinler, S. (2013), “Defining a common ground for supply chain risk management–a case study in the fast-moving consumer goods industry”, International Journal of Logistics Research and Applications: A Leading Journal of Supply Chain Management, Vol. In press, doi:10.1080/13675567.2013.813443.

33. Durowoju, O. A., Chan, H. K., and Wang, X. (2011), “Entropy assessment of supply chain disruption”, Journal of Manufacturing Technology Management, Vol. 23 No. 8, pp. 998–1014.

34. Norrman, A., and Jansson, U. (2004), “Ericsson’ s proactive supply chain risk management approach after a serious sub-supplier accident”, International Journal of Physical Distribution and Logistics Management, Vol. 34 No. 5, pp. 434–456.

35. Rodrigues, V. S., Stantchev, D., and Whiteing, A. (2008), “Establishing a transport operation focused uncertainty model for the supply chain”, International Journal of Physical Distribution and Logistics Management, Vol. 38 No. 5, pp. 388–411.

36. Rodrigues, V. S., Potter, A., and Naim, M. M. (2010), “Evaluating the causes of uncertainty in logistics operations”, The International Journal of Logistics Management, Vol. 21 No. 1, pp. 45–64.

37. Sutton, S. G. (2006), “Extended-enterprise system’s impact on enterprise risk management”, Journal of Enterprise Information Management, Vol. 19 No. 1, pp. 97–114.

38. Papadakis, I. S. (2006), “Financial performance of supply chains after disruptions: An event study”, Supply Chain Management: An International Journal, Vol. 11 No. 1, pp. 25–33.

39. Manuj, I., and Mentzer, J. T. (2008), “Global supply chain risk management strategies”, International Journal of Physical Distribution and Logistics Management, Vol. 38 No. 3, pp. 192–223.

40. Pujawan, I. N., and Geraldin, L. H. (2009), “House of risk: A model for proactive supply chain risk management”, Business Process Management Journal, Vol. 15 No. 6, pp. 953–967.

41. Faisal, M. N., Banwet, D. K., and Shankar, R. (2007), “Information risks management in supply chains: An assessment and mitigation framework”, Journal of Enterprise Information Management, Vol. 20 No. 6, pp. 677–699.

42. Elleuch, H., Hachicha, W. and Chabchoub, H. (2013), “A combined approach for supply chain risk management: description and application to a real hospital pharmaceutical case study”, Journal of Risk Research, In press, doi:10.1080/13669877.2013.815653.

43. Pfohl, H., Gallus, P., and Thomas, D. (2011), “Interpretive structural modeling of supply chain risks”, International Journal of Physical Distribution and Logistics Management, Vol. 41 No. 9, pp. 839–859.

44. Goran, S. (2004), “Key areas, causes and contingency planning of corporate vulnerability in supply chains”, International Journal of Physical Distribution and Logistics Management, Vol. 34 No.9, pp. 728–748.

45. Kam, B. H., Chen, L., and Wilding, R. (2011), “Managing production outsourcing risks in China’s apparel industry: A case study of two apparel retailers”, Supply Chain Management: An International Journal, Vol. 16 No. 6, pp. 428–445.

46. Gaudenzi, B., and Borghesi, A. (2006), “Managing risks in the supply chain using the AHP method”, The International Journal of Logistics Management, Vol. 17 No. 1, pp. 114–136.

47. Faisal, M. N., Banwet, D. K., and Shankar, R. (2006a), “Mapping supply chains on risk and customer sensitivity dimensions”, Industrial Management and Data Systems, Vol. 106 No. 6, pp. 878–895.

48. Skipper, J. B., and Hanna, J. B. (2001), “Minimizing supply chain disruption risk through enhanced flexibility”, International Journal of Physical Distribution and Logistics Management, Vol. 39 No. 5, pp. 404–427.

49. Deane, J. K., Craighead, C. W., and Ragsdale, C. T. (2009), “Mitigating environmental and density risk in global sourcing”, International Journal of Physical Distribution and Logistics Management, Vol. 39 No. 10, pp. 861–883.

50. Christopher, M., and Lee, H. (2004), “Mitigating supply chain risk through improved confidence”, International Journal of Physical Distribution and Logistics Management, Vol. 34 No. 5, pp. 388–396.

51. Lockamy, A., and McCormack, K. (2012), “Modeling supplier risks using Bayesian networks”, Industrial Management and Data Systems, Vol. 112 No. 2, pp. 313–333.

52. Hofmann, E. (2011), “Natural hedging as a risk prophylaxis and supplier financing instrument in automotive supply chains”, Supply Chain Management: An International Journal, Vol. 16 No. 2, pp. 128–141.

53. Elzarka, S.M. (2013), “Supply chain risk management: the lessons learned from the Egyptian revolution 2011”, International Journal of Logistics Research and Applications, Vol. 16 No. 6, pp. 482–492.

54. Shukla, A., Lalit, V. A., and Venkatasubramanian, V. (2010), “Optimizing efficiency-robustness trade-offs in supply chain design under uncertainty due to disruptions”, International Journal of Physical Distribution and Logistics Management, Vol. 41 No. 6, pp. 623–646.

55. Shimizu, T., Park, Y. W., and Hong, P. (2012), “Project managers for risk management: case for Japan”, Benchmarking: An International Journal, Vol. 19 No. 4/5, pp. 532–547.

56. Fahimnia, B., Tang, C.S., Davarzani, H. and Sarkis, J. (2014), "Quantitative models for managing supply chain risks: a review", European Journal of Operational Research, Vol. In press, pp. 1–15.

57. Tse, Y. K., Tan, K. H., Chung, S. H., and Lim, M. K. (2011), "Quality risk in global supply network", Journal of Manufacturing Technology Management, Vol. 22 No. 8, pp. 1002–1013.

58. Levary, R. R. (2007), "Ranking foreign suppliers based on supply risk", Supply Chain Management: An International Journal, Vol. 12 No. 6, pp. 392–394.

59. Cannon, A. R., Reyes, P. M., Frazier, G. V., and Prater, E. L. (2008), "RFID in the contemporary supply chain: multiple perspectives on its benefits and risks", International Journal of Operations and Production Management, Vol. 28 No. 5, pp. 433–454.

60. Leat, P., and Revoredo-giha, C. (2013), "Risk and resilience in agri-food supply chains: The case of the ASDA PorkLink supply chain in Scotland", Supply Chain Management: An International Journal, Vol. 18 No. 2, pp. 219–231.

61. Khan, O., and Burnes, B. (2007), "Risk and supply chain management: Creating a research agenda", The International Journal of Logistics Management, Vol. 18 No. 2, pp. 197 – 216.

62. Farooq, S., and Brien, C. O. (2010), "Risk calculations in the manufacturing technology selection process", Journal of Manufacturing Technology Management, Vol. 21 No. 1, pp. 28–49.

63. Cucchiella, F., and Gastaldi, M. (2006), "Risk management in supply chain: A real option approach", Journal of Manufacturing Technology Management, Vol. 17 No. 6, pp. 700–720.

64. Olson, D. L., and Wu, D. (2011), "Risk management models for supply chain: A scenario analysis of outsourcing to China", Supply Chain Management: An International Journal, Vol. 16 No. 6, pp. 401–408.

65. Tsai, M., Liao, C., and Han, C. (2008), "Risk perception on logistics outsourcing of retail chains: model development and empirical verification in Taiwan", Supply Chain Management: An International Journal, Vol. 13 No. 6, pp. 415–424.

66. Shin, K., Shin, Y., Kwon, J., and Kang, S. (2012b), "Risk propagation based dynamic transportation route finding mechanism risk propagation based dynamic transportation route finding mechanism", Industrial Management and Data Systems, Vol. 112 No. 1, pp. 102 – 124.

67. Spekman, R. E., and Davis, E. W. (2004), "Risky business: Expanding the discussion on risk and the extended enterprise", International Journal of Physical Distribution and Logistics Management, Vol. 34 No. 5, pp. 414–433.

68. Kayis, B. (2012), "SCRIS: A knowledge-based system tool for assisting manufacturing organizations in identifying supply chain risks", Journal of Manufacturing Technology Management, Vol. 23 No. 7, pp. 834–852.

69. Baldini, G., Oliveri, F., Braun, M., Seuschek, H., and Hess, E. (2012), "Securing disaster supply chains with cryptography enhanced RFID", Disaster Prevention and Management, Vol. 21 No. 1, pp. 51–70.

70. Giunipero, L. C., and Eltantawy, R. A. (2004), "Securing the upstream supply chain: a risk management approach", International Journal of Physical Distribution and Logistics Management, Vol. 34 No. 9, pp. 698–713.

71. Caridi, M., Perego, A., and Tumino, A. (2013), "Measuring supply chain visibility in the apparel industry", Benchmarking: An International Journal, Vol. 20 No. 1, pp. 25–44.

72. Kavcic, K., and Bertoncelj, A. (2010), "Strategic orientation of organizations: risk management perspective", Kybernetes, Vol. 39 No. 5, pp. 735–749.

73. Blackhurst, J. V., Scheibe, K. P., and Johnson, D. J. (2008), "Supplier risk assessment and monitoring for the automotive industry", International Journal of Physical Distribution and Logistics Management, Vol. 38 No. 2, pp. 143–165.

74. Wu, L. (2009), "Supplier selection under uncertainty: a switching options perspective", Industrial Management and Data Systems, Vol. 109 No. 2, pp. 191–205.

75. Christopher, M., and Holweg, M. (2011), "Supply Chain 2.0: Managing supply chains in the era of turbulence", International Journal of Physical Distribution and Logistics Management, Vol. 41 No. 1, pp. 63–82.

76. Cavinato, J. L. (2004), "Supply chain logistics risks: From the back room to the board room", International Journal of Physical Distribution and Logistics Management, Vol. 34 No. 5, pp. 383–387.

77. Aloini, D., Dulmin, R., Mininno, V., and Ponticelli, S. (2012), "Supply chain management: A review of implementation risks in the construction industry", Business Process Management Journal, Vol. 18 No. 5, pp. 735–761.

78. Olson, E. G. (2010), "Supply chain opportunity in an uncertain economic recovery", Supply Chain Management: An International Journal, Vol. 15 No. 6, pp. 488–492.

79. Laeequddin, M., Waheed, K. A., and Sahay, V. (2009), "Supply chain partner's trust building process through risk evaluation: The perspectives of UAE packaged food industry", Supply Chain Management: An International Journal, Vol. 14 No. 4, pp. 280–290.

80. Juttner, U., and Maklan, S. (2011), "Supply chain resilience in the global financial crisis: an empirical study", Supply Chain Management: An International Journal, Vol. 16 No. 4, pp. 246–259.

81. Wong, C., Skipworth, H., Godsell, J., Achimugu, N., and Wong, C. (2012), "Towards a theory of supply chain alignment enablers: a systematic literature review", Supply Chain Management: An International Journal, Vol. 17 No. 4, pp. 419–437.

82. Blos, M. F., Quaddus, M., Wee, H. M., and Watanabe, K. (2009), "Supply chain risk management (SCRM): a case study on the automotive and electronic industries in Brazil", Supply Chain Management: An International Journal, Vol. 14 No. 4, pp. 247–252.

83. Ritchie, B., and Brindley, C. (2007), "Supply chain risk management and performance: a guiding framework for future development", International Journal of Operations and Production Management, Vol. 27 No. 3, pp. 303–322.

84. Juttner, U. (2005), "Requirements from a practitioner perspective supply chain risk management: Understanding the business requirements", The International Journal of Logistics Management, Vol. 16 No. 1, pp. 120–141.

85. Faisal, M. N., Banwet, D. K., and Shankar, R. (2006b), "Supply chain risk mitigation: modeling the enablers", Business Process Management Journal, Vol. 12 No. 4, pp. 535–552.

86. Rao, S., and Goldsby, T. J. (2009), "Supply chain risks: a review and typology", The International Journal of Logistics Management, Vol. 20 No. 1, pp. 97–123.

87. Williams, Z., Lueg, J. E., and LeMay, S. A. (2008), "Supply chain security: An overview and research agenda", The International Journal of Logistics Management, Vol. 19 No. 2, pp. 254–281.

88. Ellegaard, C. (2008), "Supply risk management in a small company perspective", Supply Chain Management: An International Journal, Vol. 13 No. 6, pp. 425–434.

89. Kern, D., and Moser, R. (2012), "Supply risk management: Model development and empirical analysis", International Journal of Physical Distribution and Logistics Management, Vol. 42 No. 1, pp. 60–82.

90. Micheli, G. J. L., Cagno, E., and Zorzini, M. (2006), "Supply risk management v/s supplier selection to manage the supply risk in the EPC supply chain", Management Research News, Vol. 31 No. 11, pp. 846–866.

91. Sun, S., Hsu, M., and Hwang, W.-J. (2007), "The impact of alignment between supply chain strategy and environmental uncertainty on SCM performance", Supply Chain Management: An International Journal, Vol. 14 No. 3, pp. 201–212.

92. Towill, D. R. (2005), “The impact of business policy on bullwhip induced risk in supply chain management”, International Journal of Physical Distribution and Logistics Management, Vol. 35 No. 8, pp. 555–575.

93. Khan, O., Christopher, M., and Burnes, B. (2008), “The impact of product design on supply chain risk: a case study”, International Journal of Physical Distribution and Logistics Management, Vol. 38 No. 5, pp. 412–432.

94. Zhao, L., Huo, B., Sun, L., and Zhao, X. (2013), “The impact of supply chain risk on supply chain integration and company performance: A global investigation”, Supply Chain Management: An International Journal, Vol. 18 No. 2, pp. 115–131.

95. Adenso-diaz, B., Mena, C., and Liechty, M. (2012), “The impact of supply network characteristics on reliability”, Supply Chain Management: An International Journal, Vol. 17 No. 3, pp. 263–276.

96. Lin, Y., and Zhou, L. (2011), “The impacts of product design changes on supply chain risk: a case study”, International Journal of Physical Distribution and Logistics Management, Vol. 41 No. 2, pp. 162–186.

97. Cousins, P. D., and Bowen, F. (2004), “The role of risk in environment-related supplier initiatives”, International Journal of Operations and Production Management, Vol. 24 No. 6, pp. 554–565.

98. Fischl, M., Scherrer-Rathje, M. and Friedli, T. (2014), “Digging deeper into supply risk: a systematic literature review on price risks”, Supply Chain Management: An International Journal, Vol. 19 No. 5/6, pp. 480–503.

99. Richey J., R. G. (2009), “The supply chain crisis and disaster pyramid preparedness and recovery”, International Journal of Physical Distribution and Logistics Management, Vol. 39 No. 7, pp. 619–628.

100. Koh, S. C. L., and Tan, K. H. (2005), “Translating knowledge of supply chain uncertainty into business strategy and actions”, Journal of Manufacturing Technology Management, Vol. 17 No. 4, pp. 472–485.

101. Ponomarov, S. Y., and Holcomb, M. C. (2009), “Understanding the concept of supply chain resilience”, The International Journal of Logistics Management, Vol. 20 No. 1, pp. 124–143.

102. Stonebraker, P. W., Goldhar, J., and Nassos, G. (2009), “Weak links in the supply chain: measuring fragility and sustainability”, Journal of Manufacturing Technology Management, Vol. 20 No. 2, pp. 161–177.

103. Christtopher, M., and Peck, H. (2004), “Building the resilient supply chain”, The International Journal of Logistics Management, Vol. 15 No. 2, pp. 1–13.

104. Sinha, P. R., Whitman, L. E., and Malzahn, D. (2004), “Methodology to mitigate supplier risk in an aerospace supply chain”, Supply Chain Management: An International Journal, Vol. 9 No. 2, pp. 154–168.

105. Allal-cherif, O., and Maira, S. (2011), “Collaboration as an anti-crisis solution: the role of the procurement function”, International Journal of Physical Distribution and Logistics Management, Vol. 41 No. 9, pp. 860–877.

106. Wieland, A. (2013), “Selecting the right supply chain based on risks”, Journal of Manufacturing Technology Management, Vol. 24 No. 5, pp. 652–668.

107. Grötsch, V.M., Blome, C. and Schleper, M.C. (2013), “Antecedents of proactive supply chain risk management – a contingency theory perspective”, International Journal of Production Research, Vol. 51 No. 10, pp. 2842–2867.

108. Wagner, S. M., and Neshat, N. (2012), “A comparison of supply chain vulnerability indices for different categories of firms”, International Journal of Production Research, Vol. 50 No. 11, pp. 2877–2891.

109. Spiegler, V. L. M., Naim, M. M., and Wikner, J. (2012), “A control engineering approach to the assessment of supply chain resilience”, International Journal of Production Research, Vol. 50 No. 21, pp. 6162–6187.

110. Wang, X., Li, D., and Shi, X. (2012), "A fuzzy model for aggregative food safety risk assessment in food supply chains", Production Planning and Control: The Management of Operations, Vol. 23 No. 5, pp. 377–395.

111. Cagliano, A. C., Marco, A. D., Grimaldi, S., and Rafele, C. (2012), "An integrated approach to supply chain risk analysis", Journal of Risk Research, Vol. 15 No. 7, pp. 817–840.

112. Xiao, R., Cai, Z., and Zhang, X. (2012), "An optimization approach to risk decision-making of closed-loop logistics based on SCOR model", Optimization: A Journal of Mathematical Programming and Operations Research, Vol. 61 No. 10, pp. 1221–1251.

113. Lockamy, A., and McCormack, K. (2010), "Analysing risks in supply networks to facilitate outsourcing decisions", International Journal of Production Research, Vol. 48 No. 2, pp. 593–611.

114. Grötsch, V. M., Blome, C., and Schleper, M. C. (2013), "Antecedents of proactive supply chain risk management – a contingency theory perspective", International Journal of Production Research, Vol. 51 No. 10, pp. 2842–2867.

115. Mizgier, K. J., Jüttner, M. P., and Wagner, S. M. (2012), "Bottleneck identification in supply chain networks", International Journal of Production Research, Vol. 51 No. 5, pp. 1477–1490.

116. Hung, K., and Ryu, S. (2008), "Changing risk preferences in supply chain inventory decisions", Production Planning and Control: The Management of Operations, Vol. 19 No. 8, pp. 770–780.

117. Wagner, S. M., Mizgier, K. J., and Arnez, P. (2012), "Disruptions in tightly coupled supply chain networks: the case of the US offshore oil industry", Production Planning and Control: The Management of Operations, Vol. 25 No. 6, pp. 494-508.

118. Ji, G. (2009), "Ecological supply chains performance evaluation and disruption risk management strategies", Human and Ecological Risk Assessment: An International Journal, Vol. 15 No. 2, pp. 351–370.

119. Dani, S., and Deep, A. (2010), "Fragile food supply chains: reacting to risks", International Journal of Logistics Research and Applications: A Leading Journal of Supply Chain Management, Vol. 13 No. 5, pp. 395–410.

120. Paksoy, T., Pehlivan, N. Y., and Özceylan, E. (2012), "Fuzzy multi-objective optimization of a green supply chain network with risk management that includes environmental hazards", Human and Ecological Risk Assessment: An International Journal, Vol. 18 No. 5, pp. 1120–1151.

121. Khilwani, N., Tiwari, M. K., and Sabuncuoglu, I. (2011), "Hybrid petri-nets for modelling and performance evaluation of supply chains", International Journal of Production Research, Vol. 49 No. 15, pp. 4627–4656.

122. Kumar, S., and Schmitz, S. (2010), "Managing recalls in a consumer product supply chain – root cause analysis and measures to mitigate risks", International Journal of Production Research, Vol. 49 No. 1, pp. 235–253.

123. Colicchia, C., Dallari, F., and Melacini, M. (2010), "Increasing supply chain resilience in a global sourcing context", Production Planning and Control: The Management of Operations, Vol. 21 No. 7, pp. 680–694.

124. Cigolini, R., and Rossi, T. (2010), "Managing operational risks along the oil supply chain", Production Planning and Control: The Management of Operations, Vol. 21 No. 5, pp. 452–467.

125. Tse, Y. K., and Tan, K. H. (2011), "Managing product quality risk in a multi-tier global supply chain", International Journal of Production Research, Vol. 49 No. 1, pp. 139–158.

126. Zou, P. X. W., and Couani, P. (2012), "Managing risks in green building supply chain", Architectural Engineering and Design Management, Vol. 8 No. 2, pp. 143–158.

127. Thun, J., Drüke, M., and Hoenig, D. (2011), "Managing uncertainty – an empirical analysis of supply chain risk management in small and medium-sized enterprises", International Journal of Production Research, Vol. 49 No. 18, pp. 5511–5525.

128. Kumar, S. K., Tiwari, M. K., and Babiceanu, R. F. (2010), “Minimisation of supply chain cost with embedded risk using computational intelligence approaches”, International Journal of Production Research, Vol. 48 No. 13, pp. 3717–3739.

129. Cruz, J. M. (2013), “Mitigating global supply chain risks through corporate social responsibility”, International Journal of Production Research, Vol. 51 No. 13, pp. 3995-4010.

130. Ratnasingam, P. (2006), “Perceived risks in supply chain management e-collaboration”, Journal of Internet Commerce, Vol. 5 No. 4, pp. 105–124.

131. Yang, B., and Yang, Y. (2010), “Postponement in supply chain risk management: a complexity perspective”, International Journal of Production Research, Vol. 48 No. 7, pp. 1901–1912.

132. Samvedi, A., Jain, V., and Chan, F. T. S. (2013), “Quantifying risks in a supply chain through integration of fuzzy AHP and fuzzy TOPSIS”, International Journal of Production Research, Vol. 51 No. 8, pp. 2433–2442.

133. Peck, H. (2006), “Reconciling supply chain vulnerability, risk and supply chain management”, International Journal of Logistics Research and Applications: A Leading Journal of Supply Chain Management, Vol. 9 No. 2, pp. 127–142.

134. Wu, J., Yue, W., Yamamoto, Y., and Wang, S. (2006), “Optimization methods and software risk analysis of a pay to delay capacity reservation contract”, Optimization Methods and Software, Vol. 21 No. 4, pp. 635–651.

135. Mak, H., Shen, Z. M., Mak, H., and Shen, Z. M. A. X. (2012), “Risk diversification and risk pooling in supply chain design”, IIE Transactions, Vol. 44 No. 8, pp. 603–621.

136. Heckmann, I., Comes, T. and Nickel, S. (2014), “A critical review on supply chain risk – Definition, measure and modeling”, Omega, Vol. 52, pp. 119–132.

137. Li, Q. (2007), “Risk, risk aversion and the optimal time to produce”, IIE Transactions, Vol. 39 No. 2, pp. 145–158.

138. Tang, C. S. (2007), “Robust strategies for mitigating supply chain disruptions”, International Journal of Logistics Research and Applications: A Leading Journal of Supply Chain Management, Vol. 9 No. 1, pp. 33–45.

139. Yao, J. M. (2013), “Scheduling optimisation of co-operator selection and task allocation in mass customisation supply chain based on collaborative benefits and risks”, International Journal of Production Research, Vol. 51 No. 8, pp. 2219–2239.

140. Xia, Y., Ramachandran, K., and Gurnani, H. (2011), “Sharing demand and supply risk in a supply chain”, IIE Transactions, Vol. 43 No. 6, pp. 451–469.

141. Wakolbinger, T., and Cruz, J. M. (2011), “Supply chain disruption risk management through strategic information acquisition and sharing and risk-sharing contracts”, International Journal of Production Research, Vol. 49 No. 13, pp. 4063–4084.

142. Chen, J., Sohal, A. S., and Prajogo, D. I. (2013), “Supply chain operational risk mitigation: a collaborative approach”, International Journal of Production Research, Vol. 51 No. 7, pp. 2186–2199.

143. Taylor, P., Chaudhuri, A., Mohanty, B. K., and Singh, K. N. (2013), “Supply chain risk assessment during new product development: a group decision making approach using numeric and linguistic data”, International Journal of Production Research, Vol. 51 No. 10, pp. 2790–2804.

144. Diabat, A., Govindan, K., and Panicker, V. V. (2011), “Supply chain risk management and its mitigation in a food industry”, International Journal of Production Research, Vol. 50 No. 11, pp. 3039–3050.

145. Ho, W., Zheng, T., Yildiz, H. and Talluri, S. (2014), “Supply chain risk management: a literature review”, International Journal of Production Research, Vol. In press, doi:10.1080/00207543.2015.1030467.

146. Oehmen, J., Ziegenbein, A., Alard, R., and Schönsleben, P. (2010), “System-oriented supply chain risk management”, Production Planning and Control: The Management of Operations, Vol. 20 No. 4, pp. 343–361.

147. Oliveira, F., Gupta, V., Hamacher, S., and Grossmann, I. E. (2013),“A Lagrangean decomposition approach for oil supply chain investment planning under uncertainty with risk considerations”, Computers and Chemical Engineering, Vol. 50, 184–195.

148. Radke, A. M., and Tseng, M. M. (2012), “A risk management-based approach for inventory planning of engineering-to-order production”, CIRP Annals - Manufacturing Technology, Vol. 61 No. 1, pp. 387–390.

149. Qiang, P., and Nagurney, A. (2012), “A bi-criteria indicator to assess supply chain network performance for critical needs under capacity and demand disruptions”, Transportation Research Part A, Vol. 46 No. 5, pp. 801–812.

150. Gaur, S., and Ravindran, A. R. (2006), “A bi-criteria model for the inventory aggregation problem under risk pooling”, Computers and Industrial Engineering, Vol. 51 No. 3, pp. 482–501.

151. Cardona-Valdés Y., Álvarez, A., and Ozdemir, D. (2011), “A bi-objective supply chain design problem with uncertainty”, Transportation Research Part C, Vol. 19 No. 5, pp. 821–832.

152. Donk, D. P. V., and Vaart, T. V. D. (2005), “A case of shared resources, uncertainty and supply chain integration in the process industry”, International Journal of Production Economics, Vol. 96 No. 1, pp. 97–108.

153. Jeong, I. (2012),“A centralized-decentralized design of a full return contract for a risk-free manufacturer and a risk-neutral retailer under partial information sharing”, International Journal of Production Economics, Vol. 136 No. 1, pp. 110–115.

154. Xiong, H., Chen, B., and Xie, J. (2011), “A composite contract based on buy back and quantity flexibility contracts”, European Journal of Operational Research, Vol. 210 No. 3, pp. 559–567.

155. Xia, D., and Chen, B. (2011),“A comprehensive decision-making model for risk management of supply chain”, Expert Systems with Applications, Vol. 38 No. 5, pp. 4957–4966.

156. Markmann, C., Darkow, I., and Gracht, H. Von Der. (2013), "A Delphi-based risk analysis — identifying and assessing future challenges for supply chain security in a multi-stakeholder environment", Technological Forecasting and Social Change,Vol. 80 No. 9, pp. 1815-1833.

157. Azadeh, A., and Alem, S. M. (2010), "A flexible deterministic, stochastic and fuzzy data envelopment analysis approach for supply chain risk and vendor selection problem: simulation analysis", Expert Systems with Applications, Vol. 37 no. 12, pp. 7438–7448.

158. Peidro, D., Mula, J., Jiménez, M., and Botella, M. M. (2010),"A fuzzy linear programming based approach for tactical supply chain planning in an uncertainty environment", European Journal of Operational Research, Vol. 205 No. 1, pp. 65–80.

159. Haleh, H., and Hamidi, A. (2011),"A fuzzy MCDM model for allocating orders to suppliers in a supply chain under uncertainty over a multi-period time horizon", Expert Systems with Applications, Vol. 38 No. 8, pp. 9076–9083.

160. Samvedi, A., and Jain, V. (2013), "A grey approach for forecasting in a supply chain during intermittent disruptions". Engineering Applications of Artificial Intelligence, Vol. 26 No. 3, pp. 1044–1051.

161. Ancarani, A., Mauro, C. Di, and Urso, D. D. (2013), "A human experiment on inventory decisions under supply uncertainty". International Journal of Production Economics, Vol. 142 No. 1, pp. 61–73.

162. Ahmadi-javid, A., and Seddighi, A. H. (2013),"A location-routing problem with disruption risk", Transportation Research Part E, Vol. 53, pp. 63–82.

163. Wu, T., Blackhurst, J., and Chidambaram, V. (2006), "A model for inbound supply risk analysis", Computers in Industry, Vol. 57 No. 4, pp. 350–365.

164. Adhitya, A., Srinivasan, R., and Karimi, I. A. (2007),"A model-based rescheduling framework for managing abnormal supply chain events", Computers and Chemical Engineering, Vol. 31 No. 5–6, pp. 496–518.

165. Giannakis, M., and Louis, M. (2011), "A multi-agent based framework for supply chain risk management", Journal of Purchasing and Supply Management, Vol. 17 No. 1, pp. 23–31.

166. Al-e-hashem, S. M. J. M., Malekly, H., and Aryanezhad, M. B. (2011),“A multi-objective robust optimization model for multi-product multi-site aggregate production planning in a supply chain under uncertainty”, International Journal of Production Economics, Vol. 134 No. 1, pp. 28–42.

167. Azaron, A., Brown, K. N., Tarim, S. A., and Modarres, M. (2008), “A multi-objective stochastic programming approach for supply chain design considering risk”, International Journal of Production Economics, Vol. 116 No. 1, pp. 129–138.

168. Silbermayr, L., and Minner, S. (2013), “A multiple sourcing inventory model under disruption risk”, International Journal of Production Economics, doi:10.1016/j.ijpe.2013.03.025(accessed on 7 May 2013).

169. Nickel, S., Saldanha-da-gama, F., and Ziegler, H. (2012), “A multi-stage stochastic supply network design problem with financial decisions and risk management”, Omega, Vol. 40 No. 1, pp. 511–524.

170. Ghezavati, V. R., and Makui, A. (2009), “A new heuristic method for distribution networks considering service level constraint and coverage radius”, Expert Systems with Applications, Vol. 36 No. 3/1, pp. 5620–5629.

171. Buyukozkan, G., and Cifci, G. (2011), “A novel fuzzy multi-criteria decision framework for sustainable supplier selection with incomplete information”, Computers in Industry, Vol. 63 No. 2, pp. 164–174.

172. Pishvaee, M. S., and Torabi, S. A. (2010), “A possibilistic programming approach for closed-loop supply chain network design under uncertainty”, Fuzzy Sets and Systems, Vol. 161 No. 20, pp. 2668–2683.

173. Schmitt, A. J., and Singh, M. (2012), “A quantitative analysis of disruption risk in a multi-echelon supply chain”. International Journal of Production Economics, Vol. 139 No. 1, pp. 22–32.

174. Hishamuddin, H., Sarker, R. A., and Essam, D. (2013),“A recovery model for a two-echelon serial supply chain with consideration of transportation disruption”, Computers and Industrial Engineering, Vol. 64 No. 2, pp. 552–561.

175. Li, C., and Liu, S. (2013),“A robust optimization approach to reduce the bullwhip effect of supply chains with vendor order placement lead time delays in an uncertain environment”, Applied Mathematical Modelling, Vol. 37 No. 3, pp. 707–718.

176. El-Sayed M., Afia, N., and El-KharbotlyA. (2010), “A stochastic model for forward-reverse logistics network design under risk”, Computers and Industrial Engineering, Vol. 58 No. 3, pp. 423–431.

177. Goh, M., Lim, J. Y. S., and Meng, F. (2007), “A stochastic model for risk management in global supply chain networks”, European Journal of Operational Research, Vol. 182 No. 1, pp. 164–173.

178. Santoso, T., Ahmed, S., Goetschalckx, M., and Shapiro, A. (2005), “A stochastic programming approach for supply chain network design under uncertainty”, European Journal of Operational Research, Vol. 167 No. 1, pp. 96–115.

179. Park, S., Lee, T., and Sung, C. S. (2010), “A three-level supply chain network design model with risk-pooling and lead times”, Transportation Research Part E, Vol. 46 No. 5, pp. 563–581.

180. Hung, S. (2011), “Activity-based divergent supply chain planning for competitive advantage in the risky global environment: A DEMATEL-ANP fuzzy goal programming approach”, Expert Systems with Applications, Vol. 38 No. 8, pp. 9053–9062.

181. Chatzidimitriou, K. C., Symeonidis, A. L., and Mitkas, P. A. (2008), “Agent Mertacor: a robust design for dealing with uncertainty and variation in SCM environments”, Expert Systems with Applications, Vol. 35 No. 3, pp. 591–603.

182. Ramanathan, R. (2011), “An empirical analysis on the influence of risk on relationships between handling of product returns and customer loyalty in e-commerce”, International Journal of Production Economics, Vol. 130 No. 2, pp. 255–261.

183. Wagner, S. M., and Bode, C. (2007), “An empirical investigation into supply chain vulnerability”, Journal of Purchasing and Supply Management, Vol. 12 No. 6, pp. 301–312.

184. Wagner, S. M., and Neshat, N. (2010), "Assessing the vulnerability of supply chains using graph theory", International Journal of Production Economics, Vol. 126 No. 1, pp. 121–129.

185. Takata, S., and Yamanaka, M. (2013), "BOM based supply chain risk management", CIRP Annals - Manufacturing Technology, doi:10.1016/j. cirp.2013.03.039 (accessed on 7 May 2013).

186. Ellis, S. C., Henry, R. M., and Shockley, J. (2010), "Buyer perceptions of supply disruption risk: a behavioral view and empirical assessment", Journal of Operations Management, Vol. 28 No. 1, pp. 34–46.

187. Srinivasan, M., Mukherjee, D., and Gaur, A. S. (2011), "Buyer – supplier partnership quality and supply chain performance: Moderating role of risks, and environmental uncertainty", European Management Journal, Vol. 29 No. 4, pp. 260–271.

188. Burgherr, P., Eckle, P., and Hirschberg, S. (2012), "Comparative assessment of severe accident risks in the coal, oil and natural gas chains", Reliability Engineering and System Safety, Vol. 105, pp. 97–103.

189. Li, J., Wang, S., and Cheng, T. C. E. (2010), "Competition and cooperation in a single-retailer two-supplier supply chain with supply disruption", International Journal of Production Economics, Vol. 124 No. 1, pp. 137–150.

190. Buzacott, J. A., and Peng, H. S. (2012), "Contract design for risk sharing partnerships in manufacturing", European Journal of Operational Research, Vol. 218 No. 3, pp. 656–666.

191. Ivanov, D., and Sokolov, B. (2013), "Control and system-theoretic identification of the supply chain dynamics domain for planning, analysis and adaptation of performance under uncertainty", European Journal of Operational Research, Vol. 224 No. 2, pp. 313–323.

192. He, Y., and Zhao, X. (2012), "Coordination in multi-echelon supply chain under supply and demand uncertainty", International Journal of Production Economics, Vol. 139 No. 1, pp. 106–115.

193. Xiao, T., Shi, K., and Yang, D. (2010), "Coordination of a supply chain with consumer return under demand uncertainty", International Journal of Production Economics, Vol. 124 No. 1, pp. 171–180.

194. Cao, E., Wan, C., and Lai, M. (2013), "Coordination of a supply chain with one manufacturer and multiple competing retailers under simultaneous demand and cost disruptions", International Journal of Production Economics, Vol. 141 No. 1, pp. 425–433.

195. Xiao, T., Qi, X., and Yu, G. (2007), "Coordination of supply chain after demand disruptions when retailers compete", International Journal of Production Economics, Vol. 109 No. 1-2, pp. 162–179.

196. Zhang, W., Fu, J., Li, H., and Xu, W. (2012), "Coordination of supply chain with a revenue-sharing contract under demand disruptions when retailers compete", International Journal of Production Economics, Vol. 138 No. 1, pp. 68–75.

197. Matsui, K. (2012), "Cost-based transfer pricing under R and D risk aversion in an integrated supply chain", International Journal of Production Economics, Vol. 139 No. 1, pp. 69–79.

198. Chen, K., and Xiao, T. (2009), "Demand disruption and coordination of the supply chain with a dominant retailer", European Journal of Operational Research, Vol. 197 No. 1, pp. 225–234.

199. Cardoso, S. R., Barbosa-póvoa, A. P. F. D., and Relvas, S. (2013),"Design and planning of supply chains with integration of reverse logistics activities under demand uncertainty", European Journal of Operational Research, Vol. 226 No. 3, pp. 436–451.

200. Galasso, F., and Thierry, C. (2009), "Design of cooperative processes in a customer – supplier relationship: An approach based on simulation and decision theory", Engineering Applications of Artificial Intelligence, Vol. 22 No. 6, pp. 865–881.

201. You, F., and Grossmann, I. E. (2008), "Design of responsive supply chains under demand uncertainty", Computers and Chemical Engineering, Vol. 32 No. 12, pp. 3090–3111.

202. Buyukozkan, G., and Berkol, C. (2011), "Designing a sustainable supply chain using an integrated analytic network process and goal programming approach in quality function deployment", Expert Systems with Applications, Vol. 38 No. 11, pp. 13731–13748.

203. Shin, K., Shin, Y., Kwon, J., and Kang, S. (2012), "Development of risk based dynamic backorder replenishment planning framework using Bayesian belief network", Computers and Industrial Engineering, Vol. 62 No. 3, pp. 716–725.

204. Handfield, R., Warsing, D., and Wu, X. (2009), "(Q,r) Inventory policies in a fuzzy uncertain supply chain environment", European Journal of Operational Research, Vol. 197 No. 2, pp. 609–619.

205. Jouzdani, J., Sadjadi, S. J., and Fathian, M. (2013), "Dynamic dairy facility location and supply chain planning under traffic congestion and demand uncertainty: A case study of Tehran", Applied Mathematical Modelling, doi:10.1016/j.apm.2013.03.059 (accessed on 7 May 2013).

206. Gu, Z., and Zhang, S. (2012), "Endogenous default risk in supply chain and non-linear pricing", International Journal of Production Economics, Vol. 139 No. 1, pp. 90–96.

207. Berle, O., Egil, B., and Rice, J. B. (2011), "Formal vulnerability assessment of a maritime transportation system", Reliability Engineering and System Safety, Vol. 96 No. 6, pp. 696–705.

208. Wu, D. D., Zhang, Y., Wu, D., and Olson, D. L. (2010), "Fuzzy multi-objective programming for supplier selection and risk modeling: a possibility approach", European Journal of Operational Research, Vol. 200 No. 3, pp. 774–787.

209. Yin, S., and Nishi, T. (2012), "Game theoretic approach for global manufacturing planning under risk and uncertainty", Procedia CIRP, Vol. 3, pp. 251–256.

210. Speier, C., Whipple, J. M., Closs, D. J., and Voss, M. D. (2011), "Global supply chain design considerations: Mitigating product safety and security risks", Journal of Operations Management, Vol. 29, No. 7-8, pp. 721–736.

211. Tang, O., and Musa, N. S. (2011), "Identifying risk issues and research advancements in supply chain risk management", International Journal of Production Economics, Vol. 133 No. 1, pp. 25–34.

212. Hua, Z., Li, S., and Liang, L. (2006), "Impact of demand uncertainty on supply chain cooperation of single-period products", International Journal of Production Economics, Vol. 100 No. 2, pp. 268–284.

213. Wu, J., Wang, S., Chao, X., Ng, C. T., and Cheng, T. C. E. (2010), "Impact of risk aversion on optimal decisions in supply contracts", International Journal of Production Economics, Vol. 128 No. 2, pp. 569–576.

214. Li, L., and Zabinsky, Z. B. (2011), "Incorporating uncertainty into a supplier selection problem", International Journal of Production Economics, Vol. 134 No. 2, pp. 344–356.

215. Bidhandi, H. M., and Yusuff, R. M. (2011), "Integrated supply chain planning under uncertainty using an improved stochastic approach", Applied Mathematical Modelling, Vol. 35 No. 6, pp. 2618–2630.

216. Bai, C., andSarkis, J. (2010), "Integrating sustainability into supplier selection with grey system and rough set methodologies", International Journal of Production Economics, Vol. 124 No. 1, pp. 252–264.

217. Tabrizi, B. H., and Razmi, J. (2013), "Introducing a mixed-integer non-linear fuzzy model for risk management in designing supply chain networks", Journal of Manufacturing Systems, Vol. 32 No. 2, pp. 295–307.

218. Kang, J., and Kim, Y. (2012), "Inventory control in a two-level supply chain with risk pooling effect", International Journal of Production Economics, Vol. 135 No. 1, pp. 116–124.

219. Ojala, M., and Hallikas, J. (2006), "Investment decision-making in supplier networks: Management of risk", International Journal of Production Economics, Vol. 104 No. 1, pp. 201–213.

220. Kocabasoglu, C., Prahinski, C., and Klassen, R. D. (2007), "Linking forward and reverse supply chain investments: The role of business uncertainty", Journal of Operations Management, Vol. 25 No. 6, pp. 1141–1160.

221. Oke, A., and Gopalakrishnan, M. (2009), "Managing disruptions in supply chains: A case study of a retail supply chain", International Journal of Production Economics, Vol. 118 No. 1, pp. 168–174.

222. Tse, Y. K., and Tan, K. H. (2012), "Managing product quality risk and visibility in multi-layer supply chain", International Journal of Production Economics, Vol. 139 No. 1, pp. 49–57.

223. Talluri, S., Narasimhan, R., and Chung, W. (2010), "Manufacturer cooperation in supplier development under risk", European Journal of Operational Research, Vol. 207 No. 1, pp. 165–173.

224. Bogataj, D., and Bogataj, M. (2007), "Measuring the supply chain risk and vulnerability in frequency space", International Journal of Production Economics, Vol. 108 No. 1-2, pp. 291–301.

225. Zhang, D. Y., Zeng, Y., Wang, L., Li, H., and Geng, Y. (2011),"Modeling and evaluating information leakage caused by inferences in supply chains", Computers in Industry, Vol. 62 No. 3-2, pp. 351–363.

226. Özkir, V., and Baslıgil, H. (2013), "Multi-objective optimization of closed-loop supply chains in uncertain environment", Journal of Cleaner Production Journal, Vol. 41, pp. 114–125.

227. Ruiz-Femenia R., Guillen-Gosalbez G., Jimenez L., and Caballero, J. A. (2013),"Multi-objective optimization of environmentally conscious chemical supply chains under demand uncertainty", Chemical Engineering Science, Vol. 95, pp. 1–11.

228. Chen, C., and Lee, W. (2004),"Multi-objective optimization of multi-echelon supply chain networks with uncertain product demands and prices", Computers and Chemical Engineering, Vol. 28 No. 6-7, pp. 1131–1144.

229. Tsai, C. (2008), "On supply chain cash flow risks", Decision Support Systems, Vol. 44 No. 4, pp. 1031–1042.

230. Meidan, X., Ye, L., and ZhiQiang, S. (2011), "On the measure method of electronic supply chain risk", Procedia Engineering, Vol.15, pp. 3805–4813.

231. Tazelaar, F., and Snijders, C. (2013), “Operational risk assessments by supply chain professionals: Process and performance”, Journal of Operations Management, Vol. 31 No. 1-2, pp. 37–51.

232. Yeo, W. M., and Yuan, X. (2011), “Optimal inventory policy with supply uncertainty and demand cancellation”, European Journal of Operational Research, Vol. 211 No. 1, pp. 26–34.

233. Xanthopoulos, A., Vlachos, D., and Iakovou, E. (2012),“Optimal newsvendor policies for dual-sourcing supply chains: A disruption risk management framework”, Computers and Operation Research, Vol. 39 No. 2, pp. 350–357.

234. Chen, K., and Xiao, T. (2011), “Ordering policy and coordination of a supply chain with two-period demand uncertainty”, European Journal of Operational Research, Vol. 215 No. 2, pp. 347–357.

235. Kim, H., Lu, J., Kvam, P. H., and Tsao, Y. (2011),“Ordering quantity decisions considering uncertainty in supply-chain logistics operations”, International Journal of Production Economics, Vol. 134 No. 1, pp. 16–27.

236. Xiao, T., Jin, J., Chen, G., Shi, J., and Xie, M. (2010),“Ordering, wholesale pricing and lead-time decisions in a three-stage supply chain under demand uncertainty”, Computers and Industrial Engineering, Vol. 59 No. 4, pp. 840–852.

237. Wu, Y., Dong, M., Fan, T., and Liu, S. (2012), “Performance evaluation of supply chain networks with assembly structure under system disruptions”, Computers and Operation Research, Vol. 39 No. 12, pp. 3229–3243.

238. Tang, C. S. (2006), “Perspectives in supply chain risk management”, International Journal of Production Economics, Vol. 103 No. 2, pp. 451–488.

239. Peng, M., Peng, Y., and Chen, H. (2013), “Post-seismic supply chain risk management: A system dynamics disruption analysis approach for inventory and logistics planning”, Computers and Operation Research, doi:10.1016/j.cor.2013.03.003 (accessed on 7 May 2013).

240. Knemeyer, A. M., Zinn, W., and Eroglu, C. (2009), "Proactive planning for catastrophic events in supply chains", Journal of Operations Management, Vol. 27 No. 2, pp. 141–153.

241. Deng, X., Huet, G., and Tan, S. (2012), "Product decomposition using design structure matrix for intellectual property protection in supply chain outsourcing", Computers in Industry, Vol. 63 No. 6, pp. 632–641.

242. He, Yuanjie., and Zhang, J. (2008),"Random yield risk sharing in a two-level supply chain", International Journal of Production Economics, Vol. 112 No. 2, pp. 769–781.

243. Oh, S., Ryu, K., and Jung, M. (2013),"Reconfiguration framework of a supply network based on flexibility strategies", Computers and Industrial Engineering, Vol. 65 No. 1, pp. 156–165.

244. Lundin, J. F. (2012), "Redesigning a closed-loop supply chain exposed to risks", International Journal of Production Economics, Vol. 140 No. 2, pp. 596–603.

245. Boyle, E., Humphreys, P., and Mcivor, R. (2008), "Reducing supply chain environmental uncertainty through e-intermediation: an organisation theory perspective", International Journal Production Economics, Vol. 114 No. 1, pp. 347–362.

246. Peng, P., Snyder, L. V., Lim, A., and Liu, Z. (2011),"Reliable logistics networks design with facility disruptions", Transportation Research Part B:Methodological, Vol. 45 No. 8, pp. 1190–1211.

247. Hamedi, M., Haghani, A., and Yang, S. (2012), "Reliable transportation of humanitarian supplies in disaster response: model and heuristic", Procedia - Social and Behavioral Sciences, Vol. 54, pp. 1205–1219.

248. Tsao, Y. (2011),"Replenishment policies considering trade credit and logistics risk", ScientiaIranica Transactions E: Industrial Engineering, Vol. 18 No. 3, pp. 753–758.

249. Wang, H., and Hsu, H. (2010),"Resolution of an uncertain closed-loop logistics model: an application to fuzzy linear programs with risk analysis", Journal of Environmental Management, Vol. 91 No. 11, pp. 2148–2162.

250. Lavastre, O., Gunasekaran, A. and Spalanzani, A. (2014), "Effect of firm characteristics, supplier relationships and techniques used on Supply Chain Risk Management (SCRM): an empirical investigation on French industrial firms", International Journal of Production Research, Vol. 52 No. 11, pp. 3381–3403.

251. Wang, Q., Chu, B., Wang, J., and Kumakiri, Y. (2012), "Risk analysis of supply contract with call options for buyers", International Journal of Production Economics, Vol. 139 No. 1, pp. 97–105.

252. Peng, M., Peng, Y. and Chen, H. (2014), "Post-seismic supply chain risk management: a system dynamics disruption analysis approach for inventory and logistics planning", Computers and Operations Research, Vol. 42, pp. 14–24.

253. Tuncel, G., and Alpan, G. (2010), "Risk assessment and management for supply chain networks: a case study", Computers in Industry, Vol. 61 No. 3, 250–259.

254. Vilko, J. P. P., and Hallikas, J. M. (2012), "Risk assessment in multimodal supply chains", International Journal of Production Economics, Vol. 140 No. 2, pp. 586–595.

255. Wu, D. D., Olson, D. L., and Birge, J. R. (2013), "Risk management in cleaner production", Journal of Cleaner Production. Vol. 53 No. 2, pp. 1-6.

256. Schrödl, H., and Turowski, K. (2013), "Risk management in hybrid value creation", Decision Support Systems, doi:10.1016/j.dss.2012.12.042 (accessed on 7 May 2013).

257. Yang, Y.C. (2011), "Risk management of Taiwan's maritime supply chain security", Safety Science, Vol. 49 No. 3, pp. 382–393.

258. Hallikas, J., Karvonen, I., Pulkkinen, U., and Virolainen, V. (2004), "Risk management processes in supplier networks", International Journal of Production Economics, Vol. 90 No. 1, pp. 47–58.

259. Xiao, T., and Yang, D. (2009), "Risk sharing and information revelation mechanism of a one-manufacturer and one-retailer supply chain facing an integrated competitor", European Journal of Operational Research, Vol. 196 No. 3, pp. 1076–1085.

260. Scheller-wolf, A., and Tayur, S. (2009), “Risk sharing in supply chains using order bands — analytical results and managerial insights”, International Journal of Production Economics, Vol. 121 No. 2, pp. 715–727.

261. Arcelus, F. J., Kumar, S., and Srinivasan, G. (2012), “Risk tolerance and a retailer’s pricing and ordering policies within a newsvendor framework”, Omega, Vol. 40 No. 2, pp. 188–198.

262. Simangunsong, E.S., Hendry, L. and Stevenson, M. (2012), “Supply chain uncertainty: a review and theoretical foundation for future research”, International Journal of Production Research, Vol. 50 No. 16, pp. 4493–4523.

263. Ben-tal, A., Chung, B. D., Mandala, S. R., and Yao, T. (2011), “Robust optimization for emergency logistics planning: Risk mitigation in humanitarian relief supply chains”, Transportation Research Part B, Vol. 45 No. 8, pp. 1177–1189.

264. Baghalian, A., Rezapour, S., and Zanjirani, R. (2013), “Robust supply chain network design with service level against disruptions and demand uncertainties: A real-life case”, European Journal of Operational Research, Vol. 227 No. 1, pp. 199–215.

265. Klibi, W., and Martel, A. (2012), “Scenario-based supply chain network risk modeling”, European Journal of Operational Research, Vol. 223 No. 3, pp. 644–658.

266. Sawik, T. (2011a), “Selection of a dynamic supply portfolio in make-to-order environment with risks”, Computers and Operation Research, Vol. 38 No. 4, pp. 782–796.

267. Sawik, T. (2013), “Selection of resilient supply portfolio under disruption risks”, Omega, Vol. 41 No. 2, pp. 259–269.

268. Sawik, T. (2011b), “Selection of supply portfolio under disruption risks”, Omega, Vol. 39 No. 2, pp. 194–208.

269. Soni, U., Jain, V. and Kumar, S. (2014), “Measuring supply chain resilience using a deterministic modeling approach”, Computers and Industrial Engineering, Elsevier Ltd, Vol. 74 No. 1, pp. 11–25.

270. Yu, H., Zeng, A. Z., and Zhao, L. (2009), “Single or dual sourcing: Decision-making in the presence of supply chain disruption risks”, Omega, Vol. 37 No. 4, pp. 788–800.

271. Meena, P. L., Sarmah, S. P., and Sarkar, A. (2011), “Sourcing decisions under risks of catastrophic event disruptions”, Transportation Research Part E, Vol. 47 No. 6, pp. 1058–1074. .

272. Fang, J., Zhao, L., Fransoo, J. C., and Woensel, T. Van. (2013), “Sourcing strategies in supply risk management: an approximate dynamic programming approach”, Computers and Operation Research, Vol. 40 No. 5, pp. 1371–1382.

273. Ketkar, M., and Vaidya, O. S. (2012), “Study of emerging issues in supply risk management in India”, Procedia - Social and Behavioral Sciences, Vol. 37 No. , pp. 57–66.

274. Sun, J., Matsui, M., and Yin, Y. (2012), “Supplier risk management: an economic model of p-chart considered due-date and quality risks”, International Journal of Production Economics, Vol. 139 No. 1, pp. 58–64.

275. Sawik, T. (2011c), “Supplier selection in make-to-order environment with risks”, Mathematical and Computer Modelling, Vol. 53 No. 9-10, pp. 1670–1679.

276. Qi, X., Bard, J. F., and Yu, G. (2004), “Supply chain coordination with demand disruptions”, Omega, Vol. 32 No. 4, pp. 301–312.

277. Chiu, C., Choi, T., and Li, X. (2011), “Supply chain coordination with risk sensitive retailer under target sales rebate”, Automatica, Vol. 47 No. 8, pp. 1617–1625.

278. Schütz, P., Tomasgard, A., and Ahmed, S. (2009), “Supply chain design under uncertainty using sample average approximation and dual decomposition”, European Journal of Operational Research, Vol. 199 No. 2, pp. 409–419.

279. Mahnam, M., Yadollahpour, M. R., Famil-dardashti, V., and Hejazi, S. R. (2009), “Supply chain modeling in uncertain environment with bi-objective approach”, Computers and Industrial Engineering, Vol. 56 No. 4, pp. 1535–1544.

280. Nagurney, A. (2005), “Supply chain networks, electronic commerce, and supply side and demand side risk”, European Journal of Operational Research, Vol. 164 No. 1, pp. 120–142.

281. Wu, D. D., Zhang, Y., and Olson, D. L. (2013), “Supply chain outsourcing risk using an integrated stochastic-fuzzy optimization approach”, Information Sciences, Vol. 235 No. 1 , pp. 242–258.

282. Neiger, D., Rotaru, K., and Churilov, L. (2009), “Supply chain risk identification with value-focused process engineering”, Journal of Operations Management, Vol. 27 No. 2, pp. 154–168.

283. Trkman, P., andMccormack, K. (2009), “Supply chain risk in turbulent environments - a conceptual model for managing supply chain network risk”, International Journal of Production Economics, Vol. 119 No. 2, pp. 247–258.

284. Blome, C., andSchoenherr, T. (2011), “Supply chain risk management in financial crises- a multiple case-study approach”, International Journal of Production Economics, Vol. 134 No. 1, pp. 43–57.

285. Lavastre, O., Gunasekaran, A., and Spalanzani, A. (2012), “Supply chain risk management in French companies”, Decision Support Systems, Vol. 52 No. 4, pp. 828–838.

286. Fitrianto, A. R. (2012), “Supply chain risk management in Shrimp industry before and during mud volcano disaster: an initial concept”, Procedia - Social and Behavioral Sciences, Vol. 65, pp. 427–435.

287. Wu, D. D., and Olson, D. L. (2008), “Supply chain risk simulation, and vendor selection”, International Journal of Production Economics,Vol. 114 No. 2, pp. 646–655.

288. Chen, Y., and Seshadri, S. (2006), “Supply chain structure and demand risk”, Automatica, Vol. 42 No. 8, pp. 1291–1299.

289. Kumar, S. K., and Tiwari, M. K. (2013), “Supply chain system design integrated with risk pooling”, Computers and Industrial Engineering, Vol. 64 No. 2, pp. 580–588.

290. Ross, A. M., Rong, Y., and Snyder, L. V. (2008), “Supply disruptions with time-dependent parameters”, Computers and Operations Research, Vol. 35 No. 11, pp. 3504–3529.

291. Huang, M., Yang, M., Zhang, Y., and Liu, B. (2012), “System dynamics modeling-based study of contingent sourcing under supply disruptions”, Systems Engineering Procedia, Vol. 4, pp. 290 – 297.

292. Sucky, E. (2009), “The bullwhip effect in supply chains — an overestimated problem?”, International Journal of Production Economics, Vol. 118 No. 1, pp. 311–322.

293. Wilson, M. C. (2007), “The impact of transportation disruptions on supply chain performance”, Transportation Research Part E, Vol. 43 No. 4, pp. 295–320.

294. Braunscheidel, M. J., and Suresh, N. C. (2009),“The organizational antecedents of a firm’s supply chain agility for risk mitigation and response”, Journal of Operations Management, Vol. 27 No. 2, pp. 119–140.

295. Tang, C., and Tomlin, B. (2008), “The power of flexibility for mitigating supply chain risks”, International Journal of Production Economics, Vol. 116 No. 1, pp. 12–27.

296. Demirkan, H., and Cheng, H. K. (2008),“The risk and information sharing of application services supply chain”, European Journal of Operational Research, Vol. 187 No. 3, pp. 765–784.

297. Sofyahoglu, C., and Kartal, B. (2012),“The selection of global supply chain risk management strategies by using fuzzy analytical hierarchy process a case from Turkey”, Procedia - Social and Behavioral Sciences, Vol. 58, pp. 1448–1457.

298. Choi, T. Y., and Krause, D. R. (2006), “The supply base and its complexity: Implications for transaction costs, risks, responsiveness, and innovation”, Journal of Operations Management, Vol. 24 No. 5, pp. 637–652.

299. Goetschalckx, M., Huang, E., and Mital, P. (2013), "Trading off supply chain risk and efficiency through supply chain design", Procedia Computer Science, Vol. 16, pp. 658–667.

300. Aggarwal, P., and Ganeshan, R. (2007), "Using risk-management tools on B2Bs: An exploratory investigation", International Journal of Production Economics, Vol. 108 No. 1-2, pp. 2–7.

301. Hahn, G. J., and Kuhn, H. A. (2012), "Value-based performance and risk management in supply chains: a robust optimization approach", International Journal of Production Economics, Vol. 139 No. 1, pp. 135–144.

302. Golicic, S. L., and Smith, C. D. (2013), "A meta-analysis of environmentally sustainable supply chain management practices and firm performance", Journal of Supply Chain Management, Vol. 49 No. 2, pp.78–95.

303. Pettit, T. J., Croxton, K. L., and Fiksel, J. (2013), "Ensuring supply chain resilience: development and implementation of an assessment tool", Journal of Business Logistics, Vol. 34 No.1, pp. 46–76.

304. Chopra, S., Reinhardt, G., and Mohan, U. (2007), "The importance of decoupling recurrent and disruption risks in a supply chain", Naval Research Logistics, Vol. 54 No.5, pp. 544–555.

305. Nagurney, A., and Qiang, Q. (2012), "Fragile networks: Identifying vulnerabilities and synergies in an uncertain age", International Transactions in Operational Research, Vol. 19 no. 1-2, pp. 123–160.

306. Neyens, D. M., and Boyle, L. N. (2006),"A theoretical framework of risk compensation in supply chain management decision making", Proceedings of the Human Factors and Ergonomics Society Annual Meeting, Vol. 50 No. 15, pp. 1488–1491.

307. Faisal, M. N., Banwet, D. K., and Shankar, R. (2006), "An analysis of the dynamics of information risk in supply chains of select SME clusters", Vision: The Journal of Business Perspective, Vol. 10 No. 4, pp. 49–61.

308. Miman, M., and Pohl, E. (2008), "Modelling and analysis of risk and reliability for a contingency logistics supply chain", Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, Vol. 222 No. 4, pp. 477–494.

309. Gümüs, A. T., and Güneri, A. F. (2007), “Multi-echelon inventory management in supply chains with uncertain demand and lead times: literature review from an operational research perspective”, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 221 No. 10, pp. 1553–1569.

310. Srai, J. S., Alinaghian, L. S., and Kirkwood, D. A. (2013),“Understanding sustainable supply network capabilities of multinationals: a capability maturity model approach”, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 227 No. 4, pp. 595–615.

311. Burgholzer, W., Bauer, G., Posset, M., and Jammernegg, W. (2013), “Analysing the impact of disruptions in intermodal transport networks: A micro simulation-based model”, Decision Support Systems, Vol. 54 No. 4, pp. 1580–1586.

312. Nakashima, K., and Gupta, S. M. (2012), “A study on the risk management of multi Kanban system in a closed loop supply chain”. International Journal of Production Economics, Vol. 139 No. 1, pp. 65–68.

313. Choi, T., and Chiu, C. (2012), “Mean-downside-risk and mean-variance newsvendor models: implications for sustainable fashion retailing”, International Journal of Production Economics, Vol. 135 No. 2, pp. 552–560.

314. Tan, Z., Zhao, Y., and Zhang, C. (2012), “Prevention and control strategies and mechanism analysis for risk derivative of coal energy supply chain”, Energy Procedia, Vol. 14, pp. 529 – 532.

315. Noyan, N. (2012), “Risk-averse two-stage stochastic programming with an application to disaster management”, Computers and Operation Research, Vol. 39 No. 3, pp. 541–559.

316. Caliskan-demirag, O., Frank, Y., and Li, J. (2011), “Customer and retailer rebates under risk aversion”, International Journal of Production Economics, Vol. 133 No. 2, pp. 736–750.

317. Dolgui, A., and Prodhon, C. (2007), “Supply planning under uncertainties in MRP environments: a state of the art”, Annual Reviews in Control, Vol. 31 No. 2, pp. 269–279.

318. Liu, L., Li, S., Fan, T., and Chang, X. (2011), "Transportation risk assessment of chemical industry supply chain based on a dual model", Procedia Environmental Sciences: Part A, Vol.11, pp. 393–397.

319. Xie, G., Yue, W., Wang, S., and Keung, K. (2011), "Quality investment and price decision in a risk-averse supply chain", European Journal of Operational Research, Vol. 214 No. 2, pp. 403–410.

320. Merschmann, U., and Thonemann, U. W. (2011), "Supply chain flexibility, uncertainty and firm performance: an empirical analysis of German manufacturing firms", International Journal of Production Economics, Vol. 130 No. 1, pp. 43–53.

321. Carvalho, H., Barroso, A. P., Machado, V. H., Azevedo, S., and Cruz-machado, V. (2012), "Supply chain redesign for resilience using simulation", Computers and Industrial Engineering, Vol. 62 No. 1, pp. 329–341.

322. Zegordi, S. H., and Davarzani, H. (2012), "Developing a supply chain disruption analysis model: application of colored Petri-nets", Expert Systems with Applications, Vol. 39 2, pp. 2102–2111.

323. Ji, G., and Zhu, C. (2012), "A study on emergency supply chain and risk based on urgent relief service in disasters", Systems Engineering Procedia, Vol. 5, pp. 313–325.

324. Mitra, K., Gudi, R. D., Patwardhan, S. C., and Sardar, G. (2009), "Towards resilient supply chains: uncertainty analysis using fuzzy mathematical programming", Chemical Engineering Research and Design, Vol. 87 No. 7, pp. 967–981.

325. Dabbene, F., Gay, P., and Sacco, N. (2008), "Optimisation of fresh-food supply chains in uncertain environments, part II: a case study", Biosystems Engineering, Vol. 99 No. 3, pp. 360–371.

326. Wong, C. Y., Boonitt, S., and Wong, C. W. Y. (2011), "The contingency effects of environmental uncertainty on the relationship between supply chain integration and operational performance", Journal of Operations Management, Vol. 29 No. 6, pp. 604–615.

327. Shoemaker, D., III, J. R., and Wilson, C. (2012), “A governance framework for ICT supply chain risk management”, EDPACS: The EDP Audit, Control, and Security Newsletter, Vol. 46 No. 6, pp. 1–8.

328. Chen, X., Shen, Z. M., Chen, X. U., and Shen, Z. M. A. X. (2012), “An analysis of a supply chain with options contracts and service requirements: An analysis of a supply chain with options contracts and service requirements”, IIE Transactions, Vol. 44 No. 10, pp. 805–819.

329. Pyke, D., and Tang, C. S. (2010), “How to mitigate product safety risks proactively? Process, challenges and opportunities”, International Journal of Logistics Research and Applications: A Leading Journal of Supply Chain Management, Vol. 13 No. 4, pp. 243–256.

330. Ahsan, D. A. (2011), “Farmer’s motivations, risk perceptions and risk management strategies in a developing economy: Bangladesh experience”, Journal of Risk Research, Vol. 14 No. 3, pp. 325–349.

331. Li, H., and Amini, M. (2012), “A hybrid optimisation approach to configure a supply chain for new product diffusion: A case study of multiple-sourcing strategy”, International Journal of Production Research, Vol. 50 No. 11, pp. 3152–3171.

332. Fernando, B., and Federgruen, A. (2005), “Decentralized supply chains with competing retailers under demand uncertainty”, Management Science, Vol. 51 No. 1, pp. 18–29.

333. Ray, S., Li, S., and Song, Y. (2005), “Tailored supply chain decision making and price-sensitive stochastic demand and delivery”, Management Science, Vol. 51 No. 12, pp. 1873–1891.

334. Allen, P. M., Datta, P. P., Christopher, M., Allena, P. M., Dattab, P. P., and Christopherc, M. (2006), “Improving the resilience and performance of organizations using multi-agent modelling of a complex production”, Risk Management, Vol. 8 No. 4, pp. 294–309.

335. Narayanan, V. G. (2005), “Agency costs in a supply chain with demand uncertainty and price competition”, Management Science, Vol. 51 No. 1, pp. 120–132.

336. Cachon, G. P. (2004), “The allocation of inventory risk in a supply chain: Push, pull, and advance-purchase discount contracts”, Management Science, Vol. 50 No. 2, pp. 222–238.

337. Lodree, E. J. (2011), “Pre-storm emergency supplies inventory planning”, Journal of Humanitarian Logistics and Supply Chain Management, Vol. 1 No. 1, pp. 50–77.

338. Cagliano, A. C., Marco, A. D., and Rafele, C. (2012), “A decision-making approach for investigating the potential effects of near sourcing on supply chain”, Strategic Outsourcing: An International Journal, Vol. 5 No. 2, pp. 100–120.

339. Vanvactor, J. D. (2011), “Cognizant healthcare logistics management: Ensuring resilience during crisis”, International Journal of Disaster Resilience in the Built Environment, Vol. 2 No. 3, pp. 245–255.

340. Sawhney, R., and Sumukadas, N. (2005), “Coping with customs clearance uncertainties in global sourcing”, International Journal of Physical Distribution and Logistics Management, Vol. 35 No. 4, pp. 278–295.

341. Subulan, K., Baykasoğlu, A., Özsoydan, F.B., Taşan, a. S. and Selim, H. (2014), “A case-oriented approach to a lead/acid battery closed-loop supply chain network design under risk and uncertainty”, Journal of Manufacturing Systems, Vol.1, In press, doi:10.1016/j.jmsy.2014.07.013.

342. Yanes- Estevez, V., Oreja-Rodriguez, J. R., and Garcıa Perez, A. M. (2010), “Perceived environmental uncertainty in the agrifood supply chain”, British Food Journal, Vol. 112 No. 7, pp. 688–709.

343. Sanchez-rodrigues, V., Potter, A., andNaim, M. M. (2010), “The impact of logistics uncertainty on sustainable transport operations”, International Journal of Physical Distribution and Logistics Management, Vol. 40 No. 1/2, pp. 61–83.

344. Heckmann, I., Comes, T. and Nickel, S. (2015), -A critical review on supply chain risk – definition, measure and modeling, Omega, Vol. 52, pp. 119–132.

345. Ho, W., Zheng, T., Yildiz, H. and Talluri, S. (2015), - Supply chain risk management: a literature review, International Journal of Production Research, In press, April 2015, pp. 1–39.

346. Nepal, B. and Yadav, O.P. (2015), - Bayesian belief network-based framework for sourcing risk analysis during supplier selection, International Journal of Production Research, In press.

347. Prakash, S., Soni, G. and Rathore, A.P.S. (2015), - A grey based approach for assessment of risk associated with facility location in global supply chain, Grey Systems: Theory and Application, Vol. 5 No. 3, pp. 419 – 43.

Appendix-II: AIMMS Codes and screen shots

1. Deterministic Model

```
Model Main_Modeling {
    Section CommonSets {
        Set PlantCumCollectionCenter {
            Index: i;
            Definition:
ElementRange(from:1,to:8,prefix:'Plant Cum
Collection Center-');
        }
        Set DistributionCenter {
            Index: j;
            Definition:
ElementRange(from:1,to:20,prefix:'Distributi
on Center-');
        }
        Set Customer {
            Index: k, k_;
            Definition:
ElementRange(from:1,to:28,prefix:'Customer-
');
        }
        Set DisposalCenter {
            Index: l;
            Definition:
ElementRange(from:1,to:3,prefix:'Disposal
Center-');
        }
    }
    Section DeterministicModel {
        Variable Deterministic_code {
            Range: free;
        }
        Parameter Demand {
            IndexDomain: k;
        }
        Parameter ReturnRate {
            IndexDomain: k;
        }
        Parameter ProductionCap {
            IndexDomain: i;
        }
        Parameter DistributionCap {
            IndexDomain: j;
        }
        Parameter CollectionCap {
            IndexDomain: i;
        }
        Parameter DisposalCap {
            IndexDomain: l;
        }
        Parameter DisposalFraction {
            IndexDomain: (i);
            Range: (0, 1);
        }
        Parameter FCPlant {
            IndexDomain: i;
        }
        Parameter FCDC {
            IndexDomain: j;
        }
Parameter FCDisposalCenter {
    IndexDomain: l;
}
Parameter ProductionCost {
    IndexDomain: i;
}
Parameter DistributionCost {
    IndexDomain: j;
}
Parameter TCPlantToDC {
    IndexDomain: (i,j);
}
Parameter TCDCToCustomer {
    IndexDomain: (j,k);
}
Parameter TCPlantToCustomer {
    IndexDomain: (i,k);
}
Parameter CollectionCost {
    IndexDomain: i;
}
Parameter DisposalCost {
    IndexDomain: l;
}
Parameter RecoveryCost {
    IndexDomain: i;
}
Parameter ReturnTC {
    IndexDomain: (k,i);
}
Parameter DisposalTC {
    IndexDomain: (i,l);
}
Parameter PenaltyCost {
    IndexDomain: k;
    Range: nonnegative;
}
Variable QuantityRecovered {
    IndexDomain: i;
    Range: integer;
}
Variable QuantityRecoveredDirect {
    IndexDomain: (i,k);
    Range: integer;
}
Variable QuantityRecoveredProduct {
    IndexDomain: (i,j);
    Range: {
        {0..inf}
    }
}
Variable QuantityProduced {
    IndexDomain: i;
    Range: integer;
}
Variable QuantityNewProduct {
    IndexDomain: (i,j);
    Range: {
        {0..inf}
    }
}
Variable QuantityDirectToCustomer {
    IndexDomain: (i,k);
    Range: integer;
}
Variable QuantityDCtoCustomer {
```

```
            IndexDomain: (j,k);
            Range: {
                {0..inf}
            }
        }
        Variable QuantityReturn {
            IndexDomain: (k,i);
            Range: {
                {0..inf}
            }
        }
        Variable QuantityDisposed {
            IndexDomain: (i,l);
            Range: {
                {0..inf}
            }
        }
        Variable QuantityNonSatsfiedDemand {
            IndexDomain: k;
            Range: {
                {0..inf}
            }
        }
        Variable PlantOC {
            IndexDomain: i;
            Range: binary;
        }
        Variable DCOC {
            IndexDomain: j;
            Range: binary;
        }
        Variable DisposalCenterOC {
            IndexDomain: l;
            Range: binary;
        }
        Variable FixedCosts {
            Range: free;
            Definition:
sum[i,FCPlant(i)*PlantOC(i)]+sum[j,FCDC(j)*D
COC(j)]+sum[l,FCDisposalCenter(l)*DisposalCe
nterOC(l)];
        }
        Variable ProDisCost {
            Range: free;
            Definition:
sum[(i),(ProductionCost(i))*QuantityProduced
(i)]+sum[(j,k),(DistributionCost(j))*Quantit
yDCtoCustomer(j,k)];
        }
        Variable RecoveryTotal {
            Range: free;
            Definition:
sum[(i),RecoveryCost(i)*QuantityRecovered(i)
]+sum[(k,i),(CollectionCost(i)+ReturnTC(k,i)
)*QuantityReturn(k,i)]+sum[(i,l),(DisposalCo
st(l)+DisposalTC(i,l))*QuantityDisposed(i,l)
];
        }
        Variable AllTC {
            Range: free;
            Definition:
sum[(i,j),TCPlantToDC(i,j)*QuantityRecovered
Product(i,j)]+sum[(i,k),TCPlantToCustomer(i,
k)*QuantityRecoveredDirect(i,k)]+sum[(i,j),T
CPlantToDC(i,j)*QuantityNewProduct(i,j)]+sum
[(i,k),TCPlantToCustomer(i,k)*QuantityDirect
ToCustomer(i,k)]+sum[(j,k),TCDCtoCustomer(j,
k)*QuantityDCToCustomer(j,k)];
        }
        Variable TotalPenelty {
            Range: free;
            Definition:
sum[(k),PenaltyCost(k)*QuantityNonSatsfiedDe
mand(k)];
        }
        Variable TotalCost {
            Range: free;
            Definition:
FixedCosts+ProDisCost+RecoveryTotal+AllTC+su
m[(k),PenaltyCost(k)*QuantityNonSatsfiedDema
nd(k)];
        }
        Constraint
QuantityRecoveredConstraint {
            IndexDomain: i;
            Definition:
QuantityRecovered(i)=sum[(j),QuantityRecover
edProduct(i,j)]+sum[(k),QuantityRecoveredDir
ect(i,k)];
        }
        Constraint
QuantityProducedConstraint {
            IndexDomain: (i);
            Definition:
QuantityProduced(i)=sum[(j),QuantityNewProdu
ct(i,j)]+sum[(k),QuantityDirectToCustomer(i,
k)];
        }
        Constraint DemandRestrictionDirect {
            IndexDomain: k;
            Definition:
sum[(i),QuantityDirectToCustomer(i,k)]+sum[(
i),QuantityRecoveredDirect(i,k)]+sum[(j),Qua
ntityDCtoCustomer(j,k)]+QuantityNonSatsfiedD
emand(k)>=Demand(k);
        }
        Constraint ReturnRestriction {
            IndexDomain: k;
            Definition: {

sum[(i),QuantityReturn(k,i)]<=ReturnRate(k)*
(Demand(k)-QuantityNonSatsfiedDemand(k));
            }
        }
        Constraint FlowPlantToDC {
            IndexDomain: j;
            Definition: {

sum[(i),QuantityNewProduct(i,j)]+sum[(i),Qua
ntityRecoveredProduct(i,j)]=sum[(k),Quantity
DCtoCustomer(j,k)];
            }
        }
        Constraint DisposalRestriction {
            IndexDomain: (i);
            Definition: {

sum[(l),QuantityDisposed(i,l)]=(DisposalFrac
tion(i)*sum[(k),QuantityReturn(k,i)]);
            }
        }
        Constraint RecoverRestriction {
```

```
            IndexDomain: i;
            Definition: {
                QuantityRecovered(i)=((1-
DisposalFraction(i))*sum[(k),QuantityReturn(
k,i)]);
            }
        }
        Constraint PlantCapacityRestriction
{
            IndexDomain: i;
            Definition: {

QuantityProduced(i)<=(ProductionCap(i)*Plant
OC(i));
            }
        }
        Constraint DCCapRestriction {
            IndexDomain: j;
            Definition: {

sum[(k),QuantityDCtoCustomer(j,k)]<=(Distrib
utionCap(j)*DCOC(j));
            }
        }
        Constraint ReturnCapRestriction {
            IndexDomain: i;
            Definition: {

sum[(k),QuantityReturn(k,i)]<=(CollectionCap
(i)*PlantOC(i));
            }
        }
        Constraint DisposalCapRestriction {
            IndexDomain: l;
            Definition: {

sum[(i),QuantityDisposed(i,l)]<=(DisposalCap
(l)*DisposalCenterOC(l));
            }
        }
        Set DetVariable {
            SubsetOf: AllVariables;
            Definition: DeterministicModel *
AllVariables;
        }
        Set DetConstraint {
            SubsetOf: AllConstraints;
            Definition: DeterministicModel *
AllConstraints;
        }
        MathematicalProgram Modeling {
            Objective: TotalCost;
            Direction: minimize;
            Constraints: DetConstraint;
            Variables: DetVariable;
            Type: MIP;
        }
        DeclarationSection
ResultsDeclaration;
    }
    Procedure MainInitialization;
    Procedure MainExecution {
        Body: {
            MainInitialization;
            solve Modeling;
        }
    }
    Procedure SolveDeterministic {
        Body: {
            solve Modeling;
        }
    }
    Procedure MainTermination {
        Body: {
            return 1;
        }
    }
}
```

2. Robust Model

```
Model Main_Modeling {
    Section CommonSets {
        Set PlantCumCollectionCenter {
            Index: i;
            Definition:
ElementRange(from:1,to:8,prefix:'Plant
Cum Collection Center-');
        }
        Set DistributionCenter {
            Index: j;
            Definition:
ElementRange(from:1,to:20,prefix:'Distr
ibution Center-');
        }
        Set Customer {
            Index: k, k_;
            Definition:
ElementRange(from:1,to:28,prefix:'Custo
mer-');
        }
        Set DisposalCenter {
            Index: l;
            Definition:
ElementRange(from:1,to:3,prefix:'Dispos
al Center-');
        }
    }
    Section DeterministicModel {
        Variable RO_AIMMS_Code {
            Range: free;
        }
        Parameter Demand {
            IndexDomain: k;
            Property: Uncertain;
            Region: Box
(Demand.level(k)-
(0.8*Demand.level(k)),Demand.level(k)+(
0.8*Demand.level(k)));
        }
        Parameter ReturnRate {
            IndexDomain: k;
        }
```

```
Parameter ProductionCap {
    IndexDomain: i;
}
Parameter DistributionCap {
    IndexDomain: j;
}
Parameter CollectionCap {
    IndexDomain: i;
}
Parameter DisposalCap {
    IndexDomain: l;
}
Parameter DisposalFraction {
    IndexDomain: (i);
    Range: (0, 1);
}
Parameter FCPlant {
    IndexDomain: i;
}
Parameter FCDC {
    IndexDomain: j;
}
Parameter FCDisposalCenter {
    IndexDomain: l;
}
Parameter ProductionCost {
    IndexDomain: i;
}
Parameter DistributionCost {
    IndexDomain: j;
}
Parameter TCPlantToDC {
    IndexDomain: (i,j);
}
Parameter TCDCToCustomer {
    IndexDomain: (j,k);
}
Parameter TCPlantToCustomer {
    IndexDomain: (i,k);
}
Parameter CollectionCost {
    IndexDomain: i;
}
Parameter DisposalCost {
    IndexDomain: l;
}
Parameter RecoveryCost {
    IndexDomain: i;
}
Parameter ReturnTC {
    IndexDomain: (k,i);
}
Parameter DisposalTC {
    IndexDomain: (i,l);
}
Parameter PenaltyCost {
    IndexDomain: k;
    Range: nonnegative;
```

```
        }
        Variable QuantityRecovered {
            IndexDomain: i;
            Range: integer;
        }
        Variable
QuantityRecoveredDirect {
            IndexDomain: (i,k);
            Range: integer;
        }
        Variable
QuantityRecoveredProduct {
            IndexDomain: (i,j);
            Range: {
                {0..inf}
            }
        }
        Variable
QuantityNonSatsfiedDemand {
            IndexDomain: k;
            Range: {
                {0..inf}
            }
        }
        Variable QuantityProduced {
            IndexDomain: i;
            Range: integer;
        }
        Variable QuantityNewProduct {
            IndexDomain: (i,j);
            Range: {
                {0..inf}
            }
        }
        Variable
QuantityDirectToCustomer {
            IndexDomain: (i,k);
            Range: integer;
        }
        Variable QuantityDCtoCustomer {
            IndexDomain: (j,k);
            Range: {
                {0..inf}
            }
        }
        Variable QuantityReturn {
            IndexDomain: (k,i);
            Range: {
                {0..inf}
            }
        }
        Variable QuantityDisposed {
            IndexDomain: (i,l);
            Range: {
                {0..inf}
            }
        }
        Variable PlantOC {
```

```
            IndexDomain: i;
            Range: binary;
        }
        Variable DCOC {
            IndexDomain: j;
            Range: binary;
        }
        Variable DisposalCenterOC {
            IndexDomain: l;
            Range: binary;
        }
        Variable FixedCosts {
            Range: free;
            Definition:
sum[i,FCPlant(i)*PlantOC(i)]+sum[j,FCDC
(j)*DCOC(j)]+sum[l,FCDisposalCenter(l)*
DisposalCenterOC(l)];
        }
        Variable ProDisCost {
            Range: free;
            Definition:
sum[(i),(ProductionCost(i))*QuantityPro
duced(i)]+sum[(j,k),(DistributionCost(j
))*QuantityDCtoCustomer(j,k)];
        }
        Variable RecoveryTotal {
            Range: free;
            Definition:
sum[(i),RecoveryCost(i)*QuantityRecover
ed(i)]+sum[(k,i),(CollectionCost(i)+Ret
urnTC(k,i))*QuantityReturn(k,i)]+sum[(i
,l),(DisposalCost(l)+DisposalTC(i,l))*Q
uantityDisposed(i,l)];
        }
        Variable AllTC {
            Range: free;
            Definition:
sum[(i,j),TCPlantToDC(i,j)*QuantityReco
veredProduct(i,j)]+sum[(i,k),TCPlantToC
ustomer(i,k)*QuantityRecoveredDirect(i,
k)]+sum[(i,j),TCPlantToDC(i,j)*Quantity
NewProduct(i,j)]+sum[(i,k),TCPlantToCus
tomer(i,k)*QuantityDirectToCustomer(i,k
)]+sum[(j,k),TCDCtoCustomer(j,k)*Quanti
tyDCToCustomer(j,k)];
        }
        Variable TotalPenelty {
            Range: free;
            Definition:
sum[(k),PenaltyCost(k)*QuantityNonSatsf
iedDemand(k)];
        }
        Variable TotalCost {
            Range: free;
            Definition:
FixedCosts+ProDisCost+RecoveryTotal+All
TC+sum[(k),PenaltyCost(k)*QuantityNonSa
tsfiedDemand(k)];
        }
        Constraint
QuantityRecoveredConstraint {
            IndexDomain: i;
            Definition:
QuantityRecovered(i)=sum[(j),QuantityRe
coveredProduct(i,j)]+sum[(k),QuantityRe
coveredDirect(i,k)];
        }
        Constraint
QuantityProducedConstraint {
            IndexDomain: (i);
            Definition:
QuantityProduced(i)=sum[(j),QuantityNew
Product(i,j)]+sum[(k),QuantityDirectToC
ustomer(i,k)];
        }
        Constraint
DemandRestrictionDirect {
            IndexDomain: k;
            Definition:
sum[(i),QuantityDirectToCustomer(i,k)]+
sum[(i),QuantityRecoveredDirect(i,k)]+s
um[(j),QuantityDCtoCustomer(j,k)]+Quant
ityNonSatsfiedDemand(k)>=Demand(k);
        }
        Constraint ReturnRestriction {
            IndexDomain: k;
            Definition: {

sum[(i),QuantityReturn(k,i)]<=ReturnRat
e(k)*(Demand(k)-
QuantityNonSatsfiedDemand(k));
            }
        }
        Constraint FlowPlantToDC {
            IndexDomain: j;
            Definition: {

sum[(i),QuantityNewProduct(i,j)]+sum[(i
),QuantityRecoveredProduct(i,j)]=sum[(k
),QuantityDCtoCustomer(j,k)];
            }
        }
        Constraint DisposalRestriction
{
            IndexDomain: (i);
            Definition: {

sum[(l),QuantityDisposed(i,l)]=(Disposa
lFraction(i)*sum[(k),QuantityReturn(k,i
)]);
            }
        }
        Constraint RecoverRestriction {
            IndexDomain: i;
            Definition: {
```

```
QuantityRecovered(i)=((1-
DisposalFraction(i))*sum[(k),QuantityRe
turn(k,i)]);
            }
        }
        Constraint
PlantCapacityRestriction {
            IndexDomain: i;
            Definition: {

QuantityProduced(i)<=(ProductionCap(i)*
PlantOC(i));
            }
        }
        Constraint DCCapRestriction {
            IndexDomain: j;
            Definition: {

sum[(k),QuantityDCtoCustomer(j,k)]<=(Di
stributionCap(j)*DCOC(j));
            }
        }
        Constraint ReturnCapRestriction
{
            IndexDomain: i;
            Definition: {

sum[(k),QuantityReturn(k,i)]<=(Collecti
onCap(i)*PlantOC(i));
            }
        }
        Constraint
DisposalCapRestriction {
            IndexDomain: l;
            Definition: {

sum[(i),QuantityDisposed(i,l)]<=(Dispos
alCap(l)*DisposalCenterOC(l));
            }
        }
        Set DetVariable {
            SubsetOf: AllVariables;
            Definition:
DeterministicModel * AllVariables;
        }
        Set DetConstraint {
            SubsetOf: AllConstraints;
            Definition:
DeterministicModel * AllConstraints;
        }
        MathematicalProgram Modeling {
            Objective: TotalCost;
            Direction: minimize;
            Constraints: DetConstraint;
            Variables: DetVariable;
            Type: MIP;
        }
```

```
        DeclarationSection
ResultsDeclaration;
        DeclarationSection
RobustDeclarationSection {
            ElementParameter
RC_Modeling {
                Range:
AllGeneratedMathematicalPrograms;
            }
        }
    }
    Procedure MainInitialization;
    Procedure MainExecution {
        Body: {
            MainInitialization;
            solve Modeling;

            RC_Modeling :=
GMP::Instance::GenerateRobustCounterpar
t(
             MP : Modeling,
             UncertainParameters :
AllUncertainParameters,
             UncertaintyConstraints :
AllUncertaintyConstraints,
             );


GMP::Instance::Solve(RC_Modeling);
        }
    }
    Procedure SolveDeterministic {
        Body: {
            solve Modeling;
        }
    }
    Procedure SolveRobust {
        Body: {
            RC_Modeling :=
GMP::Instance::GenerateRobustCounterpar
t(
             MP                     :
Modeling,
             UncertainParameters    :
AllUncertainParameters,
             UncertaintyConstraints :
AllUncertaintyConstraints,
             Name                   :
"Robust Control");


GMP::Instance::Solve(RC_Modeling);
        }
    }
    Procedure MainTermination {
        Body: {
            return 1;
        }
```

```
    }
}
```

3. Robust and reliable model

```
Model Main_Modeling {
    Section CommonSets {
        Set PlantCumCollectionCenter {
            Index: i;
            Definition:
ElementRange(from:1,to:8,prefix:'Plant
Cum Collection Center-');
        }
        Set DistributionCenter {
            Index: j;
            Definition:
ElementRange(from:1,to:20,prefix:'Distr
ibution Center-');
        }
        Set Customer {
            Index: k, k_;
            Definition:
ElementRange(from:1,to:28,prefix:'Custo
mer-');
        }
        Set DisposalCenter {
            Index: l;
            Definition:
ElementRange(from:1,to:3,prefix:'Dispos
al Center-');
        }
    }
    Section DeterministicModel {
        Parameter PlantProbFailure {
            IndexDomain: i;
            Range: free;
        }
        Parameter ReliabilityPlant {
            IndexDomain: i;
            Range: free;
        }
        Parameter DCProbFailure {
            IndexDomain: j;
            Range: free;
        }
        Parameter ReliabilityDC {
            IndexDomain: j;
            Range: free;
        }
        Parameter ProbofleadtimePDC {
            IndexDomain: (i,j);
            Range: free;
        }
        Parameter ProbofleadtimeDSP {
            IndexDomain: (i,k);
            Range: free;
        }
        Parameter
ProbofleadtimeDCtoCust {
            IndexDomain: (j,k);
            Range: free;
        }
        Parameter Demand {
            IndexDomain: k;
            Property: Uncertain;
            Region: Box
(Demand.level(k)-
(0.2*Demand.level(k)),Demand.level(k)+(
0.2*Demand.level(k)));
        }
        Parameter ReturnRate {
            IndexDomain: k;
        }
        Parameter ProductionCap {
            IndexDomain: i;
        }
        Parameter DistributionCap {
            IndexDomain: j;
        }
        Parameter CollectionCap {
            IndexDomain: i;
        }
        Parameter DisposalCap {
            IndexDomain: l;
        }
        Parameter DisposalFraction {
            IndexDomain: (i);
            Range: (0, 1);
        }
        Parameter FCPlant {
            IndexDomain: i;
        }
        Parameter FCDC {
            IndexDomain: j;
        }
        Parameter FCDisposalCenter {
            IndexDomain: l;
        }
        Parameter ProductionCost {
            IndexDomain: i;
        }
        Parameter DistributionCost {
            IndexDomain: j;
        }
        Parameter TCPlantToDC {
            IndexDomain: (i,j);
        }
        Parameter TCDCToCustomer {
            IndexDomain: (j,k);
        }
        Parameter TCPlantToCustomer {
            IndexDomain: (i,k);
        }
        Parameter CollectionCost {
            IndexDomain: i;
```

```
        }
        Parameter DisposalCost {
            IndexDomain: l;
        }
        Parameter RecoveryCost {
            IndexDomain: i;
        }
        Parameter ReturnTC {
            IndexDomain: (k,i);
        }
        Parameter DisposalTC {
            IndexDomain: (i,l);
        }
        Parameter PenaltyCost {
            IndexDomain: k;
            Range: nonnegative;
        }
        Variable QuantityRecovered {
            IndexDomain: i;
            Range: integer;
        }
        Variable
QuantityRecoveredDirect {
            IndexDomain: (i,k);
            Range: integer;
        }
        Variable
QuantityRecoveredProduct {
            IndexDomain: (i,j);
            Range: {
                {0..inf}
            }
        }
        Variable
QuantityNonSatsfiedDemand {
            IndexDomain: k;
            Range: {
                {0..inf}
            }
        }
        Variable QuantityProduced {
            IndexDomain: i;
            Range: integer;
        }
        Variable QuantityNewProduct {
            IndexDomain: (i,j);
            Range: {
                {0..inf}
            }
        }
        Variable
QuantityDirectToCustomer {
            IndexDomain: (i,k);
            Range: integer;
        }
        Variable QuantityDCtoCustomer {
            IndexDomain: (j,k);
            Range: {
                {0..inf}
            }
        }
        Variable QuantityReturn {
            IndexDomain: (k,i);
            Range: {
                {0..inf}
            }
        }
        Variable QuantityDisposed {
            IndexDomain: (i,l);
            Range: {
                {0..inf}
            }
        }
        Variable PlantOC {
            IndexDomain: i;
            Range: binary;
        }
        Variable DCOC {
            IndexDomain: j;
            Range: binary;
        }
        Variable DisposalCenterOC {
            IndexDomain: l;
            Range: binary;
        }
        Variable TotalCost {
            Range: free;
            Definition:
FixedCosts+ProDisCost+RecoveryTotal+All
TC+sum[(k),PenaltyCost(k)*QuantityNonSa
tsfiedDemand(k)];
        }
        Variable FixedCosts {
            Range: free;
            Definition:
sum[i,FCPlant(i)*PlantOC(i)]+sum[j,FCDC
(j)*DCOC(j)]+sum[l,FCDisposalCenter(l)*
DisposalCenterOC(l)];
        }
        Variable RecoveryTotal {
            Range: free;
            Definition:
sum[(i),RecoveryCost(i)*QuantityRecover
ed(i)]+sum[(k,i),(CollectionCost(i)+Ret
urnTC(k,i))*QuantityReturn(k,i)]+sum[(i
,l),(DisposalCost(l)+DisposalTC(i,l))*Q
uantityDisposed(i,l)];
        }
        Variable ProDisCost {
            Range: free;
            Definition: {

sum[(i),[((ProductionCost(i))*Reliabili
tyPlant(i))/(PlantProbFailure(i))]*Quan
tityProduced(i)]
```

```
+sum[(j,k),[((DistributionCost(j))*ReliabilityDC(j))/(DCProbFailure(j))]*QuantityDCtoCustomer(j,k)]
            }
        }
        Variable AllTC {
            Range: free;
            Definition: {

sum[(i,j),TCPlantToDC(i,j)*QuantityRecoveredProduct(i,j)*ProbofleadtimePDC(i,j)]


+sum[(i,j),[1.15*TCPlantToDC(i,j)*QuantityRecoveredProduct(i,j)]*[1-ProbofleadtimePDC(i,j)]]


+sum[(i,j),TCPlantToDC(i,j)*QuantityNewProduct(i,j)*ProbofleadtimePDC(i,j)]


+sum[(i,j),[1.21*TCPlantToDC(i,j)*QuantityNewProduct(i,j)]*[1-ProbofleadtimePDC(i,j)]]


+sum[(i,k),TCPlantToCustomer(i,k)*QuantityDirectToCustomer(i,k)*
ProbofleadtimeDSP(i,k)]

                +sum[(i,k),[1.18*
TCPlantToCustomer(i,k)*
QuantityDirectToCustomer(i,k)]*[1-ProbofleadtimeDSP(i,k)]]


+sum[(j,k),TCDCtoCustomer(j,k)*QuantityDCToCustomer(j,k)*ProbofleadtimeDCtoCust(j,k)]


+sum[(j,k),[1.16*TCDCtoCustomer(j,k)*QuantityDCToCustomer(j,k)]*[1-ProbofleadtimeDCtoCust(j,k)]]
            }
        }
        Constraint
QuantityRecoveredConstraint {
            IndexDomain: i;
            Definition:
QuantityRecovered(i)=sum[(j),QuantityRecoveredProduct(i,j)]+sum[(k),QuantityRecoveredDirect(i,k)];
        }
```

```
        Constraint
QuantityProducedConstraint {
            IndexDomain: (i);
            Definition:
QuantityProduced(i)=sum[(j),QuantityNewProduct(i,j)]+sum[(k),QuantityDirectToCustomer(i,k)];
        }
        Constraint
DemandRestrictionDirect {
            IndexDomain: k;
            Definition:
sum[(i),QuantityDirectToCustomer(i,k)]+sum[(i),QuantityRecoveredDirect(i,k)]+sum[(j),QuantityDCtoCustomer(j,k)]+QuantityNonSatsfiedDemand(k)>=Demand(k);
        }
        Constraint ReturnRestriction {
            IndexDomain: k;
            Definition: {

sum[(i),QuantityReturn(k,i)]<=ReturnRate(k)*(Demand(k)-
QuantityNonSatsfiedDemand(k));
            }
        }
        Constraint FlowPlantToDC {
            IndexDomain: j;
            Definition: {

sum[(i),QuantityNewProduct(i,j)]+sum[(i),QuantityRecoveredProduct(i,j)]=sum[(k),QuantityDCtoCustomer(j,k)];
            }
        }
        Constraint DisposalRestriction
{
            IndexDomain: (i);
            Definition: {

sum[(l),QuantityDisposed(i,l)]=(DisposalFraction(i)*sum[(k),QuantityReturn(k,i)]);
            }
        }
        Constraint RecoverRestriction {
            IndexDomain: i;
            Definition: {

QuantityRecovered(i)=((1-
DisposalFraction(i))*sum[(k),QuantityReturn(k,i)]);
            }
        }
        Constraint
PlantCapacityRestriction {
            IndexDomain: i;
            Definition: {
```

```
QuantityProduced(i)<=(ProductionCap(i)*
PlantOC(i));
            }
        }
        Constraint DCCapRestriction {
            IndexDomain: j;
            Definition: {

sum[(k),QuantityDCtoCustomer(j,k)]<=(Di
stributionCap(j)*DCOC(j));
            }
        }
        Constraint ReturnCapRestriction
{
            IndexDomain: i;
            Definition: {

sum[(k),QuantityReturn(k,i)]<=(Collecti
onCap(i)*PlantOC(i));
            }
        }
        Constraint
DisposalCapRestriction {
            IndexDomain: l;
            Definition: {

sum[(i),QuantityDisposed(i,l)]<=(Dispos
alCap(l)*DisposalCenterOC(l));
            }
        }
        Set DetVariable {
            SubsetOf: AllVariables;
            Definition:
DeterministicModel * AllVariables;
        }
        Set DetConstraint {
            SubsetOf: AllConstraints;
            Definition:
DeterministicModel * AllConstraints;
        }
        MathematicalProgram Modeling {
            Objective: TotalCost;
            Direction: minimize;
            Constraints: DetConstraint;
            Variables: DetVariable;
            Type: MIP;
        }
        DeclarationSection
ResultsDeclaration;
        DeclarationSection
RobustDeclarationSection {
            ElementParameter
RC_Modeling {
                Range:
AllGeneratedMathematicalPrograms;
            }
        }
    }
    Procedure MainInitialization;
    Procedure MainExecution {
        Body: {
            MainInitialization;
            solve Modeling;

            RC_Modeling :=
GMP::Instance::GenerateRobustCounterpar
t(
             MP : Modeling,
             UncertainParameters :
AllUncertainParameters,
             UncertaintyConstraints :
AllUncertaintyConstraints,
             );


GMP::Instance::Solve(RC_Modeling);
        }
    }
    Procedure SolveDeterministic {
        Body: {
            solve Modeling;
        }
    }
    Procedure SolveRobust {
        Body: {
            RC_Modeling :=
GMP::Instance::GenerateRobustCounterpar
t(
             MP                     :
Modeling,
             UncertainParameters    :
AllUncertainParameters,
             UncertaintyConstraints :
AllUncertaintyConstraints,
             Name                   :
"Robust Control");


GMP::Instance::Solve(RC_Modeling);
        }
    }
    Procedure MainTermination {
        Body: {
            return 1;
        }
    }
}
```

4. ROBS Code (Validation)

```
Model Main_Modeling {
    Section CommonSets {
        Set PlantCumCollectionCenter {
            Index: i;
```

```
            Definition:
ElementRange(from:1,to:8,prefix:'Plant
Cum Collection Center-');
        }
        Set DistributionCenter {
            Index: j;
            Definition:
ElementRange(from:1,to:20,prefix:'Distr
ibution Center-');
        }
        Set Customer {
            Index: k, k_;
            Definition:
ElementRange(from:1,to:28,prefix:'Custo
mer-');
        }
        Set DisposalCenter {
            Index: l;
            Definition:
ElementRange(from:1,to:3,prefix:'Dispos
al Center-');
        }
    }
    Section DeterministicModel {
        Parameter PlantProbFailure {
            IndexDomain: i;
            Range: free;
        }
        Parameter DCProbFailure {
            IndexDomain: j;
            Range: free;
        }
        Parameter ProbofleadtimePDC {
            IndexDomain: (i,j);
            Range: free;
        }
        Parameter ProbofleadtimeDSP {
            IndexDomain: (i,k);
            Range: free;
        }
        Parameter
ProbofleadtimeDCtoCust {
            IndexDomain: (j,k);
            Range: free;
        }
        Parameter DeviationDemand {
            IndexDomain: k;
        }
        Parameter BOUDemand {
            IndexDomain: k;
        }
        Parameter BOUDemandF {
            IndexDomain: k;
        }
        Parameter Demand {
            IndexDomain: k;
        }
        Parameter ReturnRate {
            IndexDomain: k;
        }
        Parameter ProductionCap {
            IndexDomain: i;
        }
        Parameter DistributionCap {
            IndexDomain: j;
        }
        Parameter CollectionCap {
            IndexDomain: i;
        }
        Parameter DisposalCap {
            IndexDomain: l;
        }
        Parameter DisposalFraction {
            IndexDomain: (i);
            Range: (0, 1);
        }
        Parameter FCPlant {
            IndexDomain: i;
        }
        Parameter FCDC {
            IndexDomain: j;
        }
        Parameter FCDisposalCenter {
            IndexDomain: l;
        }
        Parameter ProductionCost {
            IndexDomain: i;
        }
        Parameter DistributionCost {
            IndexDomain: j;
        }
        Parameter TCPlantToDC {
            IndexDomain: (i,j);
        }
        Parameter TCDCToCustomer {
            IndexDomain: (j,k);
        }
        Parameter TCPlantToCustomer {
            IndexDomain: (i,k);
        }
        Parameter CollectionCost {
            IndexDomain: i;
        }
        Parameter DisposalCost {
            IndexDomain: l;
        }
        Parameter RecoveryCost {
            IndexDomain: i;
        }
        Parameter ReturnTC {
            IndexDomain: (k,i);
        }
        Parameter DisposalTC {
            IndexDomain: (i,l);
        }
        Parameter PenaltyCost {
```

```
            IndexDomain: k;
            Range: nonnegative;
        }
        Variable QuantityRecovered {
            IndexDomain: i;
            Range: integer;
        }
        Variable
QuantityRecoveredDirect {
            IndexDomain: (i,k);
            Range: integer;
        }
        Variable
QuantityRecoveredProduct {
            IndexDomain: (i,j);
            Range: {
                {0..inf}
            }
        }
        Variable
QuantityNonSatsfiedDemand {
            IndexDomain: k;
            Range: {
                {0..inf}
            }
        }
        Variable QuantityProduced {
            IndexDomain: i;
            Range: integer;
        }
        Variable QuantityNewProduct {
            IndexDomain: (i,j);
            Range: {
                {0..inf}
            }
        }
        Variable
QuantityDirectToCustomer {
            IndexDomain: (i,k);
            Range: integer;
        }
        Variable QuantityDCtoCustomer {
            IndexDomain: (j,k);
            Range: {
                {0..inf}
            }
        }
        Variable QuantityReturn {
            IndexDomain: (k,i);
            Range: {
                {0..inf}
            }
        }
        Variable QuantityDisposed {
            IndexDomain: (i,l);
            Range: {
                {0..inf}
            }
        }
        Variable PlantOC {
            IndexDomain: i;
            Range: binary;
        }
        Variable DCOC {
            IndexDomain: j;
            Range: binary;
        }
        Variable DisposalCenterOC {
            IndexDomain: l;
            Range: binary;
        }
        Variable TotalCost {
            Range: free;
            Definition:
FixedCosts+ProDisCost+RecoveryTotal+All
TC+sum[(k),PenaltyCost(k)*QuantityNonSa
tsfiedDemand(k)];
        }
        Variable FixedCosts {
            Range: free;
            Definition:
sum[i,FCPlant(i)*PlantOC(i)]+sum[j,FCDC
(j)*DCOC(j)]+sum[l,FCDisposalCenter(l)*
DisposalCenterOC(l)];
        }
        Variable RecoveryTotal {
            Range: free;
            Definition:
sum[(i),RecoveryCost(i)*QuantityRecover
ed(i)]+sum[(k,i),(CollectionCost(i)+Ret
urnTC(k,i))*QuantityReturn(k,i)]+sum[(i
,l),(DisposalCost(l)+DisposalTC(i,l))*Q
uantityDisposed(i,l)];
        }
        Variable ProDisCost {
            Range: free;
            Definition: {

!sum[(i),(ProductionCost(i))*QuantityPr
oduced(i)]+sum[(j,k),(DistributionCost(
j))*QuantityDCtoCustomer(j,k)]

sum[(i),[(ProductionCost(i))/(PlantProb
Failure(i))]*QuantityProduced(i)]

+sum[(j,k),[(DistributionCost(j))/(DCPr
obFailure(j))]*QuantityDCtoCustomer(j,k
)]
            }
        }
        Variable AllTC {
            Range: free;
            Definition: {

!sum[(i,j),TCPlantToDC(i,j)*QuantityRec
overedProduct(i,j)]+sum[(i,k),TCPlantTo
```

```
Customer(i,k)*QuantityRecoveredDirect(i
,k)]+sum[(i,j),TCPlantToDC(i,j)*Quantit
yNewProduct(i,j)]+sum[(i,k),TCPlantToCu
stomer(i,k)*QuantityDirectToCustomer(i,
k)]+sum[(j,k),TCDCtoCustomer(j,k)*Quant
ityDCToCustomer(j,k)]

sum[(i,j),TCPlantToDC(i,j)*QuantityReco
veredProduct(i,j)*ProbofleadtimePDC(i,j
)]


+sum[(i,j),[1.3*TCPlantToDC(i,j)*Quanti
tyRecoveredProduct(i,j)]*[1-
ProbofleadtimePDC(i,j)]]


+sum[(i,j),TCPlantToDC(i,j)*QuantityNew
Product(i,j)*ProbofleadtimePDC(i,j)]


+sum[(i,j),[1.3*TCPlantToDC(i,j)*Quanti
tyNewProduct(i,j)]*[1-
ProbofleadtimePDC(i,j)]]


+sum[(i,k),TCPlantToCustomer(i,k)*Quant
ityDirectToCustomer(i,k)*
ProbofleadtimeDSP(i,k)]

                +sum[(i,k),[1.3*
TCPlantToCustomer(i,k)*
QuantityDirectToCustomer(i,k)]*[1-
ProbofleadtimeDSP(i,k)]]


+sum[(j,k),TCDCtoCustomer(j,k)*Quantity
DCToCustomer(j,k)*ProbofleadtimeDCtoCus
t(j,k)]


+sum[(j,k),[1.3*TCDCtoCustomer(j,k)*Qua
ntityDCToCustomer(j,k)]*[1-
ProbofleadtimeDCtoCust(j,k)]]
            }
        }
        Constraint
QuantityRecoveredConstraint {
            IndexDomain: i;
            Definition:
QuantityRecovered(i)=sum[(j),QuantityRe
coveredProduct(i,j)]+sum[(k),QuantityRe
coveredDirect(i,k)];
        }
        Constraint
QuantityProducedConstraint {
            IndexDomain: (i);
            Definition:
QuantityProduced(i)=sum[(j),QuantityNew
Product(i,j)]+sum[(k),QuantityDirectToC
ustomer(i,k)];
        }
        Constraint
DemandRestrictionDirect {
            IndexDomain: k;
            Definition:
sum[(i),QuantityDirectToCustomer(i,k)]+
sum[(i),QuantityRecoveredDirect(i,k)]+s
um[(j),QuantityDCtoCustomer(j,k)]+Quant
ityNonSatsfiedDemand(k)>=Demand(k) +
(DeviationDemand(k)*BOUDemand(k));
        }
        Constraint ReturnRestriction {
            IndexDomain: k;
            Definition: {

sum[(i),QuantityReturn(k,i)]<=(ReturnRa
te(k)*(Demand(k)+(DeviationDemand(k)*BO
UDemandF(k))))-
(ReturnRate(k)*QuantityNonSatsfiedDeman
d(k));
            }
        }
        Constraint ReturnRestrictionTwo
{
            IndexDomain: k;
            Definition: {

sum[(i),QuantityReturn(k,i)]>=(ReturnRa
te(k)*(Demand(k)-
(DeviationDemand(k)*BOUDemandF(k))))-
(ReturnRate(k)*QuantityNonSatsfiedDeman
d(k));
            }
        }
        Constraint FlowPlantToDC {
            IndexDomain: j;
            Definition: {

sum[(i),QuantityNewProduct(i,j)]+sum[(i
),QuantityRecoveredProduct(i,j)]=sum[(k
),QuantityDCtoCustomer(j,k)];
            }
        }
        Constraint DisposalRestriction
{
            IndexDomain: (i);
            Definition: {

sum[(l),QuantityDisposed(i,l)]=(Disposa
lFraction(i)*sum[(k),QuantityReturn(k,i
)]);
            }
        }
        Constraint RecoverRestriction {
```

```
            IndexDomain: i;
            Definition: {
QuantityRecovered(i)=((1-
DisposalFraction(i))*sum[(k),QuantityRe
turn(k,i)]);
            }
        }
        Constraint
PlantCapacityRestriction {
            IndexDomain: i;
            Definition: {
QuantityProduced(i)<=(ProductionCap(i)*
PlantOC(i));
            }
        }
        Constraint DCCapRestriction {
            IndexDomain: j;
            Definition: {
sum[(k),QuantityDCtoCustomer(j,k)]<=(Di
stributionCap(j)*DCOC(j));
            }
        }
        Constraint ReturnCapRestriction
{
            IndexDomain: i;
            Definition: {
sum[(k),QuantityReturn(k,i)]<=(Collecti
onCap(i)*PlantOC(i));
            }
        }
        Constraint
DisposalCapRestriction {
            IndexDomain: l;
            Definition: {
sum[(i),QuantityDisposed(i,l)]<=(Dispos
alCap(l)*DisposalCenterOC(l));
            }
        }
        Set DetVariable {
            SubsetOf: AllVariables;
            Definition:
DeterministicModel * AllVariables;
        }
        Set DetConstraint {
            SubsetOf: AllConstraints;
            Definition:
DeterministicModel * AllConstraints;
        }
        MathematicalProgram Modeling {
            Objective: TotalCost;
            Direction: minimize;
            Constraints: DetConstraint;
            Variables: DetVariable;
            Type: MIP;
        }
    }
    Procedure MainInitialization;
    Procedure MainExecution {
        Body: {
            MainInitialization;
            solve Modeling;
        }
    }
    Procedure MainTermination {
        Body: {
            return 1;
        }
    }
}
```

Screenshots of solutions obtained in AIMMS (reported in Table 4.3)

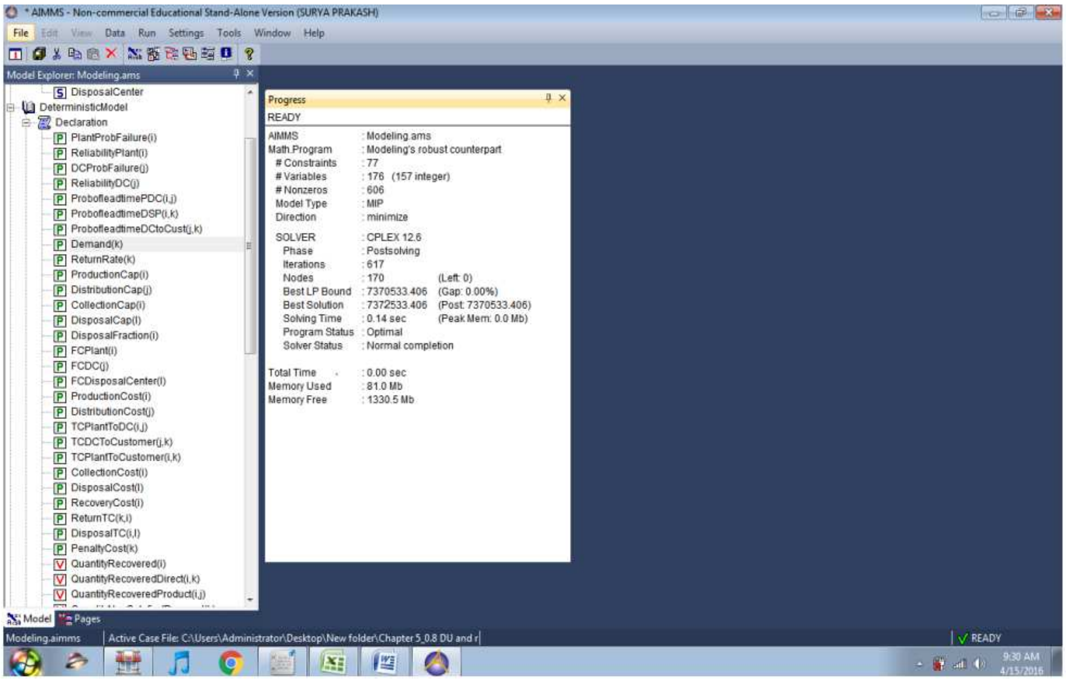


Figure 1: Snapshot of results window of AIMMS environment for RORU model with network-1 of size 3*5*7*2 at 0.2 uncertainty level

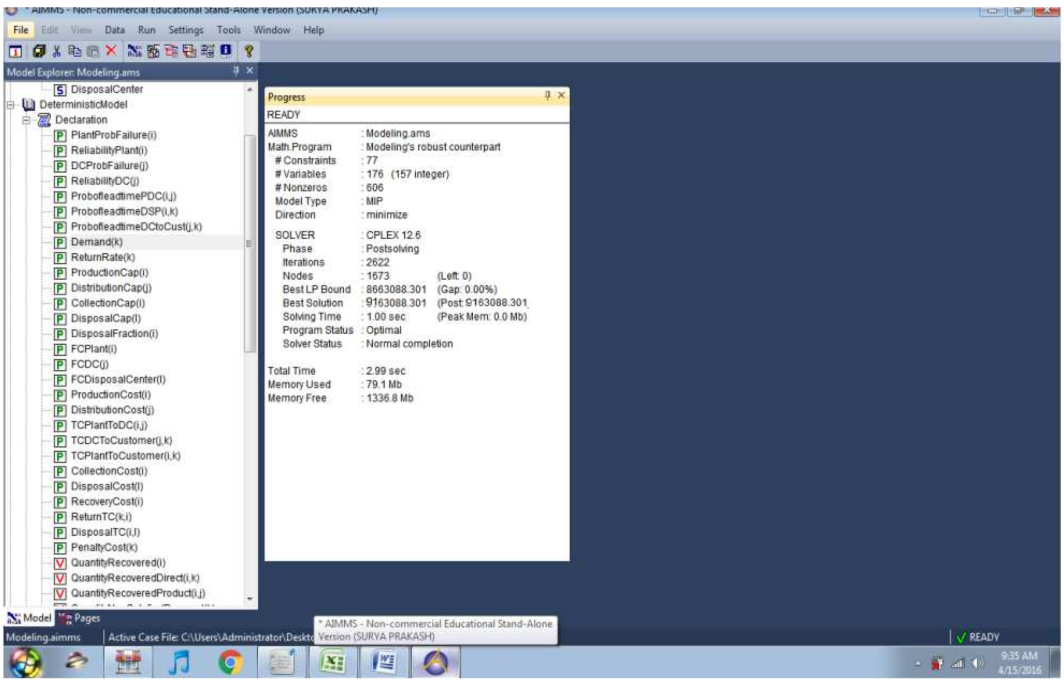


Figure 2: Snapshot of results window of AIMMS environment for RORU model with network-1 of size 3*5*7*2 at 0.4 uncertainty level

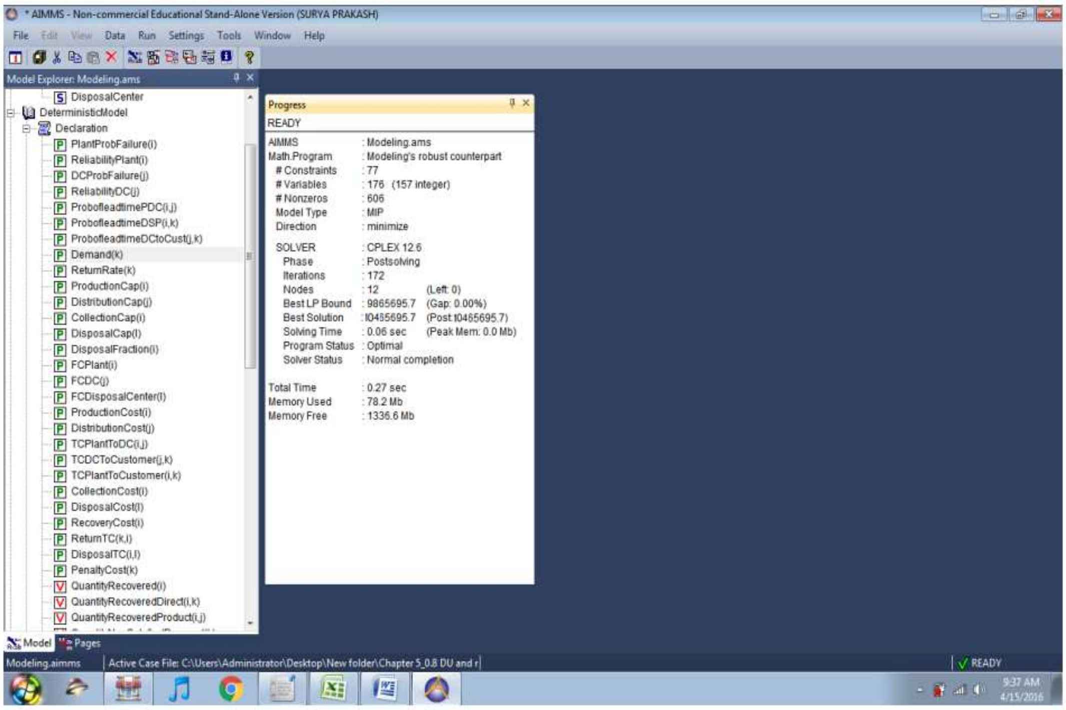


Figure 3: Snapshot of results window of AIMMS environment for RORU model with network-1 of size 3*5*7*2 at 0.6 uncertainty level

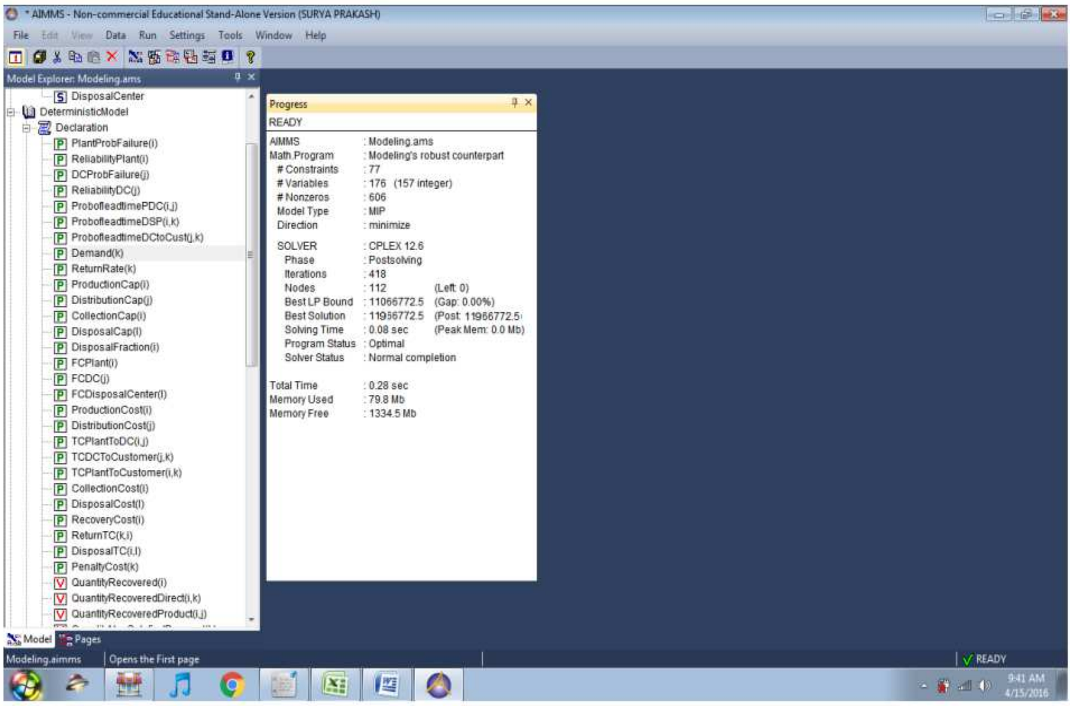


Figure 4: Snapshot of results window of AIMMS environment for RORU model with network-1 of size 3*5*7*2 at 0.8 uncertainty level

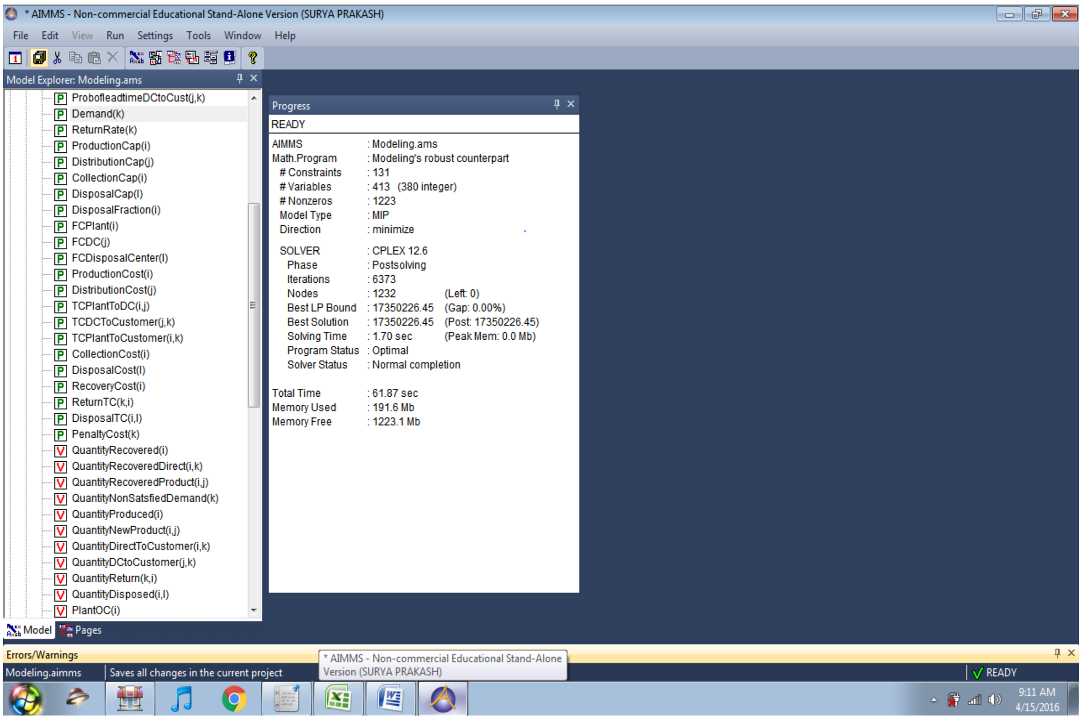


Figure 5: Snapshot of results window of AIMMS environment for RORU model with network-2 of size 4*8*14*2 at 0.2 uncertainty level

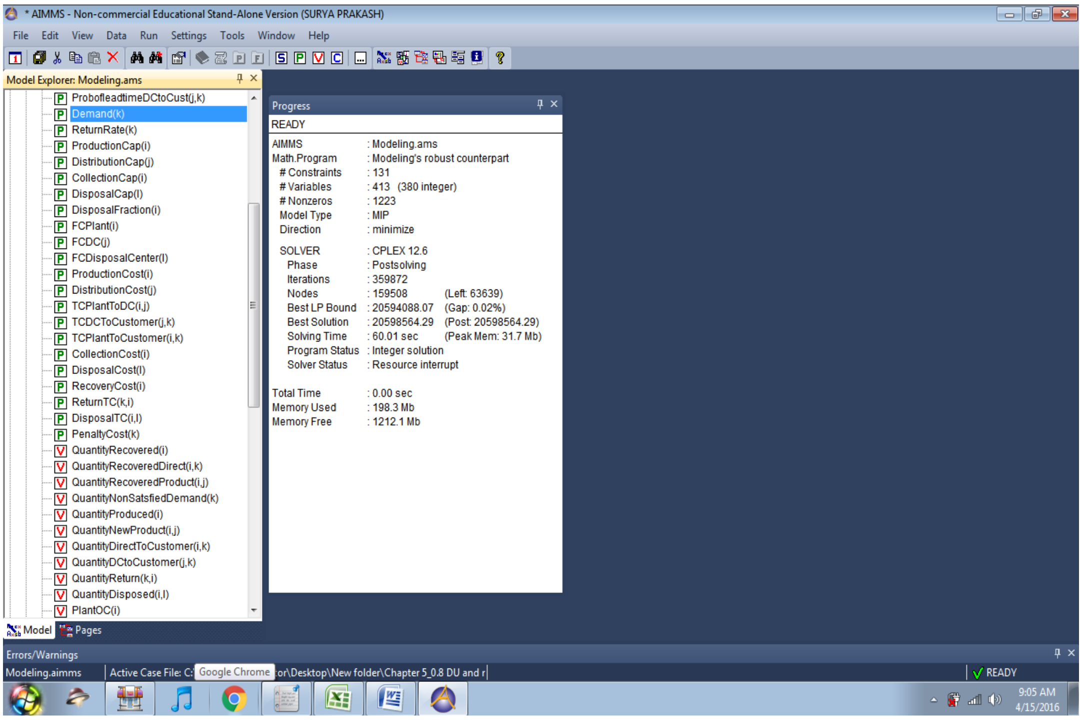


Figure 6: Snapshot of results window of AIMMS environment for RORU model with network-2 of size 4*8*14*2 at 0.4 uncertainty level

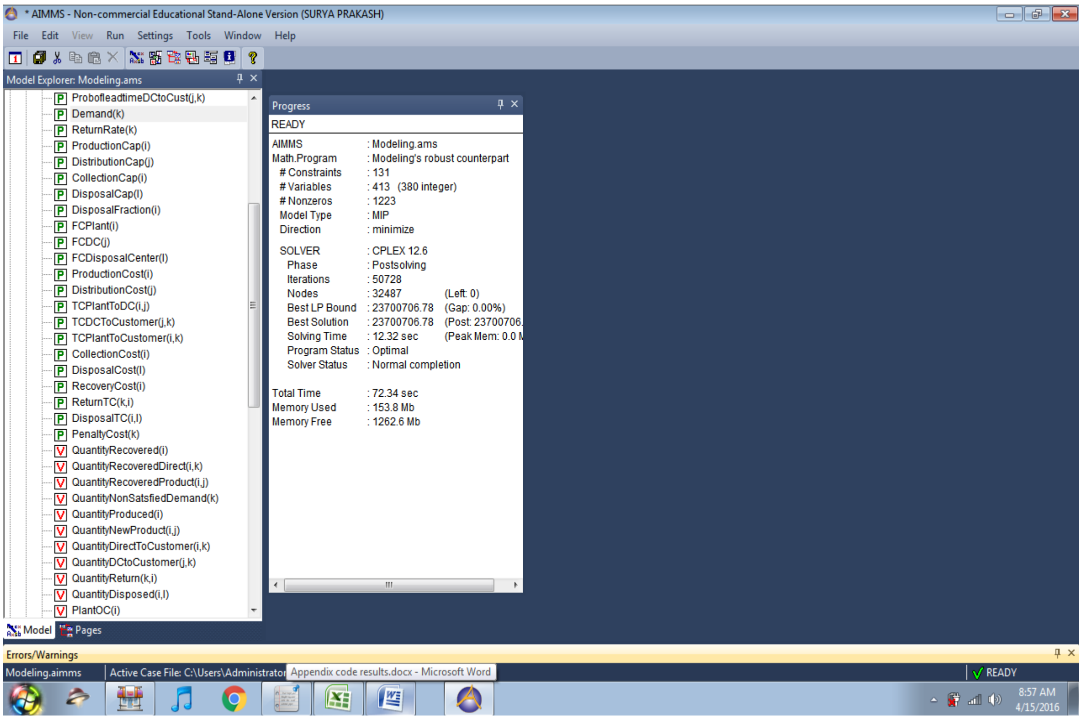


Figure 7: Snapshot of results window of AIMMS environment for RORU model with network-2of size 4*8*14*2 at 0.6 uncertainty level

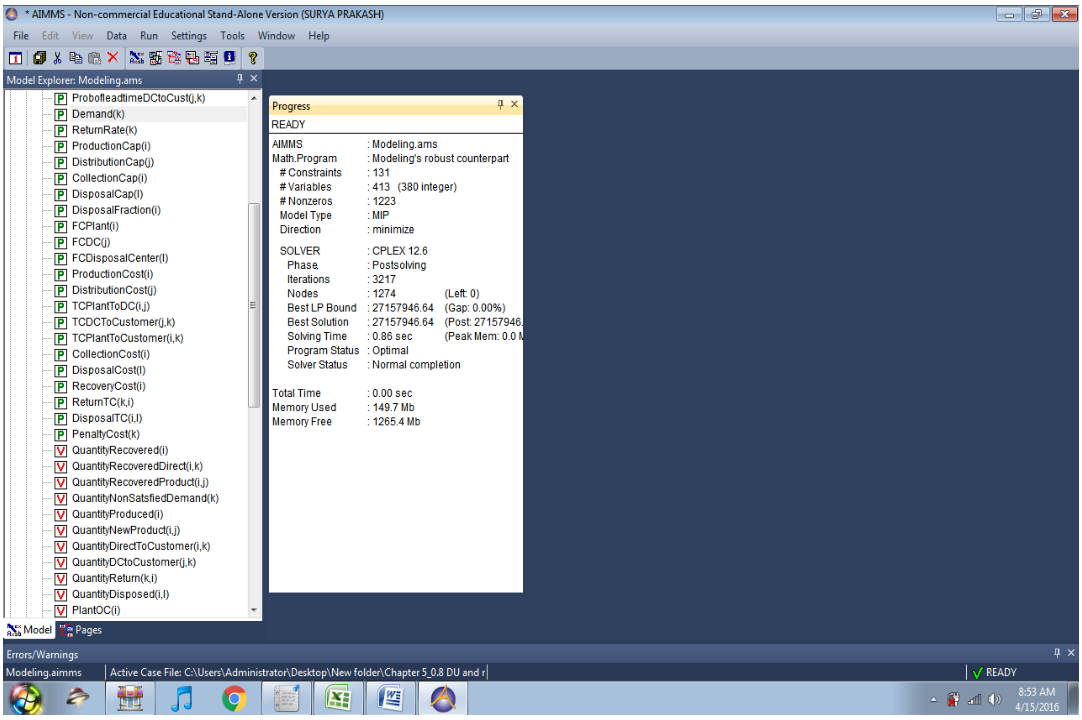


Figure 8: Snapshot of results window of AIMMS environment for RORU model with network-2 of size 4*8*14*2 at 0.8 uncertainty level

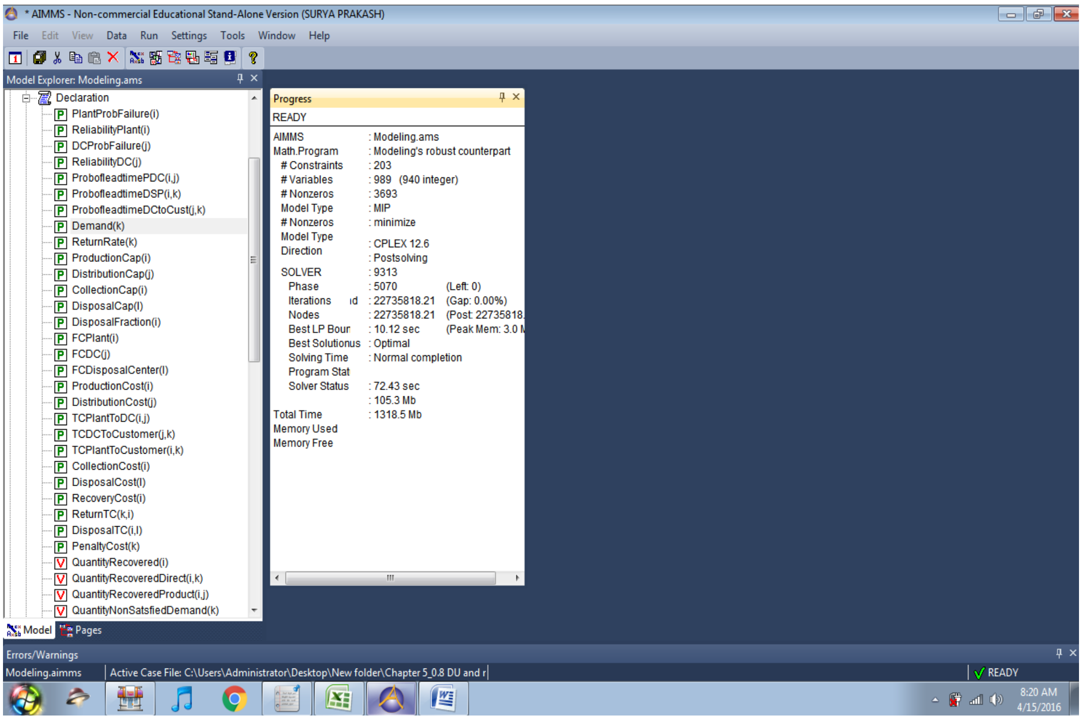


Figure 9: Snapshot of results window of AIMMS environment for RORU model with network-3 of size 6*14*22*2 at 0.2 uncertainty level

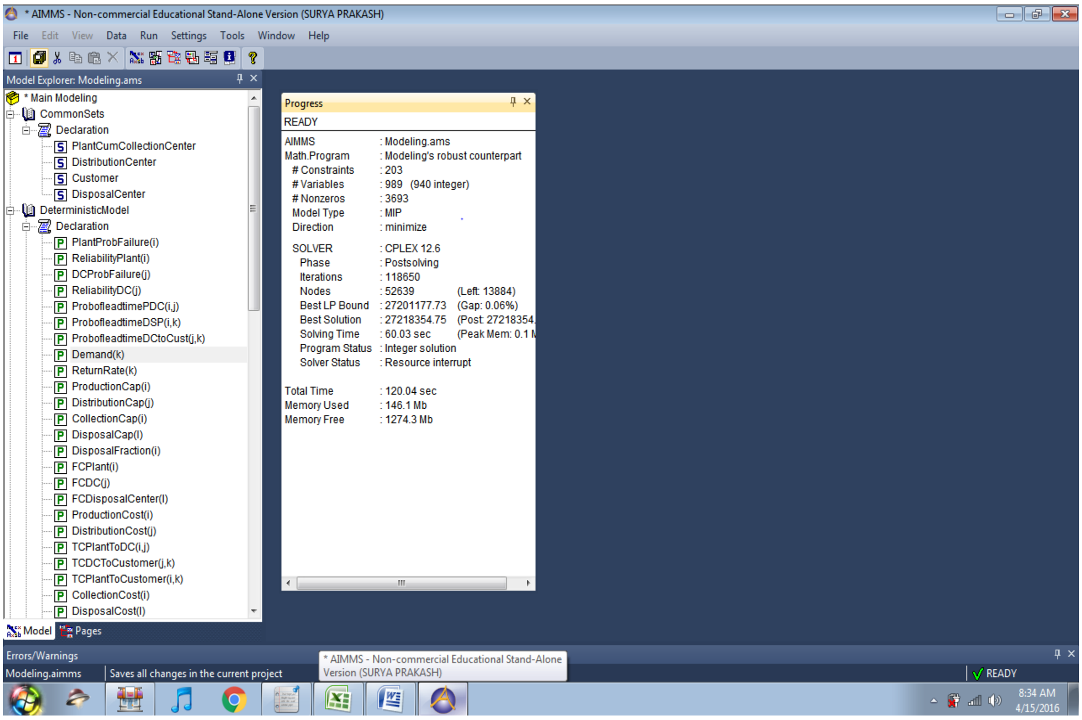


Figure 10: Snapshot of results window of AIMMS environment for RORU model with network-3 of size 6*14*22*2 at 0.4 uncertainty level

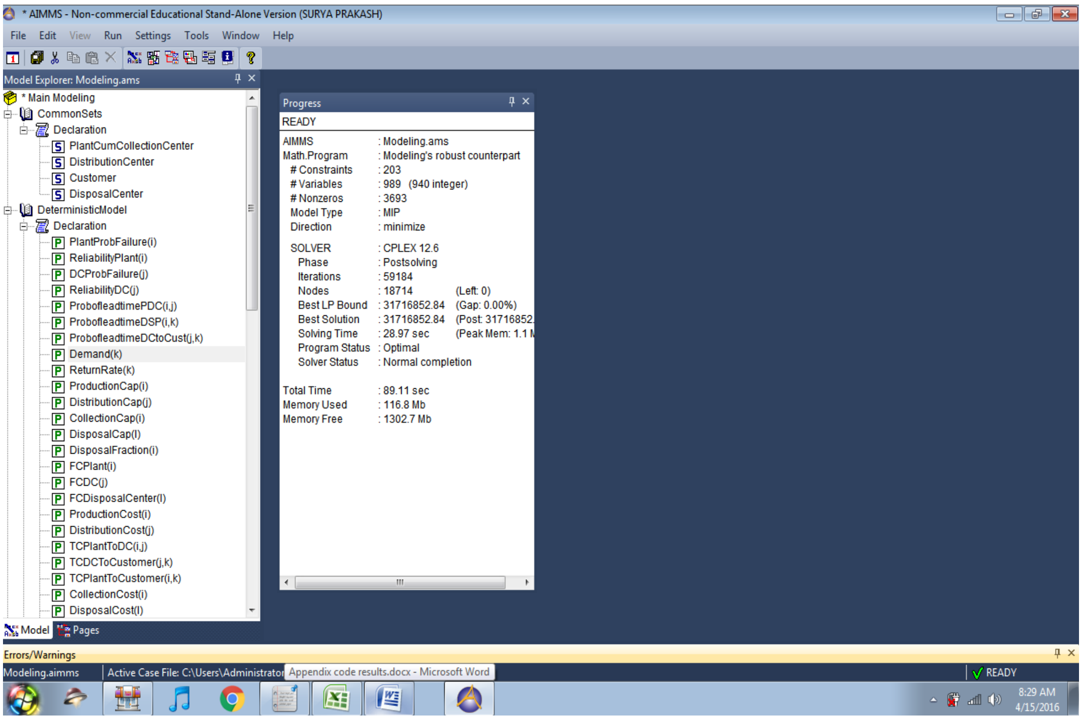


Figure 11: Snapshot of results window of AIMMS environment for RORU model with network-3 of size 6*14*22*2 at 0.6 uncertainty level

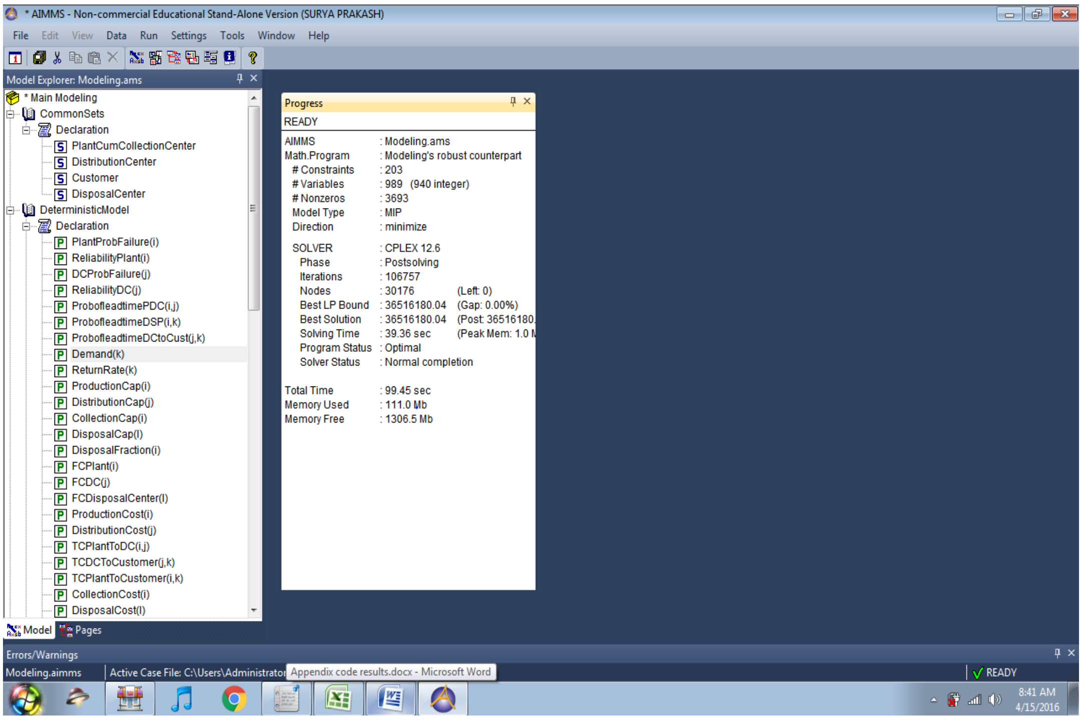


Figure 12: Snapshot of results window of AIMMS environment for RORU model with network-3 of size 6*14*22*2 at 0.8 uncertainty level

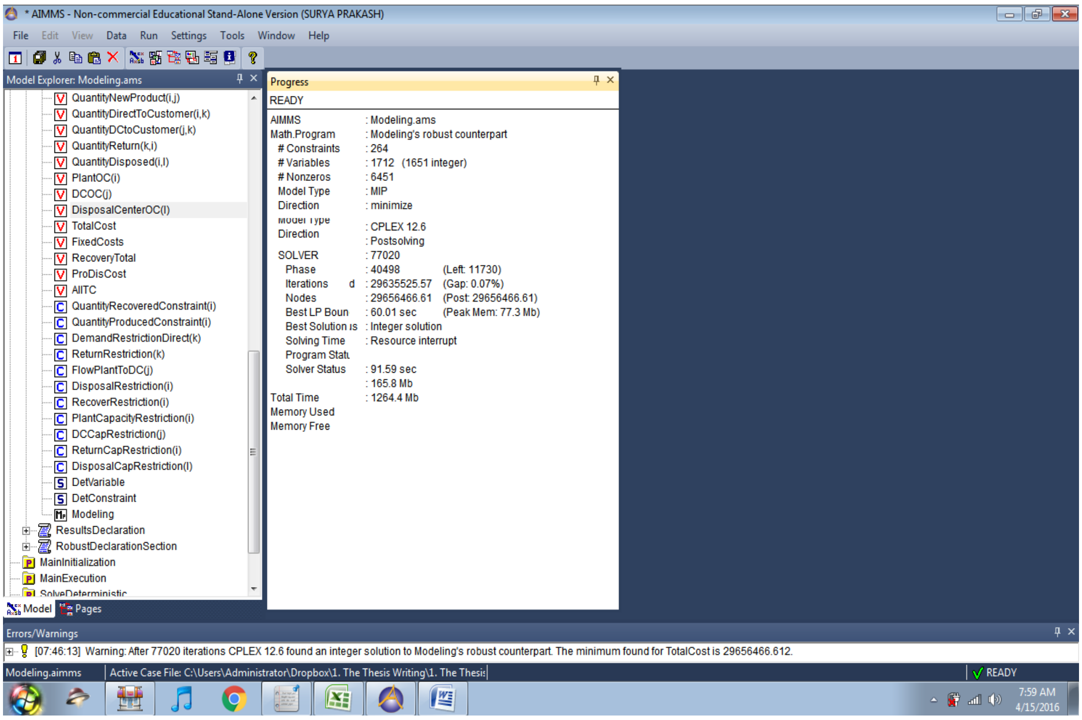


Figure 13: Snapshot of results window of AIMMS environment for RORU model with network -4 of size 8*20*28*3 at 0.2 uncertainty level

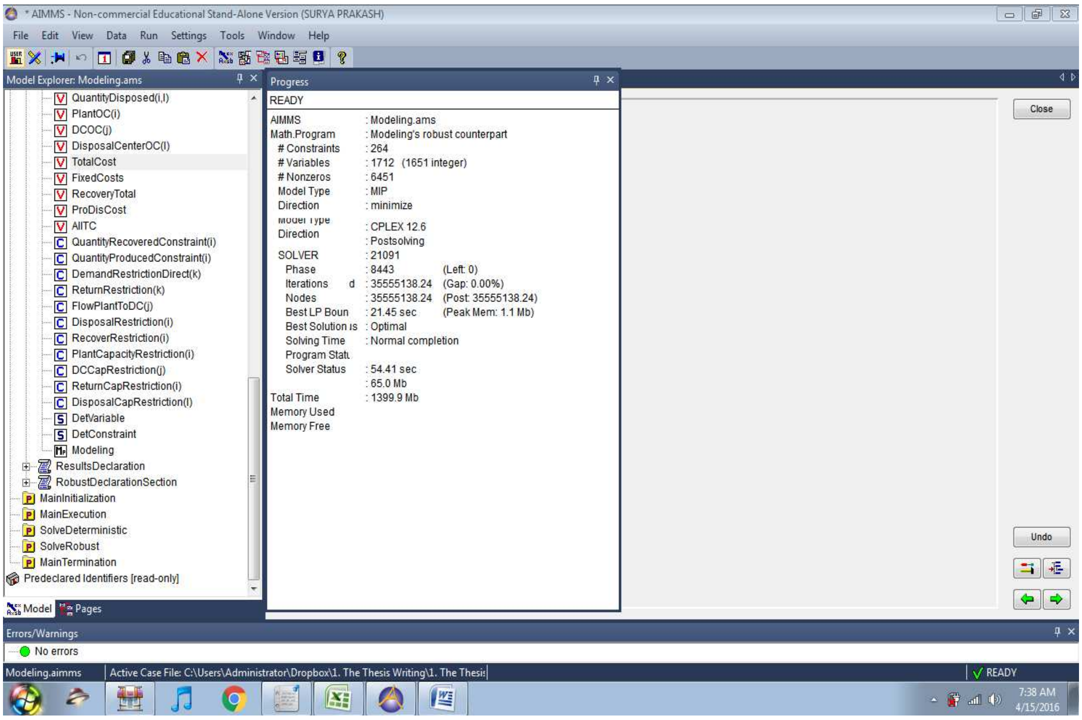


Figure 14: Snapshot of results window of AIMMS environment for RORU model with network-4 of size 8*20*28*3 at 0.4 uncertainty level

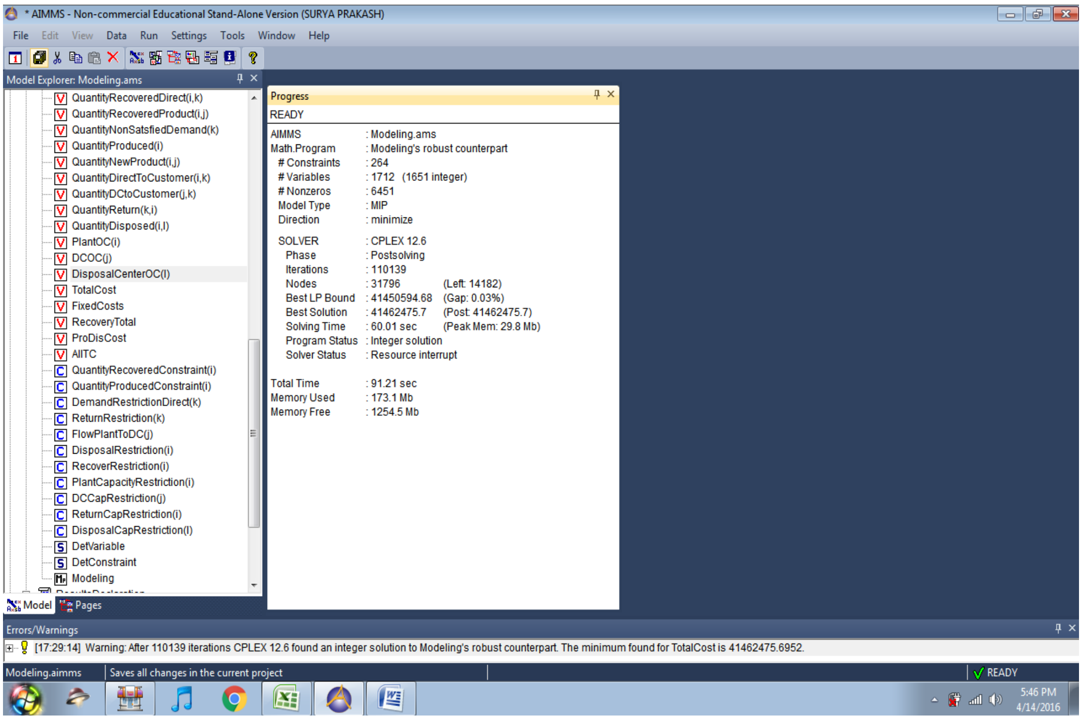


Figure 15: Snapshot of results window of AIMMS environment for RORU model with network-4 of size 8*20*28*3 at 0.6 uncertainty level

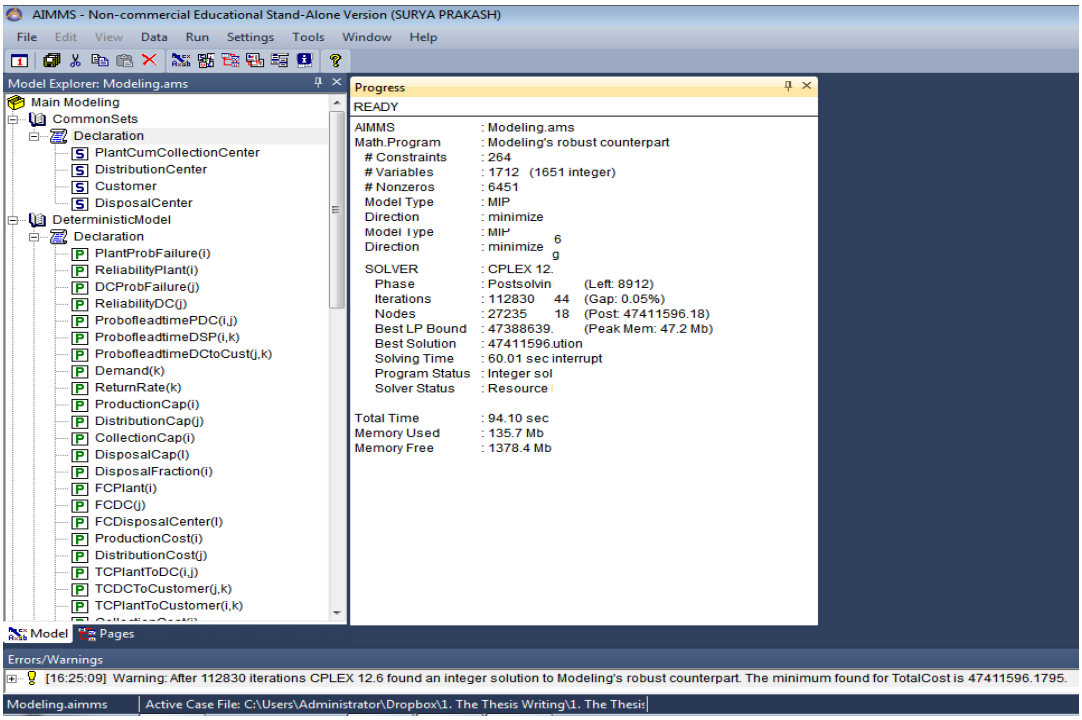


Figure 16: Snapshot of results window of AIMMS environment for RORU model with network-4 of size 8*20*28*3 at 0.8 uncertainty level

Appendix-III: List of publications

Papers published or accepted in international journals:

1. **Surya Prakash**, Gunjan Soni, Ajay Pal Singh Rathore (2015), *"A grey based approach for assessment of risk associated with facility location in global supply chain"*, Grey Systems: Theory and Application, Vol. 5, No.3, pp 419-436, Emerald (UK).
2. **Surya Prakash**, Gunjan Soni, Ajay Pal Singh Rathore (2015), *"Mitigating risk in perishable food supply chain using interpretive structural modeling"* (ISM), Benchmarking: An International Journal. Vol: 24, No.1, Emerald (UK) (In press).
3. **Surya Prakash**, Gunjan Soni, Ajay Pal Singh Rathore (2016), *"Embedding Risk in Closed-Loop Supply Chain Network Design: Case of a Hospital Furniture Manufacturer"*, Journal of Modelling in Management, Emerald (UK) (In press).
4. **Surya Prakash**, Gunjan Soni, Ajay Pal Singh Rathore (2016), *"Multi-echelon Closed-Loop Supply Chain Network Design and Configuration under Supply Risks and Logistics Risks"*, International Journal of Logistics Systems and Management, Inderscience (In press).
5. **Surya Prakash**, Gunjan Soni, Ajay Pal Singh Rathore (2016), *"A critical analysis of supply chain risk management content: A structured literature review"*, Journal of Advances in Management Research, Emerald (UK) (In press).
6. **Surya Prakash**, Gunjan Soni, Satydev (2016), *"Prioritization and assessment of collaboration decisions for supply chain with risk considerations using TOPSIS"*, International Journal of Advanced Operations Management, Inderscience (In press).

Papers under review for publication in international journals:

1. **Surya Prakash**, Gunjan Soni, Ajay Pal Singh Rathore (2014), Robust optimization for closed-loop e-supply chain network design and planning with direct shipping from plant and shipping through distribution center under demand uncertainty, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, (*Communicated).

Papers published in proceedings of peer reviewed international conferences:

1. **Surya Prakash**, Gunjan Soni, Ajay Pal Singh Rathore, Sameer Mittal (2014), *"Information Risks Modeling in e-business Supply Chain using AHP, Recent Advances in Engineering and Computational Sciences"* (RAECS), IEEE Xplore Digital Library, pp. 1–5. ISBN: 978-1-4799-2290-1.
2. **Surya Prakash**, Gunjan Soni, Ajay Pal Singh Rathore, Sameer Mittal (2014), *"Systematically Investigating Literature of Supply Chain Risk Management: A Review for Risk Prioritisation",* 5th International & 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR), Vol. 1, pp. 825–1–6. ISBN: 978-8-19274-610-4.
3. **Surya Prakash**, Sandeep, Gunjan Soni, Ajay Pal Singh Rathore (2013), *"Supply Chain Operations Reference (SCOR) Model: An Overview and A Structured Literature Review of Its Applications*", Proceedings of International Conference on Smart Technologies for Mechanical Engineering-2013, Delhi Technological University, p. pp–55. ISBN: 978-93-83083-35-0.
4. **Surya Prakash**, Gunjan Soni, Ajay Pal Singh Rathore, S.K. Agrawal (2014), *"A systematic investigation of risk mitigation for supply chain risk management",* 3rd International conference on supply chain management on Best Practices in Supply Chain Management, Organized by Indian Institution of Industrial Engineering (IIIE) (BPSCM-2014) on November 28th-30th, 2014 at Udaipur, India, p. 09.

Appendix-IV: Biographical profile of researcher

Surya Prakash is born in Nagwai (Jalesar), Uttar Pradesh (India). He did his B.E. in Mechanical Engineering from Dr. B. R. Ambedkar University, Agra (India) and M.E. in Manufacturing Systems Engineering from Birla Institute of Technology and Science, Pilani (BITS-Pilani) (India). He is presently working as Assistant Professor for Mechanical Engineering Department, School of Engineering, BML Munjal University, Gurgaon and pursuing Ph.D. form Malaviya National Institute of Technology, Jaipur, India. He had worked as an Assistant Professor in Mechanical Engineering Department, The NorthCap University, Gurgaon, India. He has over four years teaching experience at undergraduate and graduate levels. His areas of research interest are robust optimization, risk management, supply chain management, network optimization, artificial intelligence, and operations management.

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Chapter 1

Introduction

1.1 Introduction

In today's globalized, aggressive and uncertain business environment, companies continue to discover that designing and operating a robust and reliable supply chain is essential to meet customer demands and maintain profits (Solo, 2009). For the contemporary firms, supply chain management (SCM) is playing a vital role to remain competitive and integrated with world economies. A supply chain has to manage the flow of a large amount of information and variety of products across all its echelons. The organizations have to deliver the right quantities, to the right places at the right time with the minimum costs and at best customer service levels. Apart from it, the organizations need to leverage performance on the frontiers of product variety, product customization, service, quality improvement, flexibility, technology, employee involvement, environmental and sustainability issues. Such expectations subject the supply chain members under a lot of pressure to become efficient.

An efficient supply chain can reduce costs and raise the profit of a firm. One of the most important features of SCM is supply chain network design (SCND) (Dai and Zheng, 2015). The SCND involves defining network topology to serve the customers in the best way. When a forward and reverse logistics network is considered simultaneously, a closed-loop supply chain (CLSC) network is formed and it has a bidirectional flow of products (Dai and Zheng, 2015). Because of interdependent decisions in CLSC environment, considering the designing of forward and reverse network separately lead to suboptimal results. The interdependence in supply chain can be understood by the complex nature of relations and decisions among supply chain members such as supplier, manufacturer and end user. Thus, decisions regarding forward and reverse flow in CLSC should be considered simultaneously. Apart from it, uncertainty in designing supply chain network is the another important concern, and inherent uncertainty of reverse logistics flow makes the problem harder to address (Dai and Zheng, 2015). All such challenges

Robust supply chain design and optimization under risks and uncertainties

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