DEVELOPMENT OF CAPACITY RESERVATION CONTRACT MODELS UNDER SUPPLY CHAIN DISRUPTIONS

by

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AUTHOR'S DECLARATION

I, Sidharath Joshi, declare that the research work carried out for this dissertation was in accordance with the regulations of the Asian Institute of Technology. The works presented in it are my own and have been generated by me as the result of my own original research, and if external sources were used, such sources have been cited. It is original and has not been submitted to any other institution to obtain another degree or qualification. This is a true copy of the dissertation, including final revisions.

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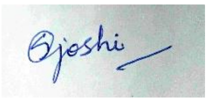
Signature: 

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ABSTRACT

In the current complex global environment, the need of strategic sourcing, fostering long-term relationships, implementing risk-sharing mechanisms, and ensuring mutually beneficial outcomes for all members of supply chain networks have gained significant attention. Many high-tech items with high clock speed nature are currently seeing shorter life cycles leading to uncertain demand with high chances of prediction errors. Moreover, the recent upsurge in disruptive events globally has emphasized the importance of resilience in supply chain management. In this dissertation, we developed three mathematical models to establish capacity reservation contract for different supply chain network to address challenges of high-tech products with longer lead time and disruptions at supply side. The research focuses on interaction of retailers and suppliers while optimizing the profits independently to achieve Nash equilibrium. These models provide unique optimal capacity decision for retailers and suppliers.

In the first model, a single supplier and single retailer mathematical model was developed. The proposed model helps to find the unique optimal solutions for the reserved capacity of retailer to the supplier and constructed capacity of the supplier. This model provides a flexible capacity construction decision for supplier to maximize his profit under demand uncertainty of the retailer. To build risk sharing mechanism, penalties to retailer for not exercising the reserved capacity were added in the model. Sensitivity analyses were also conducted to examine the impact of contract parameters on decision variables.

In the second model, we derived a dual sourcing model using capacity reservation contracts for a supply chain consisting of a retailer, a primary supplier who may experience disruption, and a reliable backup supplier. This dual sourcing model is a reactive strategy that balances flexibility and redundancy to improve supply chain resilience. The aim of the proposed model is to help find optimal solutions for the reserved capacities of the retailer to the suppliers and the constructed capacities of the suppliers. It has been derived in this model that the reserved capacities and constructed capacities exist uniquely. Sensitivity analyses were also conducted to examine the impact of contract parameters on decision variables. This model

contributes to existing knowledge by providing deeper insights into the application of the capacity reservation contract to handle supply disruption.

In the third model, a single supplier and dual retailers mathematical model was developed, in which supplier may experience disruption. When the disruption occurs at the supplier, she acquires the capacity from the other suppliers. The proposed model helps to find the unique optimal solutions for the reserved capacity of retailers to the supplier. This model provides the supplier a flexible capacity construction decision to maximize his profit. Sensitivity analyses were also conducted to examine the impact of contract parameters on decision variables.

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LIST OF ABBREVIATIONS

SC	=	Supply chain
SCM	=	Supply chain management
SCR	=	Supply chain resilience
SCN	=	Supply chain network
LP	=	Linear programming
NLP	=	Non-linear programming
IP	=	Integer programming
MILP	=	Mixed Integer Linear programming
IOT	=	Internet of Things
GA	=	Genetic Algorithm
PSO	=	Particle swarm optimization
ERP	=	Enterprise resource planning
RFID	=	Radio frequency identification
GPS	=	Global positioning system
AI	=	Artificial intelligence
ML	=	Machine learning

CHAPTER 1
INTRODUCTION

1.1 Background

Supply chain (SC) is a crucial part of any company which covers the network of suppliers, manufacturers, production centers, distribution centers and warehouses (Burgess et al., 2023). Raw materials are acquired, transformed into finished product, distributed to the customers and delivered through supply chains. SC is also referred as logistics network, in which a series of procedures are interconnected, followed by the various costs and related activities (Simchi-Levi et al., 2008; Ivanov, 2017). In SCs, the network comprises of various upstream and downstream members with range from two to several tiers. However, the majority of supply chain network designs simply take into account the supplier and the manufacturer, the manufacturer and the distributor, or the supplier and the retailer. The performance of the SC as a whole is not optimised in a traditional SC since each party tries to maximise their own goals while paying less attention to how their actions will affect others. In recent years, there has been a notable increase in outsourcing decisions among firms, leading to a greater emphasis on the criticality of procurement functions (Pan et al., 2022). SC's are becoming multi-facet, multi-dimensional due to resurgence of globalization as many companies are expanding their networks throughout the globe, leading to increase in SC design parameters which includes gigantic volume of data, hence are exposed to various risks resulting in poor estimations due to forecasting errors or wrong analysis of modelling processes (Simchi-Levi et al., 2008; Li et al., 2020). Most of the industries are forced to invest in SCs in order to acquire efficiency and efficacy in the network (Jabbarzadeh et al., 2018). The success of global SCs is highly dependent on the selection and allocation of suppliers, which poses complex decision-making challenges that involve multiple tangible and intangible criteria (Chen et al., 2019).

Moreover, from the black swan tragedies like 9/11, 26/11 terrorist attacks or wars between Russia-Ukraine, Israel-Gaza to recent natural disasters or earthquakes in Turkey 2023 and Japan 2024, it is clear that the world is exposed to highly vulnerable disruptive events (Brusset & Teller, 2017; Gao et al., 2019; Namdar et al., 2018). A disruption at any point in the supply chain can threaten the continuity and normal operation of the entire chain. The severity, frequency, likelihood, and duration of a disruption are all parameters that characterize its profile which are inherently uncertain and difficult to measure (Ivanov, 2020b; Luong et al., 2022). SC disruptions are considered as rare events which is reasonably true, but the impact associated with these risks is several times greater than operational risks (Jabbarzadeh et al., 2016). For instance, the recent enduring Covid-19 pandemic affected the entire world and caused huge destruction and loss of life. Many enterprises suffered huge shortages in their product supplies and some imposed lockdowns and shutoffs, triggering an enormous reduction in the demand (Li et al., 2020). The Figure 1.1 shows the timeline of disruptive events (includes volcanic activities, tsunamis, earthquakes, drought, floods, extreme weather/temperature, landslides, wildfires) since 1990. For decision makers these events create difficulties in implementing plans and managing the decisions related to the planning of future events as degree of complexity is very high when uncertainty is modelled into SC's.

Figure 1.1

Time of Disruptive Events

Resilience can be integrated into a supply chain network (SCN), which can further enhance the resistance towards uncertainties and disruptions, additionally allowing quick recoveries back to basic working state. Resilience is capacity to recuperate quickly from a difficult situation, so, in supply chains; resilience is the ability to retrieve back to a basic working state or relocate to a new more preferable state after being interrupted due to unfavourable events (Jabbarzadeh et al., 2018; Mikhail et al., 2019). If resilience is built into SCN, it improves the long-term performance (Mikhail et al., 2019). Various strategies (pro-active and reactive) have been used by the practitioners to combat disruptions and increase resilience of SC’s. One commonly used strategy is backup sourcing, which has been found to be effective in mitigating the impacts of disruptive events (Joshi & Luong, 2022). Incorporating backup sourcing in the SC network acts as a reactive strategy which resists disruption events more efficiently with superior efficacy (Mehrjerdi & Shafiee, 2021). In practise, many firms have used backup sourcing as a simple yet effective procurement strategy for dealing with unpredictable SC disruptions and mitigating the effects of shortages in supply (Hou et al., 2017; Li et al., 2023; Luong et al., 2022). For instance, amidst the COVID-19 pandemic, BMW Brilliance Automotive Co., Ltd.'s primary supplier responded rapidly by obtaining relevant information and enhancing its backup branch production capacity as a contingency plan. This enabled BMW to cope with the supply chain disruptions that followed the COVID-19 outbreak. Conversely, several companies, such as Nissan and Hyundai Motors, which had not prioritized backup supply prior to the pandemic, suffered severe disruptions as a result of the bullwhip effect caused in their component supply chains (Asian et al., 2020; Chen et al., 2023; Ivanov, 2020a; Käki et al., 2015; Li et al., 2023; Liu et al., 2021; Mohammed, 2020; Sharma et al., 2020; Singh et al., 2020). These instances serve as a reminder that backup sourcing, which first seems expensive, can be a beneficial tool for reducing the risk of supply disruption. Also, in response to the “*COVID-19 new normal*”, many businesses have been prioritizing and researching various backup mechanisms for improvement in production capacity. To mitigate supply-related risks, it is often advantageous for buyers to engage multiple suppliers or to procure similar products. As such, managing supplier relationships has become a significant aspect of effective supply strategy.

In addition to the aforementioned considerations regarding disruptions in supply chains and resilience, the importance of capacity planning and coordination are some paramount issues for high technology industries which produce newsvendor-type items, such as semi-conductors, chipsets, optical and telecommunication devices, due to the huge capital-intensive nature of capacity building and long lead times required (Tao et al., 2017). Newsvendor-type items are seasonal products that experience a concentrated surge in customer demand during a brief sales period. For instance, for fashion industries, on average, it takes around two years from the initiation of the design process and another year from the start of production before a garment is ready to be sold to consumers (Cheaitou & Cheaytou, 2019). This creates the need for effective capacity management which is crucial for companies to maintain a competitive edge, meet customer demands, and optimize their operational efficiency, especially when excess capacity cannot be used for other purposes. Coordination in SC has been recognized as a viable solution to address the multifaceted challenges in supply chain management. This approach involves nurturing collaboration and communication among interdependent firms or departments to facilitate the sharing of information, forecasts, and plans (Li et al., 2021). The principal objective is to optimize profit and enhance customer value by aligning and synchronizing the activities of the different members involved in the SC (Hu et al., 2013; Li et al., 2023). Through effective coordination, firms can mitigate SC risks, improve performance, and foster innovation (Cachon, 2003). The implementation of these measures can improve performance of the SC, leading to increased efficiency and adaptability to changing demand patterns. However, coordination can be hindered by profit optimization strategies implemented by different entities within the SC. For example, retailers may delay orders to reduce the risk of overstocking/understocking which further provides additional time to observe the demand patterns and enhance the accuracy of demand prediction. This delay can negatively impact suppliers who must deliver on time regardless of the ordering period (Li et al., 2014) .

Developing these strategies are in high demand and practitioners are trying to find new ways to implement them in the SCs to decrease vulnerability towards supply chain disruptions (Luong et al., 2022). Furthermore, the disruptive events caused an increase in overall costs and lead to loss of relations between suppliers and buyers. Effective procurement strategies are required to develop relationships among different SC members. SCs are multifaceted and have several levels, leading to difficulties in coordination between the players, highlighting the role of SC contracts. These contracts align the objectives of the firms and achieve superior coordination by addressing concerns that arise between various suppliers and buyers, such as purchasing quantities, lead times, material quality, return policies, and various operational costs. Substantial worthiness of contract has to be adopted and accepted by all the entities involved in the SC (Simchi-Levi et al., 2008). The use of SC contracts has received a lot of research attention in recent years, and practitioners use a variety of contracts to increase resilience.

With the consideration of these disruptive events, contracts with asymmetric information are widely used. Specifically, capacity reservation contracts are employed extensively for mitigating various SC risks and strengthening relationships of suppliers and buyer for a long term (Serel et al., 2001). Capacity reservation contract provides enormous benefits to each entities of SC like additional flexibility while dealing with demand fluctuations and disruptions of supply, counter-measuring the bullwhip effect, smarter decisions in managing the capacity (Park & Kim, 2014; Serel et al., 2001; Li et al., 2021).

1.2 Statement of the Problem

Most of the SC problems were related to decide the number, type and location of the production or distribution facilities in order to increase economic benefits (Akbari & Karimi, 2015) but few works were on adding mitigation strategies to increase stabilities or robustness and making SC resilient to these uncertainties. Supply chain resilience (SCR) has been a hot topic of research for more than three decades and requires various decisions for the proper configuration of the network and the movement of information, materials, and funds. There are plentiful failures of SCN due to operational activities but apart from these activities, disruptions have a significant role to play in causing huge losses to a firm. Disruptions are very erratic events that trigger enormous losses of SCs, infrastructure and planning. It is observed that the attributes of disruptive events are uncertain and completely vague in nature. To deal with the disruptions at supply side and to combat the impact of shortage of supplies, many firms have implemented backup sourcing as the naivest and yet quite effectual strategy. Many studies considered the concept of dual sourcing or multiple sourcing with the main focus of the studies was related to supplier selection and order allocation related to performance of price, delivery, environmental factors, bidding, quality and selection of reliable and un-reliable facilities (Tirkolaee et al., 2020; Yu & Wong, 2015; Mafakheri et al., 2011). Some of the research works focused on designing network with multiple sourcing with backup supplier as strategy to deal with disruptions (Jabbarzadeh et al., 2018).

Due to technical advancements and competitive pressure, many high-tech items with high clock speed nature, including semiconductors, consumer electronics, and biotech medications, are currently seeing shorter life cycles. Short life cycle product demand is erratic and challenging to predict with precision.

To deal with aforementioned problems related to optimal capacity building under long lead time or dealing with stochastic nature of demand and disruptions at suppliers while maximizing profit of members, we will develop various capacity reservation contract models. In traditional capacity reservation contract, a supplier asks a retailer to place an order in advance, and the supplier agrees not to raise capacity above the quantity reserved. However, we assume in this research that the supplier can construct a capacity that is different from the capacity reserved by the retailer and if the retailer placed an order for more than the amount he has reserved, the supplier could accept it if her constructed capacity is greater than what the retailer has reserved. Also, to deal with supply side disruption we develop a dual sourcing model comprising of a main supplier and a backup supplier. This dual sourcing model will serve as a reactive strategy for enhancing supply chain resilience by balancing flexibility and redundancy. This approach will provide the retailer with the flexibility to place orders with the backup supplier. The backup supplier will serve as a redundant facility as priority is always given to the primary supplier. Moreover, while a large number of academics have examined capacity reservation contracts for supply chains involving a single supplier and retailer, previous research has not given significant consideration to the capacity allocation problem involving several retailers. We, therefore, also develop a dual retailer model in which the supplier is at the risk of disruptions.

1.3 Objectives

This study focuses on the derivation of three mathematical models in the context of a supply chain with stochastic demand and under the risk of disruptions at supply side. Precisely, the objectives are communicated below to give answers for the following questions:

1. Development of single-retailer and single-supplier model.
    - How to establish capacity reservation contract with a single supplier and a retailer?

- How to derive the optimal reserved capacities of the retailer to its supplier, and the constructed capacities of the supplier?

2. Development of dual sourcing contract model.
   - How to establish capacity reservation contracts between a retailer, a risky supplier, and a backup supplier to enhance coordination and to increase resilience in the supply network in the face of supply disruption?
   - How to derive analytical solutions for reserved capacities of the retailer and constructed capacities of the suppliers?
3. Development of dual retailer and single supplier model.
   - How to establish capacity reservation contract with a single supplier and dual retailers?
   - How to decide the optimal reserved capacities of retailers to their supplier, and the constructed capacity of the supplier?

1.4 Contributions

This research contributes by bridging certain gaps in the literature. The research's primary contributions are presented below:

Mathematical Model Development:

- **Unique analytical solutions:** Using the mathematical models proposed in this research, the reserved capacities of the retailers to the suppliers and the constructed capacities of the suppliers can be determined uniquely.
- **Inclusion of penalties:** To build risk sharing mechanism, if the retailers exercise less than the reserved capacity, then they have to pay penalties to the supplier. This will help the supplier to gain profit even when the demand at retailer is low.
- **Flexible capacity construction:** The supplier can construct a capacity that is different from the capacity reserved by the retailer which gives the supplier the opportunity to sell at excess exercise price when the realized demand of retailer is more than the reserved capacity.
- **Independent profit maximization:** The derived mathematical models can be used as an effective tool for all parties involved in the contract negotiation process to help determine the combinations of contract

parameters in such a way that the optimal expected profits of all members can be achieved.

Addressing Supply Chain Resilience:

- **Incorporating flexibility and redundancy:** The dual sourcing model aims to improve supply chain resilience by achieving a balance between flexibility and redundancy. It enables the retailer to place orders with the backup supplier, thereby providing flexibility. However, the primary supplier always receives priority, making the backup supplier a redundant facility. This reactive strategy helps in mitigating SC risks and increasing the procurement flexibility for the retailer.
- **Use of capacity reservation contracts and incorporating disruption scenarios:** Capacity reservation contracts were used to enhance resilience and coordination. The dual sourcing model incorporates disruptions at supplier which acts as proactive strategy for building resilience. The last objective includes scenarios to represent complete disruption at the supplier.

1.5 Scope and Limitation

A single non-perishable product will be taken into consideration in this research. Disruptions at retailer side and intermediate disruptions like transportation failures will not be in the scope. The study is limited to design a model for implementation of sourcing strategy to deal with disruptions at supplier side as well as deriving optimal constructed capacities at suppliers and reserved capacities at retailers. For a dual sourcing model, main supplier is associated with the risk of disruptive events whereas backup supplier is reliable. For a dual retailer-single supplier model, the supplier will arrange the order from other suppliers when facing disruption. Demand observed from the retailer is assumed to follow a random normal distribution.

1.6 Organization of the Research

This dissertation is organized into six main chapters as follows: Chapter 1 introduces background of supply chain challenges, statement of problem, objectives of the research, contributions and organization of the research. In chapter 2, we review the literature about supply chain management, supply chain resilience, various strategies to improve resilience, backup sourcing, capacity reservation contracts for supply chain coordination and modelling in supply chain. In chapter 3, mathematical model for single retailer and single supplier is developed and analyzed. A dual sourcing model is presented in chapter 4. In chapter 5, mathematical model for dual retailers and single supplier is developed and analyzed. The last chapter gives some conclusions and recommendations for further study.

CHAPTER 2
LITERATURE REVIEW

2.1 Overview

In the history, the concepts of supply chain had been implemented practically; from the Silk Road to the abiding examples of human drive for armed conflict (Ribeiro & Barbosa-Povoa, 2018). Before the golden age of capitalism, logistics networks were practised mostly by military people and the operations such as procurement, maintenance, and transportation were implemented to follow up the need of military facilities and resource requirements. With the large fluctuating quantities of moving personnel and goods to various locations and under the shortage of supplies, manpower or information caused tremendous negative consequences which led the people to understand the significance of logistics and invest more in development of efficient networks for the SC (Ballou, 2007).

After the 2nd world war, the mindset of different businesses worldwide shaped towards the concerns related to value creation which made supply chain more advance and complex. These aspects led to plethora of various activities and events which are to be accomplished precisely, this fetches the function of supply chain management (SCM)(Oliver, 1982). From then, various studies have evolved to meet the challenges brought by the modern economy. SCM is an indispensable planning approach within the SC's across function, time and space, with the desire of bettering the performance of the companies or industries in the SC as well as its broad integrated network (Shapiro & Philpott, 2007). Businesses need to optimise their whole supply chain in order to meet the demands of increasing end-user expectations and competitive pressure. As a result, SCM is widely acknowledged as a crucial problem and turns into a major engine for any business. SCM main focus is to increase the effectiveness and efficiency by minimizing the SC costs and maximizing the profit and performance (Gupta et al., 2015). SCM plays a crucial role in SC decision making which leads to success of an enterprise (Khan et al., 2021).

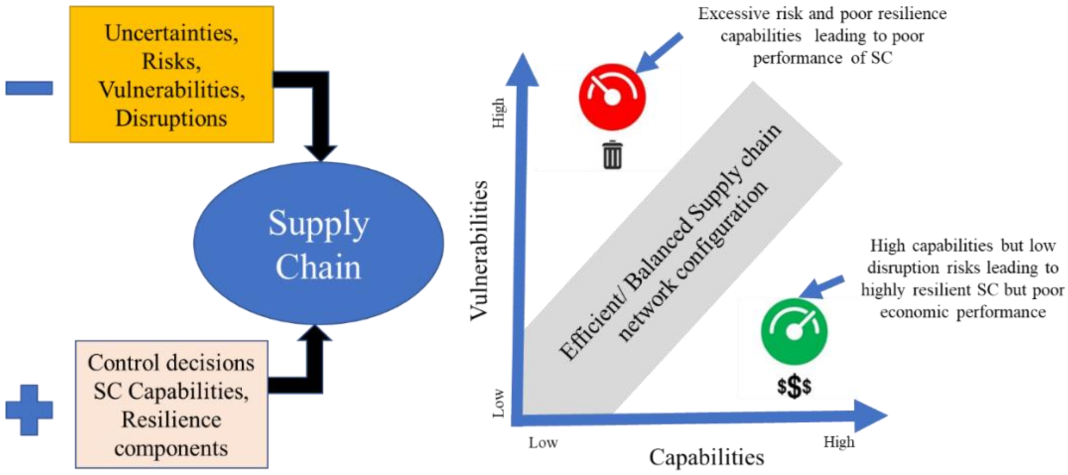
This chapter presents the known literature about SC disruptions, mitigation strategies-especially sourcing decisions, capacity reservation contracts, modelling techniques and explores the research gaps, which lead to the research objectives. Holistically, supply chain resilience (SCR) incorporates a wide body of disciplines, multifaceted and multidisciplinary. Therefore, this chapter portrays the crucial concepts related to supply chain management, such as disruptions due to disasters, risk management and resilience. These concepts build a strong foundation for a discussion of the SC resilience strategies, which involves an analysis of the resilience in SC and the key developments recorded in the literature.

2.2 Supply Chain Resilience

The resistance to withstand interruptions, adapt the mitigation strategies and retrieve back into operational state after being disrupted is referred to as resilience in SC. The focus of resilience in supply chain is to recover quickly from the temporary disruptive events (Joshi & Luong, 2022). In SCs, vulnerability is defined as the degree to which a SC is susceptible to a particular or unspecific risk event or weakness/flaws in network (Heckmann et al., 2015). By using SC modelling techniques, vulnerability can be quantified in terms of "risk", a sequence of the chance of occurrence of an event and its potential impact on the SCN. Craighead et al. (2007) described the various risks associated with SC and presented a framework of SCR and various propositions related to the impact of vulnerabilities (disturbances, disruptions) and capabilities (flexibility, agility, adaptability etc.,) of SCR. The relationship of SCR with risk and vulnerability is presented in Figure 2.1

Figure 2.1

Supply Chain Resilience Relationship with Risks and Vulnerability



Lambert & Knemeyer (2004) concluded that the if resilience is increased in the network, then the SC capability increases and vulnerabilities decreases. Its integration in the network enhances the resistance towards uncertainties and allow fast recoveries back to basic operational state. It also improves the long-term performance (Mikhail et al., 2019).

2.2.1 Resilience Strategies

In the literature, most of the studies followed two types of research directions while developing strategies to combat disruptions, one is the proactive, where optimum supply chain network structures are taken into consideration. Most of the academicians worked in building proactive strategies to combat the impact of disruptions at the planning stage. The other is reactive, where the optimum control policies are managed and applied when suffering from worst-case scenarios or disruptive events (Mikhail et al., 2019). Wang et al (2016), provided a direction for identification of risks via anticipation strategies that adds vulnerabilities concerns and awareness of the events. Although, anticipation strategies acts in collaboration to proactive and reactive strategies. The different type of strategies applied to increase resilience is shown in Table 2.1.

Table 2.1

The Strategies and Implementation to Enhance Resilience

Strategies	Implementation plan
Flexibility	Flexible production volumes, distribution, manufacturing processes, Product variety/customization, multi-skilled workforce, Sourcing flexibility (backup/multiple sourcing), Flexible supply chain contracts, Flexible pricing strategy for responsive pricing.
Robustness	Expected increase in cost inclusion during planning phase Analyze the lost sales experienced during disruptions
Redundancy	Back up capacity, Buffer stock (machinery, equipment and logistical options, Backup energy/utility source
Agility	Responsiveness, Core competencies: Manufacturing lead time, product cycle
Visibility	RFID implementation, Digitalization, ERP, Block-Chain
Velocity	Speed of recovery, loss per unit time, slack time
Collaboration	Collaborative planning (Inventory planning, Information sharing), Collaboration through smart contracts
Data analytics	Internet of Things (IoT) Business data analytics (BDA), artificial intelligence (AI), Machine learning (ML), RFID, GPS

2.2.1.1 Robustness

Robustness helps a SC to resist the perturbations by incorporating strategical planning into the model and with an acceptable loss of performance (Behzadi et al., 2018). A lot of work has been done on increasing resilience through robustness.
Strategic planning is required to build robustness in the SC's. Supply chains basically have two major objectives; one is to minimize costs and the other is to maximize the customer satisfaction. Moreover, in today's world a lot of disruptive events have been encountered, which create uncertainties. Recently, a non-linear stochastic model was proposed by Nezamoddini et al. (2020) for profit maximization with an improvement technique linked with artificial neural network making SCN robust to handle uncertainties. The authors considered uncertainties of facilities, inventory positioning, operations, demand and proposed a new genetic algorithm to handle these uncertainties. Moreover, they introduced a risk-based optimization framework to cope up internal and external risks in SC handling while considering short, medium and long-term decisions.

As risks in supply chain affects the performance and may degrade the profit output, hence, various authors introduced models to formulate a robust supply chain to help increase resilience. For instance, Dehghani et al. (2018) developed a hybrid robust scenario-based optimization model and formulated a resilient SC. The model proposed in the research is capable of handling the uncertain parameters and maintaining the level of conservatism in the solutions. The authors established a framework in two phases; firstly, a mathematical approach was used to evaluate the risk and secondly a fuzzy c-mean algorithm was developed to reduce and cluster huge disruptive scenarios. In the conclusion, they found facility allocation is the most powerful resilience strategy to mitigate disruptions.

Due to the complex nature of SC and multiple facet structure comprising of enormous levels/echelons the disruption propagation phenomena is seen causing ripple effects. In order to deal with this effect, Ojha et al. (2018) examined the propagation phenomena of SC risks at each node by the use of Bayesian network theory merged with K2 algorithm to make a robust SC. The authors implemented a discrete event simulation model with consideration of factors like fragility, lost sales, service level and total costs. Also, introduced resilience index to capture the behaviour of SC under the impact of disruptions. Another work of Li & Zobel (2020) explored the network resilience in conjunction with risk propagation by introducing a quantitative framework considering a trade-off between long term and short-term impacts of disruption. To measure resilience the authors conducted a detailed analysis of 3 resilience dimensions viz robustness, recovery time and a new dimension which covers the other two, i.e., average functionality. For the analysis of demand side and supply side uncertainty a simulation and regression analysis-based methodology is presented.

Thus, a lot of efforts has been made to make robust SCs which can work despite a few unsettling influences with the ability to resist and adapt accordingly to stuns by holding its reliability when disrupting events happen.

2.2.1.2 Flexibility

Flexibility provides capabilities to a SC for maintaining requisite internal and external conditions when disrupted accordingly though effective responses with the ability to face, resolve and exploit emergencies (Bode et al., 2011).

Some authors used flexibility as a mitigation strategy to increase resilience like Ishfaq (2012), who explored the traditional approaches focusing on efficiency and responsiveness. The research examined the consequences of including multiple modes of transportation to combat disruptions with superior efficiency by increasing flexibility as a resilience measure. The author constructed a dual mixed integer linear program based on shortest path problem and found that alternative routes for transportation under disruption will help increase resilience of SCN.
Simulation techniques have also been used to design flexible network as in the work of Carvalho et al. (2012) in which a 3-echelon SCN was redesigned for resilience using simulation techniques. To measure the performance of the SC, Lead Time Ratio and Total SC Cost were evaluated by various scenarios which are further characterized by disruptions. The disruption considered affects the delivery of a material between two SC entities, trigging an interruption in flow. To mitigate these risks, the authors introduced flexibility by selecting of route of transportation and redundancy in network using alternative transportation mode.

To increase flexibility in SC, several attempts have been made by many authors like Rajesh (2020b) who focused on flexibility as key element for building resilience in SC and encapsulated the co-relation between resilience, complexity and flexibility. A framework considering 5 business strategies was used to incorporate flexibility in SC was presented which includes multiple suppliers strategy and flexible supply contracts strategies for supply side; flexible manufacturing processes strategies and postponement strategies for product side; and flexible pricing strategy for responsive pricing. The indicators of flexibility were measured and were identified as co-related strategies and fit into Variance Inflation Factors (VIF). The research is found helpful for the practitioners as it may enable them to select the right strategy under uncertain environment.

From past literature it can be depicted that flexibility in operations can reduce the risks of failures and can lead to superior resilience in SC but the literature still uncovers flexibility strategies which can improve the network such as flexible transportation, flexible game plans, supply base, flexible supply chain contracts, etc.

2.2.1.3 **Redundancy**

Redundancy is generally having excess capacity throughout the entire SC to maintain functions and prevent a slowdown or failure of facilities in the instance of an unforeseen disruption. It enriches the proficiency of a SC by providing extra resources which include utilization of multiple suppliers and slack resources while suffering from disruption which acts as "shock absorbers" (Bode et al., 2011).

It is the most employed resilience strategy by the academicians, and it can be achieved by managing properly the strategic decisions. It has been found in literature that accurately managing sourcing decision help to achieve redundancy strategy. Ivanov (2017b) presented a simulation-based model focusing on increasing redundancy by considering sourcing strategies as potential drivers of resilience in SC. This research was first to analyse single vs. dual sourcing strategies considering capacity disruption and big data with perturbed demand patterns. The author used two approaches while designing the discrete-event model; proactive as prediction of execution plan and reactive as adjustment of SC operations, and formulated scenarios to run various models under various situations.

In another work, multi-sourcing policy as a redundancy strategy was incorporated to deal with uncertainty. Bottani et al. (2019) proposed a bi-objective mixed integer program to develop a resilient SC of demand and supply. The authors used Ant colony optimization as a metaheuristic approach to maximize total profit (TP) and minimize the total lead time (TLT) so as to increase resilience in SC. The proposed resilient SCN is able to self-adapt with the changes and self-coordinate when facing disruptive events.

However, there is a lack of research works in literature on increasing flexibility with redundancy together to maintain a balance of these two dimensions in a resilient SC.

2.2.1.4 Collaboration

Many strategies are intertwined to each other and acts together to increase resilience. Like in the study of Scholten & Schilder (2015), the authors explored the role of collaboration in enhancing resilience in SC by an empirical model and found that the resilience enablers; i.e., visibility, flexibility and velocity, can be improved by collaboration. Collaboration is an establishment of relation between two or more autonomous firms to share vital information and execute supply chain operation jointly (Kamalahmadi & Parast, 2016). Lohmer et al. (2020) introduced factors like collaboration through smart contracts to incorporate resilience in the network.
Some authors utilized a dynamic approach and found that through collaboration and SC integration, flexibility can be increased which plays a crucial role in resilience. Brusset & Teller (2017) defined the role of dynamic and organisational capabilities to analyse a trade-off between lower order capabilities and resilience of a firm. Levalle & Nof (2015) explored a collaborative control theory (CCT) approach to develop a resilient SC. The authors characterised resilience under the influence of disruption due to supply network in the agents which can take place randomly. By applying this CCT approach, it was found that the new proposed team collaboration is more resilient to disrupting fluctuations.

Collaboration helps to anticipate the disruption and manage uncertainties in the network very efficiently. A lot of works is published under this segment but still application of new disruptive information sharing technologies have not been explored so far to increase resilience in the firm.

2.2.1.5 Data analytics

Technology-driven networks and digital ecosystems are the future of supply chains. Industry 4.0, data analytics, and additive manufacturing enable the creation of end-to-end supply chain visibility based on digital information flows and dynamically reconfigurable material flows (Zheng et al., 2023). For instance, deep layer financing, a digital supply chain financing method that leverages blockchain, produces end-to-end supply chain visibility, which is essential to the robustness and viability of the supply chain (Dossou, 2019; Esmaeilian et al., 2020; Saurabh & Dey, 2021). Research has demonstrated that new technologies, such as business data analytics (BDA) and artificial intelligence (AI), are essential for maintaining business continuity, particularly in the event of external shocks.

2.2.1.6 Agility

It is an ability of a SC to quickly respond to deviations by adapting its initial steady SCN configuration (Wieland & Wallenburg, 2013). The agility is a broad strategy which leads to following two subsets, visibility and velocity. It was found that increase in agility, visibility, information sharing, trust, technological capability, strongly increases SCR. Jain et al. (2017) conducted an empirical analysis to construct an integrated framework and a hierarchy-based model to depict the relationship between the SC resilience enablers. The authors classified 13 key enablers by structural prospective analysis and a comparative analysis was done to explore the relationship based on coefficient of similarity. Moreover, statistical analysis was also conducted to see the co-relation, interaction and level of significance of the resilience enablers. Recently, mitigation strategies like visibility and velocity were implemented for increasing agility to combat disruption and were further investigated to indicate significant improvements when blockchain technology was incorporated. Lohmer et al. (2020) probed the impact of blockchain technology on SCR by using an agent-based simulation model under consideration of disruptions. The authors used different potential applications of block chain technologies on SC and explored the managerial insights of this technology on resilience of a firm. It is observed that flexibility necessitates agility to react quickly to uncertain disruptive events and fuzzy environments. Moreover, improving redundant stocks and management of suppliers play an important role in increasing agility. However, the current literature lacks integrated studies which includes agility, flexibility, redundancy together.

2.2.1.7 Visibility

Visibility is the proficiency of a SC which helps managers to detect early warnings due to turbulence/ disruption in a SC and give managers an opportunity to see through entire SC and react quickly (Blackhurst et al., 2011). It portrays the need for simple structures, measures to recognize requirements and interruptions instantaneously to have the ability to rectify changes in an efficacious way. Visibility is one of the most significant factor that affects SCR. Azadeh et al. (2014) designed a SC with a simulation-based model and identified various resilience factors and their concurrent effects on SC. A simulation framework was established to present 13 different scenarios mapped with associated resilience factor. The authors focused on the disruptions based on delays in the transportation system.

2.2.1.8 Velocity

Velocity is the speed or rate at which mitigation strategies of a SC act in response to disruptions while advertising positive changes (Jüttner & Maklan, 2011). The three prime foundations for improving SC performance are optimization of valueless time reduction, rationalization of the operations and reduced inbound time. Hence, time management is one of the eminent resilience features that practitioners must focus to improve performance. SCR dimensions such as velocity and agility were addressed and incorporated in methodology by many publications. Kristianto et al. (2014) designed a SCN with a two-stage program with first stage as inventory allocation and total costs as second. The authors used a Bender's decomposition algorithm to solve the model with higher efficiency of computing. Using the concepts of Pareto optimality, the labelling algorithm is used to find the shortest path.

2.3 Incorporating Resilience in Supply Chains

There are many strategies used by academicians and practitioners to integrate resilience into supply chains as mentioned in section 2.2. In this study, we focus on flexibility and redundancy strategies. To achieve these strategies together, backup sourcing is the best way to achieve trade-offs. The importance of supply strategy has been magnified by the increasing reliance on outsourcing and the growing value of purchased materials and components (Pan et al., 2022). As such, the success of manufacturing companies is now inextricably linked to the effectiveness of their supply strategy (Hou et al., 2017). Moreover, due to the proliferation of outsourcing practices, suppliers have become increasingly integral to supply chain performance (Aldrighetti et al., 2021; Hosseini et al., 2019; Hosseini & Ivanov, 2019; Ivanov, 2020b).

2.3.1 Backup Sourcing

There has been a significant amount of research on backup sourcing to deal with supply disruption risk, with many studies reporting results in the last decade. The literature suggests that several factors influence the decision-making process, which can result in various action plans and outcomes. To minimize the risk of supply disruption, industries can utilize an outsourcing approach by involving multiple suppliers simultaneously, thereby decreasing the likelihood of supply interruption. For instance, Li et al. (2017) examined a scenario where a company orders from one reliable supplier and another unreliable supplier while suggesting two pricing schemes considering supply side uncertainty. Also, they investigated the influence of interaction of different decisions like size of market, reliability of suppliers. Disruption risk, relationships between buyers and suppliers, and the availability of contingent delivery are these influencing aspects. The complexity of decision-making and modeling is increased by these contextual elements. Xue et al. (2022) proposed a subsidy mechanism to address supply disruption resulting from the rejection of orders by a supplier who receives fewer orders. They considered a case where a retailer sources from two suppliers. Papachristos & Pandelis (2022) found that dual sourcing is an important tool to optimize capacity decisions. Demirel et al. (2017) suggested that some retailers opt for backup procurement to eliminate the risk associated with supply disruption and investigated the related costs and advantages of this approach when suppliers become strategic price makers. Additionally, enhancing reliability can productively address supply disruption risk. With advancement in technology, blockchain is used to mitigate risks of disruptions. For instance, Dong et al. (2022) implemented a multi-tier SC framework to examine how blockchain technology can mitigate supply disruption risks in a SC finance context. Köle & Bakal. (2017) investigated the usefulness of an options contract under various levels of information according to supplier flexibility.

Much of the literature focused on dual sourcing models where a risky/unreliable supplier with a backup supplier were taken into consideration. When using the terms "unreliable" or "risky" supplier, we are specifically referring to a supplier whose availability is dependent on an uncertain environment that has two possible states: available or completely disrupted. According to Zeng & Xia (2015), dual sourcing is a prominent way to combat uncertainty for procurement firms while examining the interacting with backup suppliers. Hou et al. (2017) used backup sourcing with the goal to reduce the cost of contingency purchases and ensure merchandise availability in the face of risks. From literature, it can be seen that backup sourcing is a renowned technique used to increase resilience and to maximize profit. Hence, we use the concept of backup sourcing in this research and establish mathematical models to help improve coordination considering the occurrence of disruptive events while optimizing profits of all members involved.

2.4 Supply Chain Contracts

Supply chain contracts have emerged as a popular research topic in recent years, and there exists a substantial body of literature on this subject. However, it is challenging to devise a classification that encompasses all pertinent research works. The literature on supply contracts can be divided into various types based on their structures shown in Figure 2.2. Firstly, a backup contract has been introduced by Eppen & Iyer (1997) in which an initial order is placed at the beginning and a portion of it can be canceled later when demand is realized. Secondly, options or future contracts which involve two decisions in the initial period: a choice regarding non-refundable quantities and another concerning flexible quantities that can be converted into orders in the second period by paying an exercise cost (Dehghan-Bonari & Heydari, 2022; Meng et al., 2023; Patra & Jha, 2022; Shaban et al., 2021). The quantity flexibility contract is the third type, where an initial order can be revised later within a certain range (Heydari et al., 2020; Kord & Samouei, 2023; X. Li et al., 2016; Nikkhoo et al., 2018; Soo Kim et al., 2014). The buyback contract is the fourth type, where unsold units are returned to the supplier at a predefined value (Doganoglu & Inceoglu, 2020; Farhat et al., 2019; Tang et al., 2016; Zhang et al., 2014; Zhao et al., 2014). Other types of contract include wholesale price, revenue-sharing option, cost and risk sharing, spot purchase, payback, capacity reservation, quantity discount contracts (Cachon & Kök, 2010;

Dehghanian & Mansour, 2009; Nerja, 2022; Venkatesh et al., 2020; L. Wang et al., 2021; Yang et al., 2019).

Figure 2.2

Classification of Supply Chain Contracts

Supply chain contracts

Strategic components (Make to order)	**Make to stock**	**Contracts with asymmetric information**	**Non-strategic components**
Buy-Back contracts Revenue sharing contracts Quantity flexibility contracts Sale rebate contracts Global optimization contracts	Pay back contracts Cost sharing contracts	Capacity reservation contracts Advanced purchase contracts	Long term contracts Flexible or Optional contracts Spot purchase contracts Portfolio contracts

2.4.1 Capacity Reservation Contract

Effective coordination in the supply chain is contingent upon proper sharing of information, and capacity reservation contracts are utilized to address this issue. This type of contract is utilized to establish a relationship between the members in the supply chain. In this contract, the retailer commits to purchase a specific amount or placing an advance order, and in return, they receive the reserved units at a lower price. By reserving capacity and providing accurate forecasts to suppliers, retailers can effectively reduce costs and prevent disruptions in the SC, thereby creating a risk-sharing mechanism. This contract was firstly introduced by Serel et al. (2001) who focused on application of capacity reservation contracts to establish a durable connection between the buyer and supplier, leading to mutually advantageous outcomes in the long run. The research suggested that these contracts can assist the buyer in reducing their operational expenses, while simultaneously enabling the supplier to make more effective production schedules and strategic investment decisions. It is apparent that scholars frequently utilize capacity reservation contracts to facilitate better coordination, optimize capacities, boost resilience, reduce the likelihood of disruptions, foster long-term relationships, maximize profits, exchange information regarding actual forecasts, and improve the performance of supply chains. Schiffels & Voigt (2021) compared the advantages of a capacity reservation contract to a wholesale price contract and concluded that the capacity reservation contract outperforms the latter when non-linear capacity is involved at the supplier level. Akbalik et al. (2017) investigated the issue of lot sizes with the use of capacity reservation contracts for high technology industries. They presented a complex polynomial model that is NP-hard and proposed a solution method using dynamic programming algorithms. Hou et al. (2017) developed a model for capacity reservation contract in the presence of uncertainty arising from disruptions in the supplier's operations. The study investigated how minimum order quantity from a backup supplier affects the decisions related to the contract. Also, the authors concluded that capacity reservation contracts are effective in helping buyers and suppliers handle complex real-world situations. Cheaitou & Cheaytou (2019) introduced a two-stage capacity reservation contract between a retailer and a supplier to investigate how the availability of a risky supplier affects the contract. The model provides the capacity decision for the two stages, i.e., the capacity building stage and production stage. Li et al. (2021) studied the uncertainty of both price and demand for manufacturers and retailers independently. They proposed a capacity reservation contract and a quantity flexibility contract to encourage manufacturers to expand their capacity and enhance performance. The authors found that the proposed contracts could increase the firm's profits, and when the manufacturer had a higher bargaining power, they preferred the capacity reservation contract. Shao (2022) focused on building a capacity reservation contract where a buyer engages with multiple suppliers, and each supplier has multiple capacity blocks available for reservation. In a recent study, Roemer et al. (2023) examined a supply chain where capacity reservation contracts were used to align incentives between buyers and suppliers. They employed a choice-based optimization approach and demonstrated that the use of capacity reservation contracts can enhance the performance of the supply chain. Papachristos & Pandelis (2022) developed a model considering supply risks and used a backup supplier to increase reliability and flexibility of ordering during the events of disruptions.

2.5 Modelling and Optimizing Supply Chains

Supply chain models dealing with resilience are completely new and require a lot of effort from the academic community. With the increase in research as well as knowledge, new models are adding a particular relevance to the resilience in SC.

There are various modelling techniques used in formulating complex supply chain problems and solving them. These techniques are presented in Table 2.2.

Table 2.2

The Modelling Techniques, Various Methods and their Insights used in Supply Chains

Modelling technique	Method	Insights
Mathematical models	Stochastic programming, Linear/Mixed integer linear programming, Mixed integer non-linear programming, Robust optimization, Fuzzy programming, Goal programming	Supply chain production-distribution plans are stressed inside variously disturbed network designs. Choosing a Recuperation Plan while examining emergency preparedness strategies Supply chain designs are chosen and proactively improved to withstand specific degrees of disturbances.
Theory based models	Contingency theory, Control theory, Structure theory, Organizational theory, Statistical Theories, Graph Theory	Determination of various levels of disruption scenarios Propensity of particular supply chain configurations to propagate disruption risks. Finding the facilities and vendors that are essential to keeping the SC running.
Simulation based studies	Exact method, Agent based simulations, Structural dynamics, Heuristics, Metaheuristics	Examination of the spread of disruptions in dynamics while taking production and inventory control measures into account Operational policy simulation during disruption, during the transition to recovery, and after recovery
Miscellaneous	Blockchain, Neural networks, Machine learning, Grey prediction model	Incorporating uncertainty and resilience through new approaches,

2.6 Research Gap

From the literature reviewed, it is clear that capacity reservation contracts are widely used by academics to help improve coordination, optimize capacities, increase resilience, decrease disruption risks, maintain long-term relationships, maximize profits, share information about actual forecasts, and enhance the performance of supply chains.

In the first objective, we will introduce new mathematical model to establish capacity reservation contract. Traditional capacity reservation contracts do not include penalties for not utilizing reserved capacity at the supplier. Due to this retailer reserves more units as compared to forecasted demand leading to poor capacity planning at supplier. This model will include penalties and flexible capacity construction for supplier to help him increase profit. We will derive the model and present the unique optimal solution for reserved capacities by retailer and constructed capacity of the supplier.

In the second objective, we will develop a dual sourcing mathematical model to focus on proactive strategies for building resilience, those are flexibility and redundancy. To our understanding, all related research works in the existing literature, especially those employing the backup approach as utilized in this study, predominantly focus on primary suppliers that are susceptible to unpredictable interruptions and/or variable yield. As far as we know, none of the studies we reviewed examined the use of capacity reservation contracts that consider two supply options, i.e., from a primary supplier who faces the risk of disruption and a secondary reliable backup supplier. It should be noted that many suppliers/manufacturers in high technology industries nowadays prefer to use capacity reservation contracts due to the facts that capacity building is capital-intensive and needs to be decided in advance. Moreover, the excess capacity may be completely lost due to the high technology clock speed of the products. This objective contributes to the existing literature on the applicability of capacity reservation contracts by deriving optimal reserved capacities for the retailer and constructed capacities for the suppliers under the risk of disruption at the main supplier.

In the last objective, we will develop a dual retailer-single supplier model. While a large number of academics have examined capacity reservation contracts for supply chains involving a single supplier and retailer, previous research has not given significant consideration to the capacity allocation problem involving several retailers. This model adds contribution to academic literature by establishing capacity reservation contracts and maximizing profits of all members independently. We will derive profit function of all members and provide solutions for reserved capacities of retailers. We use heuristic techniques, i.e., genetic algorithms to determine the constructed capacity of supplier who is at risk of supply disruptions. In this model we will consider complete disruptions at the supplier.

CHAPTER 3
MATHEMATICAL MODEL DEVELOPMENT OF SINGLE-RETAILER AND SINGLE-SUPPLIER MODEL

3.1 Model Description

This chapter considers a SC with a supplier and a retailer. The retailer places orders to supplier and sells to customers. It is assumed that the demand follows a random distribution, where $f(x)$ is the probability density function and $F(x)$ is cumulative density function of the demand. For the model formulation, the following parameters and variables are used.

w_s	Selling price of the retailer (\$/unit)
S_r	Unit shortage/penalty cost for unsatisfied demand at retailer (\$/unit)
R	Reserved capacity set by the retailer for supplier.
C	Constructed capacity of supplier
w_r	Unit price for reserving products at supplier (\$/unit)
w_e	Unit exercise price set by supplier (\$/unit)
w_{ex}	Unit price for extra units set by supplier (\$/unit)
c_c	Unit construction cost at supplier (\$/unit)
c_p	Unit production cost at supplier (\$/unit)
S_s	Unit penalty cost for not exercising reserved capacity at supplier (\$/unit)
$\pi^r(.)$	Profit function of the retailer (\$)
π^s (.)	Profit function of supplier (\$)

3.2 Model Development

We assume that the retailer and the supplier adopt the capacity reservation contract following two stages. In the first stage (capacity construction stage), the supplier signs a capacity reservation contract with the retailer in which supplier offers the reservation parameters (w_r, w_e, w_{ex}). The retailer initially forecasts the demand and reserves the amounts 'R' with the supplier.

The retailer signs a reservation contract with the supplier, whereby he pays a fee to reserve units from supplier. The profit function of the retailer in this stage is shown in equation (3.1).

$$\pi_1^r(R) = -w_r * R \quad (3.1)$$

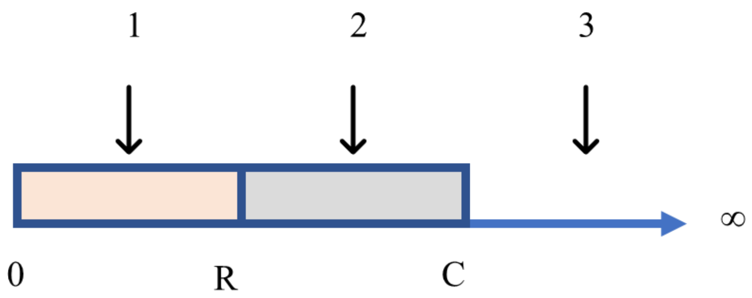
The supplier constructs the capacity as they receive the reserved quantities from the retailer. The profit function of supplier in this stage is given in equation (3.2).

$$\pi_1^s(C) = w_r * R - c_c * C \quad (3.2)$$

In the second stage, the realised demand at the retailer is 'x', the retailer places order to the supplier with reserved capacity (R) and constructed capacity (C). Due to uncertainty, the realized demand will follow a random distribution. There are 3 possible scenarios of the realized demand as illustrated in Figure 3.1.

Figure 3.1

The Possible Scenarios of Realized Demand



Scenario 1: $x < R$. In this situation, the profit of the retailer comes from the revenue generated from sales as depicted in equation (3.3). Moreover, the retailer has to pay the price charged by the supplier for exercising x units and the penalty for not exercising $(R - x)$ units at the supplier.

$$\pi_2^r(R) = w_s * x - w_e * x - S_s * (R - x) \quad (3.3)$$

The profit of the supplier is determined from the exercise price paid by the retailer for x units, his production cost, and the penalty paid by the retailer for not exercising $(R - x)$ units as presented in equation (3.4).

$$\pi_2^s(C) = w_e * x + S_s * (R - x) - c_p * x \quad (3.4)$$

Scenario 2: $\boldsymbol{R < x < C}$. In this situation, the profit of the retailer comes from the revenue generated from sales subtracting the payments to the supplier for exercising the reserved units and excess units as given in equation (3.5).

$$\pi_2^r(R) = w_s * x - w_e * R - w_{ex} * (x - R) \quad (3.5)$$

The profit of the supplier comes from the exercise charge and excess charge paid by the retailer subtracting production cost as shown in equation (3.6).

$$\pi_2^s(C) = w_e * R + w_{ex} * (x - R) - c_p * x \quad (3.6)$$

Scenario 3: $\boldsymbol{x \geq C}$. In this case, the retailer will order C units from the supplier. The retailer will experience shortage for the excess demand. The profit of the retailer comes from the revenue generated from sales, the payments to supplier for exercising the reserved units and excess units, and the shortage cost for unsatisfied demand as shown in equation (3.7).

$$\pi_2^r(R) = w_s * C - w_e * R - w_{ex} * (C - R) - S_r * (x - C) \quad (3.7)$$

The profit of the supplier comes from the exercise charge and excess charge paid by the retailer subtracting production cost as shown in equation (3.8).

$$\pi_2^s(C) = w_e * R + w_{ex} * (C - R) - c_p * C \quad (3.8)$$

From the above analyses, the overall profits of the retailer, the supplier can be determined as the cumulative profits of stage 1 and stage 2, which are shown in equations (3.9), (3.10), respectively.

$$\pi^r(R) = -w_r * R + \int_0^R \{w_s * x - w_e * x - S_s * (R - x)\} f(x)dx + \int_R^C \{w_s * x - w_e * R - w_{ex} * (x - R)\} f(x)dx + \int_C^\infty \{w_s * C - w_e * R - w_{ex} * (C - R) - S_r * (x - C)\} f(x)dx \quad (3.9)$$

$$\pi^s(C) = w_r * R - C * c_c + \int_0^R \{w_e * x + S_s * (R - x) - c_p * x\} f(x)\,dx + \int_R^C \{w_e * R + w_{ex} * (x - R) - c_p * x\} f(x)dx + \{w_e * R + w_{ex} * (C - R) - c_p * C\} * \{1 - F(C)\} \quad (3.10)$$

Proposition 3.1: *The profit function of the retailer is a concave function and unique solution of R exists as*

$$R = F^{-1}\left[\frac{(w_e + w_r - w_{ex})}{(w_e - w_{ex} - S_s)}\right]$$

Proof: From the profit function of the retailer, we have,

$\frac{\partial \pi^r(R)}{\partial R} = -w_r + \{(w_s - w_e) * R\}f(R) + \int_0^R \frac{\partial}{\partial R}\{w_s * x - w_e * x - S_s * (R - x)\}f(x)dx - \{(w_s - w_e) * R\}f(R) + \int_R^C \frac{\partial}{\partial R}\{w_s * x - w_e * R - w_{ex} * (x - R)\}f(x)dx + \int_C^\infty \frac{\partial}{\partial R}\{w_s * C - w_e * R - w_{ex} * (C - R) - S_r * (x - C)\}f(x)dx$

$= -w_r - S_s * F(R) + (w_{ex} - w_e) * \{F(C) - F(R)\} + (w_{ex} - w_e) * \{1 - F(C)\}$

$= (w_e - w_{ex} - S_s) * \{F(R)\} + (w_{ex} - w_e - w_r)$

Also,

$\frac{\partial^2 \pi^r(R)}{\partial R^2} = (w_e - w_{ex} - S_s) * \{f(R)\}$

It is noted that $(w_e < w_{ex} + S_s)$, therefore $\frac{\partial^2 \pi^r(R)}{\partial R^2} < 0$. So, $\pi^r(R)$ is a concave function, and hence, the optimal solution of R exists uniquely.

The optimal solution of R can be determined from $\frac{\partial \pi^r(R)}{\partial R} = 0$. Hence,

$\{F(R)\} = \frac{(w_e + w_r - w_{ex})}{(w_e - w_{ex} - S_s)}$

Therefore,

$R = F^{-1}\left[\frac{(w_e + w_r - w_{ex})}{(w_e - w_{ex} - S_s)}\right]$

Proposition 3.2: *The profit function of the supplier is a concave function and unique solution of C exists as*

$C = F^{-1}\left[\frac{(w_{ex} - c_p - c_c)}{(w_{ex} - c_p)}\right]$

Proof: From the profit function of the supplier, we have,

$\frac{\partial \pi^s(C)}{\partial C} = -c_c + \{w_e * R + w_{ex} * (C - R) - c_p * C\}f(C) + [w_e * R + w_{ex} * (C - R) - c_p * C] * \{-f(C)\} + [w_{ex} - c_p] * \{1 - F(C)\}$

$= -c_c + (w_{ex} - c_p) * \{1 - F(C)\}$

$= (w_{ex} - c_p - c_c) - (w_{ex} - c_p) * F(C)$

Also,

$\frac{\partial^2 \pi^s(C)}{\partial C^2} = -(w_{ex} - c_p) * f(C)$

It is noted that ($w_{ex} > c_p$), therefore $\frac{\partial^2 \pi^s(C)}{\partial C^2} < 0$. So, $\pi^s(C)$ is a concave function, and hence, the optimal solution of C exists uniquely.

The optimal solution of C can be determined from $\frac{\partial \pi^s(C)}{\partial C} = 0$. Hence,

$$\{F(C)\} = \frac{(w_{ex}-c_p-c_c)}{(w_{ex}-c_p)}$$

Therefore,

$$C = F^{-1}\left[\frac{(w_{ex}-c_p-c_c)}{(w_{ex}-c_p)}\right]$$

3.3 Numerical Experiments

To investigate the applicability of the proposed capacity reservation contract developed in section-3, different numerical experiments were conducted. The data related to various costs of the base case are given as: w_s= 300, S_r= 120, w_r= 20, w_e, = 70, w_{ex}= 105, c_c=5, c_p= 55, S_s= 50. It is assumed that the demand follows a normal distribution with mean 1000 and standard deviation 200.

From the above input parameters, the following results are achieved.
Reserved capacity set by the retailer for supplier, R = 814
Constructed capacity of the supplier, C = 1256

With the above results, the profit of all members are as follows,
Profit of the retailer ($) = 202612
Profit of the supplier ($) = 32650

3.4 Sensitivity Analysis

The following sections will present sensitivity analyses with respect to different input parameters to assess their impact on decision variables and the profits of all involved parties.

3.4.1 Effect of Unit Shortage Cost (S_r)

This section will analyze the impact of the unit shortage cost, and the findings are presented in Table 3.1.

Table 3.1

Sensitivity Analysis w.r.t Unit Shortage Cost

Parameter S_r	Capacities		Profits	
	R	**C**	**Retailer**	**Supplier**
110	814	1256	202707	32650
115	814	1256	202659	32650
120	814	1256	202612	32650
125	814	1256	202565	32650
130	814	1256	202515	32650

The results show that the unit shortage cost does not influence the reserved capacity and constructed capacity. This outcome is reasonable as the decision variables (R, C) are dependent upon the contract parameters (w_r, w_e, w_{ex}). Although, when S_r increases, the retailer's profit decreases but supplier's profit remains unchanged, which is a comprehensive trend.

3.4.2 Effect of Unit Reservation Price (w_r)

This section will analyze the impact of the unit reservation price, and the findings are presented in Table 3.2.

Table 3.2

Sensitivity Analysis w.r.t. Unit Reservation Price

Parameter w_r	Capacities		Profits	
	R	**C**	**Retailer**	**Supplier**
10	892	1256	211160	24102
15	856	1256	206790	28473
20	814	1256	202612	32650
25	763	1256	198664	36598
30	687	1256	195023	40239

From the results, the retailer's reserved capacity (R) reduces when the unit reservation price increases, as it becomes costly for the retailer to reserve units at the supplier. When the price of reserving capacity increases, the profit of retailer reduces and subsequently, the supplier's profit increases. Although, the construction capacity (C) of the supplier remains constant. The supplier wants the reservation price to increase, but the retailer does not.

3.4.3 Effect of Unit Exercise Price (w_e)

This section will analyze the impact of the unit exercise price, and the findings are presented in Table 3.3.

Table 3.3

Sensitivity Analysis w.r.t Unit Exercise Price

Parameter w_e	Capacities		Profits	
	R	C	Retailer	Supplier
60	873	1256	210816	24446
65	847	1256	206657	28605
70	814	1256	202612	32650
75	770	1256	198724	36539
80	700	1256	195078	40185

From the results, when the exercise price at supplier increases, it becomes costly for the retailer to exercise units from the supplier. Due to this, the retailer's reserved capacity (R) and his profit decreases. Although, it is observed that the supplier's constructed capacity (C) is unaffected by the changes in unit exercise price. The supplier benefits from the increase in the unit exercised price, while the retailer does not as when exercise price increases, the supplier's overall profit increases. The supplier's constructed capacity is determined independently of the cost of the unit exercise price.

3.4.4 Effect of Unit Production Cost at Supplier (c_p)

This section will analyze the impact of the unit production cost at supplier and the findings are presented in Table 3.4.

Table 3.4

Sensitivity Analysis w.r.t Unit Production Cost at Supplier

Parameter c_p	Capacities		Profits	
	R	C	Retailer	Supplier
45	814	1277	203197	42566
50	814	1267	202934	37606
55	814	1256	202612	32650
60	814	1244	202207	27701
65	814	1230	201685	22759

The results in Table 3.4 show that the supplier's constructed capacity (C) decreases as it becomes less appealing for the supplier to construct a high capacity resulting in decrease of his profit. The reserved capacity of retailer remains unchanged. Although, when c_p increases, the retailer overall profit also decreases, as retailer may face more shortages.

3.4.5 Effect of Unit Construction Cost at Supplier (c_c)

This section will analyze the impact of the unit construction cost at supplier and the findings are presented in Table 3.5.

Table 3.5

Sensitivity Analysis w.r.t Unit Construction Cost at Supplier

Parameter c_c	**Capacities**		**Profits**	
	R	**C**	**Retailer**	**Supplier**
3	814	1311	203967	35214
4	814	1281	203310	33919
5	814	1256	202612	32650
6	814	1235	201875	31405
7	814	1216	201101	30180

The results show that the supplier's constructed capacity (C) decreases as it becomes less appealing for the supplier to construct a high capacity resulting in decrease of his profit. The reserved capacity remains unchanged. Although, when c_c increases, the retailer overall profit also decreases, as retailer may face more shortages.

3.4.6 Effect of Unit Excess Exercise Price at Supplier (w_{ex})

This section will analyze the impact of the unit excess exercise price at supplier and the findings are presented in Table 3.6.

Table 3.6

Sensitivity Analysis w.r.t Unit Excess Exercise Price at Supplier

Parameter w_{ex}	Capacities		Profits	
	R	C	Retailer	Supplier
95	700	1230	204027	30293
100	770	1244	203265	31589
105	814	1256	202612	32650
110	847	1267	202022	33561
115	873	1277	201477	34361

From the results, it can be observed that the retailer is more likely to reserve a higher capacity from the supplier if the cost of exercising additional units increases to avoid purchasing units at higher prices when the demand is high. As a result of this, reserved capacity of the retailer increases. Subsequently, supplier's constructed capacity increases as with his profit. Although, the profit of retailer decreases due to increase in excess exercise price.

3.4.7 Effect of Unit Penalty Cost for Not Exercising at Supplier (S_s)

This section will analyze the impact of the unit penalty cost for not exercising at supplier and the findings are presented in Table 3.7.

Table 3.7

Sensitivity Analysis w.r.t Unit Penalty Cost for Not Exercising at Supplier

Parameter S_s	Capacities		Profits	
	R	C	Retailer	Supplier
40	832	1256	202818	32444
45	823	1256	202711	32552
50	814	1256	202612	32650
55	807	1256	202520	32742
60	799	1256	202434	32828

The results show that when S_s increases, the profit and reserve capacity of the retailer decrease. It is reasonable as retailer will reserve less units when the price of penalty is higher. Although, constructed capacities are not significantly impacted by change in unit shortage cost. But the profit of supplier increases due to increase in penalty charged.

CHAPTER 4
MATHEMATICAL MODEL DEVELOPMENT OF DUAL SOURCING CONTRACT MODEL

4.1 Model Description

This chapter takes into account a supply chain with two suppliers and one retailer. The retailer places orders to the suppliers and sells to customers. Although the two suppliers produce the identical product, their agreed-upon prices with the retailer could differ. The retailer compares numerous cost components and chooses the primary supplier with the lowest cost. The selection of supplier is done by comparing contract cost parameters such as reservation price (w_r), exercise price (w_e) and extra unit purchasing price (w_{ex}). When placing an order, the primary supplier is always given precedence. Supplier 1 serves as the primary supplier with the risk of disruption, while supplier 2 being reliable serves as a backup source. Using backup sourcing strategy, the penalty charged for not exercising the reserved capacity at backup supplier is less than that of the main supplier ($S_{s2} < S_{s1}$). It is assumed that the demand follows a random distribution, where $f(x)$ is the probability density function and $F(x)$ is cumulative distribution function of the demand. For the model formulation, the following parameters and variables are used.

w_s	Selling price of the retailer ($/unit)
S_r	Unit shortage/penalty cost for unsatisfied demand at retailer ($/unit)
R_1	Reserved capacity set by the retailer for supplier 1.
R_2	Reserved capacity set by the retailer for supplier 2.
C_1	Constructed capacity of supplier 1
C_2	Constructed capacity of supplier 2
w_{r1}	Unit price for reserving products at supplier 1 ($/unit)
w_{e1}	Unit exercise price set by supplier 1 ($/unit)
w_{ex1}	Unit price for extra units set by supplier 1 ($/unit)
c_{c1}	Unit construction cost at supplier 1 ($/unit)
c_{p1}	Unit production cost at supplier 1 ($/unit)
S_{s1}	Unit penalty cost for not exercising reserved capacity at supplier 1 ($/unit)
S_s	Unit penalty cost for not supplying the reserved units at supplier 1 ($/unit)

w_{r2}	Unit price for reserving products at supplier 2 (\$/unit)
w_{e2}	Unit exercise price set by supplier 2 (\$/unit)
w_{ex2}	Unit price for extra units set by supplier 2 (\$/unit)
c_{c2}	Unit construction cost at supplier 2 (\$/unit)
c_{p2}	Unit production cost at supplier 2 (\$/unit)
S_{s2}	Unit penalty cost for not exercising reserved capacity at supplier 2 (\$/unit)
p	Probability of disruption at supplier 1
$\pi^r(.)$	Profit function of the retailer (\$)
$\pi^{s1}(.)$	Profit function of supplier 1 (\$)
$\pi^{s2}(.)$	Profit function of supplier 2 (\$)

4.2 Model Development

We assume that the retailer and the suppliers adopt the capacity reservation contract following two stages. In the first stage (capacity construction stage), supplier 1 and supplier 2 sign capacity reservation contracts with retailer in which supplier offers the reservation parameters (w_r, w_e, w_{ex}). The retailer initially forecasts the demand and reserves the amounts 'R_1', 'R_2' with supplier 1 and supplier 2, respectively.

4.2.1 Scenario A: When Both Suppliers are Available

The retailer signs reservation contracts with both supplier 1 and supplier 2, whereby he pays a fee to reserve units from each supplier. The profit function of retailer in this stage is shown in equation (4.1).

$$\pi_1^r(R_1, R_2) = -w_{r1} * R_1 - w_{r2} * R_2 \quad (4.1)$$

Supplier 1 and supplier 2 construct the capacity as they receive the reserved quantities from the retailer accordingly. The profit functions of supplier 1 and supplier 2 in this stage are given in equation (4.2) and (4.3), respectively.

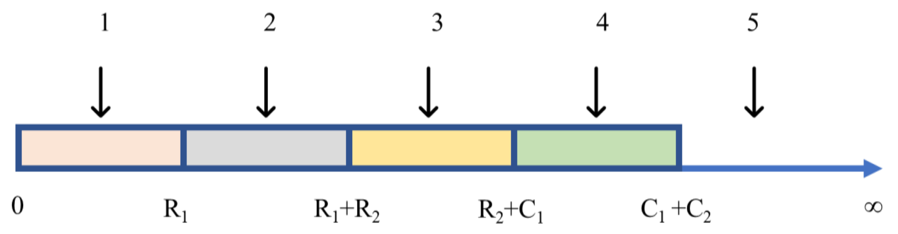
$$\pi_1^{s1}(C_1) = w_{r1} * R_1 - C_1 * c_{c1} \quad (4.2)$$

$$\pi_1^{s2}(C_2) = w_{r2} * R_2 - C_2 * c_{c2} \quad (4.3)$$

In the second stage, the realised demand at the retailer is 'x', the retailer gives the priority to the 1st supplier with reserved capacity (R_1) and constructed capacity (C_1). Due to uncertainty, the realized demand that follows a random distribution can receive value in one of the five intervals as illustrated in Figure 4.1. In the five intervals presented in Figure 4.1, the order quantities of the retailer to the two suppliers are different, and hence, the profit functions of all members will have different expressions.

Figure 4.1

Possible scenarios of realized demand for dual sourcing model



In the following sections, the profit functions of all members in each sub-scenario associated with each interval presented in Figure 4.1 will be derived:

Sub-scenario 1A: $\boldsymbol{x < R_1}$. In this situation, the retailer will order from only supplier 1. The profit of the retailer comes from the revenue generated from sales as depicted in equation (4.4). Moreover, the retailer has to pay the price charged by the supplier for exercising x units and the penalties for not exercising $(R_1 - x)$ units at supplier 1 and R_2 units at supplier 2.

$$\pi_2^r(R_1, R_2) = w_s * x - w_{e1} * x - S_{s1} * (R_1 - x) - S_{s2} * R_2 \tag{4.4}$$

The profit of supplier 1 is determined from the exercise price paid by the retailer for x units, his production cost, and the penalty paid by the retailer for not exercising $(R_1 - x)$ units as presented in equation (4.5).

$$\pi_2^{s1}(C_1) = w_{e1} * x + S_{s1} * (R_1 - x) - c_{p1} * x \tag{4.5}$$

In this case, the demand is fulfilled by supplier 1, supplier 2 will not receive any order. However, supplier 2 receives the penalty paid by the retailer for not exercising R_2 units. His profit function is shown in equation (4.6).

$$\pi_2^{s2}(C_2) = S_{s2} * R_2 \tag{4.6}$$

Sub-scenario 2A: $\boldsymbol{R_1 \leq x < R_1 + R_2}$. In this case, the retailer will order R_1 from supplier 1 and $(x - R_1)$ from supplier 2. It is noted that the retailer has an option to order remaining $(x - R_1)$ units from supplier 1 at excess price (w_{ex1}) and pays penalty of not exercising to supplier 2. However, to prevent the use of this option, i.e., for the retailer to order R_1 from supplier 1 and $(x - R_1)$ from supplier 2, the following condition must hold true $(w_{ex1}+S_{s2} > w_{e2})$. The profit of the retailer comes from the revenue generated from sales deducting the payments to supplier 1 and supplier 2 for exercising the reserved units, and the penalty paid by retailer to supplier 2 for not exercising $(R_1 + R_2 - x)$ units as given in equation (4.7).

$$\pi_2^r(R_1, R_2) = w_s * x - w_{e1} * R_1 - w_{e2} * (x - R_1) - S_{s2} * (R_1 + R_2 - x) \qquad (4.7)$$

The profit of supplier 1 comes from the exercise price paid by the retailer for R_1 units subtracting his production cost as depicted in equation (4.8).

$$\pi_2^{s1}(C_1) = w_{e1} * R_1 - c_{p1} * R_1 \qquad (4.8)$$

The profit of supplier 2 comes from the exercise price paid by the retailer for $(x - R_1)$ units, the production cost, and the penalty paid by the retailer for not exercising $(R_1 + R_2 - x)$ units as shown in equation (4.9).

$$\pi_2^{s2}(C_2) = w_{e2} * (x - R_1) + S_{s2} * (R_1 + R_2 - x) - c_{p2} * (x - R_1) \qquad (4.9)$$

Sub-scenario 3A: $\boldsymbol{R_1 + R_2 \leq x < R_2 + C_1}$. In this case, the retailer will order R_2 unit from supplier 2 and $(x - R_2)$ units from supplier 1, where $(x - R_1 - R_2)$ units will be charged at excess exercise price and R_1units at exercise price. It is noted that the condition for this decision to happen is the excess unit charge from supplier 1 is less than the excess unit charge from supplier 2, i.e., $w_{ex1} < w_{ex2}$. The profit of the retailer comes from the revenue generated from sales subtracting the payments to supplier 1 for exercising the reserved units and excess units, and payment to supplier 2 for exercising the reserved units as given in equation (4.10).

$$\pi_2^r(R_1, R_2) = w_s * x - w_{e1} * R_1 - w_{ex1} * (x - R_1 - R_2) - w_{e2} * R_2 \qquad (4.10)$$

The profit of supplier 1 comes from the exercise charge and excess charge paid by the retailer subtracting production cost as shown in equation (4.11).

$$\pi_2^{s1}(C_1) = w_{e1} * R_1 + w_{ex1} * (x - R_1 - R_2) - c_{p1} * (x - R_2) \quad (4.11)$$

The profit of supplier 2 comes from the exercise charge paid by the retailer for R_2 units subtracting production cost as shown in equation (4.12).

$$\pi_2^{s2}(C_2) = w_{e2} * R_2 - c_{p2} * R_2 \quad (4.12)$$

Sub-scenario 4A: $R_2 + C_1 \leq x < C_1 + C_2$. In this case, the retailer will order C_1 units from supplier 1 and $(x - C_1)$ from supplier 2. It is noted that the condition for this decision to happen is the excess unit charge from supplier 1 is less than the excess unit charge from supplier 2, i.e., $w_{ex1} < w_{ex2}$. The retailer orders R_1 units at normal exercise price and $(C_1 - R_1)$ units at excess price from supplier 1. He also orders R_2 units at normal exercise price, and $(x - C_1 - R_2)$ units at excess price from supplier 2. The profit of the retailer comes from the revenue generated from sales subtracting the payments to supplier 1 and supplier 2 for exercising the reserved units and excess units as presented in equation (4.13).

$$\pi_2^{r}(R_1, R_2) = w_s * x - w_{e1} * R_1 - w_{ex1} * (C_1 - R_1) - w_{e2} * R_2 - w_{ex2} * (x - R_2 - C_1) \quad (4.13)$$

The profit of supplier 1 comes from the exercise charge and excess charge paid by the retailer subtracting production cost as shown in equation (4.14).

$$\pi_2^{s1}(C_1) = w_{e1} * R_1 + w_{ex1} * (C_1 - R_1) - c_{p1} * C_1 \quad (4.14)$$

The profit of supplier 2 comes from the exercise charge and excess charge paid by the retailer subtracting production cost as shown in equation (4.15).

$$\pi_2^{s2}(C_2) = w_{e2} * R_2 + w_{ex2} * (x - R_2 - C_1) - c_{p2} * (x - C_1) \quad (4.15)$$

Sub-scenario 5A: $x \geq C_1 + C_2$. In this case, the retailer will order C_1 units from supplier 1 and C_2 units from supplier 2. The retailer will experience shortage for the excess demand. The profit of the retailer comes the revenue generated from sales, the payments to supplier 1 and supplier 2 for exercising the reserved units and excess units, and the shortage cost for unsatisfied demand as shown in equation (4.16).

$$\pi_2^r(R_1,R_2) = w_s * (C_1 + C_2) - w_{e1} * R_1 - w_{ex1} * (C_1 - R_1) - w_{e2} * R_2 - w_{ex2} * (C_2 - R_2) - S_r * (x - C_1 - C_2) \quad (4.16)$$

The profit of supplier 1 is the exercise charge and excess charge paid by the retailer subtracting production cost as shown in equation (4.17).

$$\pi_2^{s1}(C_1) = w_{e1} * R_1 + w_{ex1} * (C_1 - R_1) - c_{p1} * C_1 \quad (4.17)$$

The profit of supplier 2 is the exercise charge and excess charge paid by the retailer subtracting production cost as shown in equation (4.18).

$$\pi_2^{s2}(C_2) = w_{e2} * R_2 + w_{ex2} * (C_2 - R_2) - c_{p2} * C_2 \quad (4.18)$$

From the above analyses, the overall profit of the retailer, the supplier 1 and the supplier 2 can be determined as the cumulative profits of stage 1 and stage 2, which are shown in equations (4.19), (4.20) and (4.21), respectively.

$$\pi_A^r(R_1,R_2) = -w_{r1} * R_1 - w_{r2} * R_2 + \int_0^{R_1}[w_s * x - w_{e1} * x - S_{s1} * (R_1 - x) - S_{s2} * R_2]f(x)dx + \int_{R_1}^{R_1+R_2}[w_s * x - w_{e1} * R_1 - w_{e2} * (x - R_1) - S_{s2} * (R_1 + R_2 - x)]f(x)dx + \int_{R_1+R_2}^{R_2+C_1}[w_s * x - w_{e1} * R_1 - w_{ex1} * (x - R_1 - R_2) - w_{e2} * R_2]f(x)dx + \int_{C_1+R_2}^{C_1+C_2}[w_s * x - w_{e1} * R_1 - w_{ex1} * (C_1 - R_1) - w_{e2} * R_2 - w_{ex2} * (x - R_2 - C_1)]f(x)dx + \int_{C_1+C_2}^{\infty}[w_s * (C_1 + C_2) - w_{e1} * R_1 - w_{ex1} * (C_1 - R_1) - w_{e2} * R_2 - w_{ex2} * (C_2 - R_2) - S_r * (x - C_1 - C_2)]f(x)dx \quad (4.19)$$

$$\pi_A^{s1}(C_1) = w_{r1} * R_1 - C_1 * c_{c1} + \int_0^{R_1}[w_{e1} * x + S_{s1} * (R_1 - x) - c_{p1} * x]f(x)dx + [w_{e1} - c_{p1}] * R_1 * \{F(R_1 + R_2) - F(R_1)\} + \int_{R_1+R_2}^{R_2+C_1}[w_{e1} * R_1 + w_{ex1} * (x - R_1 - R_2) - c_{p1} * (x - R_2)]f(x)dx + [w_{e1} * R_1 + w_{ex1} * (C_1 - R_1) - c_{p1} * C_1] * \{F(C_1 + C_2) - F(C_1 + R_2)\} + [w_{e1} * R_1 + w_{ex1} * (C_1 - R_1) - c_{p1} * C_1] * \{1 - F(C_1 + C_2)\} \quad (4.20)$$

$$\pi_A^{s2}(C_2) = w_{r2} * R_2 - C_2 * c_{c2} + [S_{s2} * R_2] * F(R_1) + \int_{R_1}^{R_1+R_2}[w_{e2} * (x - R_1) + S_{s2} * (R_1 + R_2 - x) - c_{p2} * (x - R_1)]f(x)dx + [w_{e2} - c_{p2}] * R_2 * \{F(R_2 + C_1) -$$

$F(R_1 + R_2)\} + \int_{C_1+R_2}^{C_1+C_2} [w_{e2} * R_2 + w_{ex2} * (x - R_2 - C_1) - c_{p2} * (\text{x} - C_1)] f(x)\, dx + [w_{e2} * R_2 + w_{ex2} * (C_2 - R_2) - c_{p2} * C_2] * \{1 - F(C_1 + C_2)\}$

(4.21)

Proposition 4.1: *The profit function of the retailer i.e., $\pi_A^r(R_1, R_2)$ is a concave function.*

Proof of proposition 4.1: From the profit function of the retailer $\pi_A^r(R_1, R_2)$, we have

- $\frac{d\pi_A^r(R_1,R_2)}{dR_1} = -w_{r1} + [w_s * R_1 - w_{e1} * R_1 - S_{s1} * (R_1 - R_1) - S_{s2} * R_2] f(R_1) + \int_0^{R_1} \frac{\partial}{\partial R_1} [w_s * x - w_{e1} * x - S_{s1} * (R_1 - x) - S_{s2} * R_2] f(x) dx + [w_s * (R_1 + R_2) - w_{e1} * R_1 - w_{e2} * (R_1 + R_2 - R_1) - S_{s2} * (R_1 + R_2 - R_1 + R_2)] f(R_1 + R_2) - [w_s * R_1 - w_{e1} * R_1 - w_{e2} * (R_1 - R_1) - S_{s2} * (R_1 + R_2 - R_1)] f(R_1) dx + \int_{R_1}^{R_1+R_2} \frac{\partial}{\partial R_1} [w_s * x - w_{e1} * R_1 - w_{e2} * (x - R_1) - S_{s2} * (R_1 + R_2 - x)] f(x) dx - [w_s * (R_1 + R_2) - w_{e1} * R_1 - w_{ex1} * (R_1 + R_2 - R_1 - R_2) - w_{e2} * R_2] f(R_1 + R_2) + \int_{R_1+R_2}^{R_2+C_1} \frac{\partial}{\partial R_1} [w_s * x - w_{e1} * R_1 - w_{ex1} * (x - R_1 - R_2) - w_{e2} * R_2] f(x) dx + \int_{C_1+R_2}^{C_1+C_2} \frac{\partial}{\partial R_1} [w_s * x - w_{e1} * R_1 - w_{ex1} * (C_1 - R_1) - w_{e2} * R_2 - w_{ex2} * (x - R_2 - C_1)] f(x) dx + \int_{C_1+C_2}^{\infty} \frac{\partial}{\partial R_1} [w_s * (C_1 + C_2) - w_{e1} * R_1 - w_{ex1} * (C_1 - R_1) - w_{e2} * R_2 - w_{ex2} * (C_2 - R_2) - S_\text{r} * (x - C_1 - C_2)] f(x) dx$

$= -w_{r1} + [w_s * R_1 - w_{e1} * R_1 - S_{s2} * R_2] f(R_1) - (S_{s1} * R_1) \int_0^{R_1} f(x) dx + [w_s * (R_1 + R_2) - w_{e1} * R_1 - w_{e2} * R_2] f(R_1 + R_2) - [w_s * R_1 - w_{e1} * R_1 - S_{s2} * R_2] f(R_1) dx + (w_{e2} - w_{e1} - S_{s2}) \int_{R_1}^{R_1+R_2} f(x) dx - [w_s * (R_1 + R_2) - w_{e1} * R_1 - w_{e2} * R_2] f(R_1 + R_2) + (w_{ex1} - w_{e1}) \int_{R_1+R_2}^{R_2+C_1} f(x) dx + (w_{ex1} - w_{e1}) \int_{C_1+R_2}^{C_1+C_2} f(x) dx + (w_{ex1} - w_{e1}) \int_{C_1+C_2}^{\infty} f(x) dx$

$= (w_{ex1} - w_{e1} - w_{r1}) + (w_{e1} - w_{e2} - S_{s1} + S_{s2}) F(R_1) + (w_{e2} - w_{ex1} - S_{s2}) \{F(R_1 + R_2)\}$

- $\frac{d\pi_A^r(R_1,R_2)}{dR_2} = -w_{r2} + \int_0^{R_1} \frac{\partial}{\partial R_2} [w_s * x - w_{e1} * x - S_{s1} * (R_1 - x) - S_{s2} * R_2] f(x) dx + [w_s * (R_1 + R_2) - w_{e1} * R_1 - w_{e2} * (R_1 + R_2 - R_1) - S_{s2} *$

$(R_1 + R_2 - R_1 + R_2)]f(R_1 + R_2) + \int_{R_1}^{R_1+R_2} \frac{\partial}{\partial R_2}[w_s * x - w_{e1} * R_1 - w_{e2} *$

$(x - R_1) - S_{s2} * (R_1 + R_2 - x)]f(x)dx + [w_s * (R_2 + C_1) - w_{e1} * R_1 - w_{ex1} *$

$(R_2 + C_1 - R_1 - R_2) - w_{e2} * R_2]f(R_2 + C_1) - [w_s * (R_1 + R_2) - w_{e1} * R_1 -$

$w_{ex1} * (R_1 + R_2 - R_1 - R_2) - w_{e2} * R_2]f(R_1 + R_2) + \int_{R_1+R_2}^{R_2+C_1} \frac{\partial}{\partial R_2}[w_s * x -$

$w_{e1} * R_1 - w_{ex1} * (x - R_1 - R_2) - w_{e2} * R_2]f(x)dx - [w_s * (C_1 + R_2) - w_{e1} *$

$R_1 - w_{ex1} * (C_1 - R_1) - w_{e2} * R_2 - w_{ex2} * (C_1 + R_2 - R_2 - C_1)] +$

$\int_{C_1+R_2}^{C_1+C_2} \frac{\partial}{\partial R_2}[w_s * x - w_{e1} * R_1 - w_{ex1} * (C_1 - R_1) - w_{e2} * R_2 - w_{ex2} * (x - R_2 -$

$C_1)]f(x)dx + \int_{C_1+C_2}^{\infty} \frac{\partial}{\partial R_2}[w_s * (C_1 + C_2) - w_{e1} * R_1 - w_{ex1} * (C_1 - R_1) - w_{e2} *$

$R_2 - w_{ex2} * (C_2 - R_2) - S_r * (x - C_1 - C_2)]f(x)dx$

$= -w_{r2} + (-S_{s2}) \int_0^{R_1} f(x)dx + [w_s * (R_1 + R_2) - w_{e1} * R_1 - w_{e2} * R_2]f(R_1 +$

$R_2) + (-S_{s2}) \int_{R_1}^{R_1+R_2} f(x)dx + [w_s * (R_2 + C_1) - w_{e1} * R_1 - w_{ex1} * (C_1 - R_1) -$

$w_{e2} * R_2]f(R_2 + C_1) - [w_s * (R_1 + R_2) - w_{e1} * R_1 - w_{e2} * R_2]f(R_1 + R_2) +$

$(w_{ex1} - w_{e2}) \int_{R_1+R_2}^{R_2+C_1} f(x)dx - [w_s * (C_1 + R_2) - w_{e1} * R_1 - w_{ex1} * (C_1 - R_1) -$

$w_{e2} * R_2]f(R_2 + C_1) + (w_{ex2} - w_{e2}) \int_{C_1+R_2}^{C_1+C_2} f(x)dx + (w_{ex2} - w_{e2}) \int_{C_1+C_2}^{\infty} f(x)dx$

$= (w_{ex2} - w_{e2} - w_{r2}) + (w_{e2} - w_{ex1} - S_{s2})\{F(R_1 + R_2)\} + (w_{ex1} -$

$w_{ex2})\{F(R_2 + C_1)\}$

Also, we have

$\frac{d^2\pi_A^r(R_1,R_2)}{dR_1{}^2} = (w_{e1} - w_{e2} - S_{s1} + S_{s2}) * f(R_1) + (w_{e2} - w_{ex1} - S_{s2}) * \{f(R_1 + R_2)$

$\frac{d^2\pi_A^r(R_1,R_2)}{dR_1 dR_2} = (w_{e2} - w_{ex1} - S_{s2}) * \{f(R_1 + R_2)\}$

$\frac{d^2\pi_A^r(R_1,R_2)}{dR_2{}^2} = (w_{e2} - w_{ex1} - S_{s2}) * f(R_1 + R_2) + (w_{ex1} - w_{ex2}) * \{f(R_2 + C_1)\}$

We will prove that Hessian matrix of retailer's profit function is negative definite. We have

$$H(R_1, R_2) = \begin{bmatrix} \frac{d^2\pi_A^r(R_1,R_2)}{(dR_1)^2} & \frac{d^2\pi_A^r(R_1,R_2)}{dR_1 dR_2} \\ \frac{d^2\pi_A^r(R_1,R_2)}{dR_2 dR_1} & \frac{d^2\pi_A^r(R_1,R_2)}{(dR_2)^2} \end{bmatrix}$$

Denote $\mathrm{P} = (w_{e1} - w_{e2} - S_{s1} + S_{s2}) * f(R_1)$; $Q = (w_{e2} - w_{ex1} - S_{s2}) * \{f(R_1 + R_2)\}$ and $R = (w_{ex1} - w_{ex2}) * \{f(R_2 + C_1)\}$

Then,

$$H(R_1, R_2) = \begin{bmatrix} P + Q & Q \\ Q & Q + R \end{bmatrix}$$

In order to prove that $H(R_1, R_2)$ is negative definite, we have to derive that

$$A_1 = (P + Q) < 0$$

$$A_2 = (P + Q) * (Q + R) - \mathrm{Q}^2 = PQ + (P + Q) * R > 0$$

Consider A_1, we have,

$\mathrm{P} = (w_{e1} - w_{e2} - S_{s1} + S_{s2}) * f(R_1) < 0$, due to $(w_{e1} < w_{e2})$ and $(S_{s1} > S_{s2})$.

$Q = (w_{e2} - w_{ex1} - S_{s2}) * \{f(R_1 + R_2)\} < 0$, due to $(w_{ex1} + S_{s2} > w_{e2})$.
So, $A_1 < 0$

Consider A_2, we have

$R = (w_{ex1} - w_{ex2}) * \{f(R_2 + C_1)\} < 0$, due to $(w_{ex1} < w_{ex2})$.
So, $A_2 > 0$

Hence, we can conclude that the Hessian matrix of the retailer's profit function is negative definite and the retailer's profit function $\pi_A^r(R_1, R_2)$ is a concave function.

4.2.2 Scenario B: When Disruption Occurs at Supplier 1

In the first stage (capacity construction stage), supplier 1 and supplier 2 sign capacity reservation contracts with retailer in which supplier offers the reservation parameters (w_r, w_e, w_{ex}). The retailer initially forecasts the demand and reserves the amounts 'R_1', 'R_2' with supplier 1 and supplier 2, respectively. As retailer signs reservation contracts with both supplier 1 and supplier 2, he pays the reservation price for reserving units to the suppliers. The profit function of retailer in this stage is shown in equation (4.22).

$$\pi_1^r(R_1, R_2) = -w_{r1} * R_1 - w_{r2} * R_2 \quad (4.22)$$

Supplier 1 and supplier 2 receive the reserved quantities from the retailer and construct the capacity accordingly. The profit functions of supplier 1 and supplier 2 in this stage are given in equation (4.23) and (4.24), respectively.

$$\pi_1^{s1}(C_1) = w_{r1} * R_1 - C_1 * c_{c1} \quad (4.23)$$

$$\pi_1^{s2}(C_2) = w_{r2} * R_2 - C_2 * c_{c2} \quad (4.24)$$

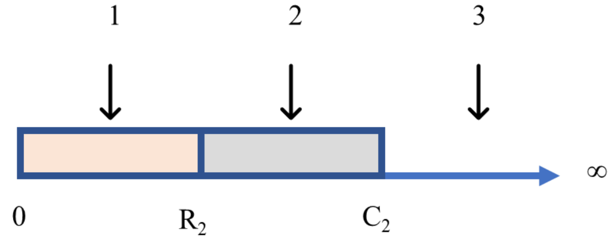
Before the beginning of stage 2, supplier 1 suffers a disruptive event, resulting into complete breakdown of its operation. Due to this, the retailer cannot receive orders from supplier 1 and supplier 1 has to pay the penalty for not supplying the units reserved by the retailer. The profit of supplier 1 are shown in equation (4.25).

$$\pi_2^{s1}(C_1) = -S_s * R_1 \quad (4.25)$$

In the second stage (production and selling stage), the realised demand at the retailer is 'x', the retailer can place order only to the 2nd supplier with reserved capacity (R_2) and constructed capacity (C_2). In this scenario, the realized demand can receive value in one of the three intervals as illustrated in Figure 4.2. In those three intervals, the order quantities of the retailer to the backup supplier are different, and hence, the profit functions of the retailer and the backup supplier will have different expressions.

Figure 4.2

Possible Scenarios of Realized Demand for Scenario B



In the following sections, the profit functions of the retailer and the backup supplier in each sub-scenario associated with each interval presented in Figure 4.2 will be derived.

Sub-scenario 1B: $x < R_2$. In this situation, the profit of the retailer comes from the revenue generated from sales as depicted in equation (4.26). Moreover, the retailer has to pay the price charged by supplier 2 for exercising x units and the penalty for not exercising $(R_2 - x)$ units at supplier 2.

$$\pi_2^r(R_1, R_2) = w_s * x - w_{e2} * x - S_{s2} * (R_2 - x) \quad (4.26)$$

The profit of supplier 2 is determined from the exercise price paid by the retailer for x units, his production cost, and the penalty paid by the retailer for not exercising $(R_2 - x)$ units as presented in equation (4.27).

$$\pi_2^{s2}(C_2) = w_{e2} * x + S_{s2} * (R_2 - x) - c_{p2} * x \quad (4.27)$$

Sub-scenario 2B: $\boldsymbol{R_2 < x < C_2}$. In this situation, the profit of the retailer comes from the revenue generated from sales subtracting the payments to supplier 2 for exercising the reserved units and excess units as given in equation (4.28).

$$\pi_2^r(R_1, R_2) = w_s * x - w_{e2} * R_2 - w_{ex2} * (x - R_2) \quad (4.28)$$

The profit of supplier 2 comes from the exercise charge and excess charge paid by the retailer subtracting production cost as shown in equation (4.29).

$$\pi_2^{s2}(C_2) = w_{e2} * R_2 + w_{ex2} * (x - R_2) - c_{p2} * x \quad (4.29)$$

Sub-scenario 3B: $\boldsymbol{x \geq C_2}$. In this case, the retailer will order C_2 units from supplier 2. The retailer will experience shortage for the excess demand. The profit of the retailer comes from the revenue generated from sales, the payments to supplier 2 for exercising the reserved units and excess units, and the shortage cost for unsatisfied demand as shown in equation (4.30).

$$\pi_2^r(R_1, R_2) = w_s * C_2 - w_{e2} * R_2 - w_{ex2} * (C_2 - R_2) - S_r * (x - C_2) \quad (4.30)$$

The profit of supplier 2 comes from the exercise charge and excess charge paid by the retailer subtracting production cost as shown in equation (4.31).

$$\pi_2^{s2}(C_2) = w_{e2} * R_2 + w_{ex2} * (C_2 - R_2) - c_{p2} * C_2 \quad (4.31)$$

From the above analyses, for the situation when disruption occurs at supplier 1, the overall profits of the retailer, the supplier 1 and the supplier 2 can be determined as the cumulative profits of stage 1 and stage 2, which are shown in equations (4.32), (4.33) and (4.34), respectively.

$[\pi_B^r(R_1, R_2)] = -w_{r1} * R_1 - w_{r2} * R_2 + S_s * R_1 + \int_0^{R_2} [w_s * x - w_{e2} * x - S_{s2} * (R_2 - x)] f(x) dx + \int_{R_2}^{C_2} [w_s * x - w_{e2} * R_2 - w_{ex2} * (x - R_2)] f(x) dx + \int_{C_2}^{\infty} [w_s * C_2 - w_{e2} * R_2 - w_{ex2} * (C_2 - R_2) - S_{\mathrm{r}} * (x - C_2)\ ] f(x) dx$

(4.32)

$$\pi_B^s(C_1) = w_{r1} * R_1 - C_1 * c_{c1} - S_s * R_1 \qquad (4.33)$$

$\pi_B^s(C_1) = w_{r2} * R_2 - C_2 * c_{c2} + \int_0^{R_2} [w_{e2} * x + S_{s2} * (R_2 - x) - c_{p2} * x] f(x)\, dx + \int_{R_2}^{C_2} [w_{e2} * R_2 + w_{ex2} * (x - R_2) - c_{p2} * x] f(x) dx + [w_{e2} * R_2 + w_{ex2} * (C_2 - R_2) - c_{p2} * C_2] * \{1 - F(C_2)\}$

(4.34)

Proposition 4.2: *The profit function of the retailer i.e.,* $\pi_B^r(R_1, R_2)$ *is a concave function.*

Proof of proposition 4.2: From the profit function of the retailer, i.e., $\pi_B^r(R_1, R_2)$, we have

- $\frac{d\pi_B^r(R_1,R_2)}{dR_1} = -w_{r1} + S_s$
- $\frac{d\pi_B^r(R_1,R_2)}{dR_2} = \Big[-w_{r2} + \{(w_s - w_{e2}) * R_2\} f(R_2) + \int_0^{R_2} \frac{\partial}{\partial R_2} [w_s * x - w_{e2} * x - S_{s2} * (R_2 - x)] f(x) - \{(w_s - w_{e2}) * R_2\} f(R_2) + \int_{R_2}^{C_2} \frac{\partial}{\partial R_2} [w_s * x - w_{e2} * R_2 - w_{ex2} * (x - R_2)] f(x) + \int_{C_2}^{\infty} \frac{\partial}{\partial R_2} [w_s * C_2 - w_{e2} * R_2 - w_{ex2} * (C_2 - R_2) - S_{\mathrm{r}} * (x - C_2)\ ] f(x)\Big]$

$= [-w_{r2} - S_{s2} * F(R_2) + (w_{ex2} - w_{e2}) * \{F(C_2) - F(R_2)\} + (w_{ex2} - w_{e2}) * \{1 - F(C_2)\}]$

$= [(w_{e2} - w_{ex2} - S_{s2}) * \{F(R_2)\} + (w_{ex2} - w_{e2} - w_{r2})]$

Also, we have

$\frac{d^2\pi_B^r(R_1,R_2)}{d{R_2}^2} = 0$

$\frac{d^2\pi_B^r(R_1,R_2)}{d{R_2}^2} = [(w_{e2} - w_{ex2} - S_{s2}) * \{f(R_2)\}]$

$\frac{d^2\pi_B^r(R_1,R_2)}{dR_1dR_2} = 0$

We will prove that Hessian matrix of retailer's profit function is negative semi-definite. We have

$$H(R_1, R_2) = \begin{bmatrix} \frac{d^2\pi_B^r(R_1,R_2)}{(dR_2)^2} & \frac{d^2\pi_B^r(R_1,R_2)}{dR_2dR_1} \\ \frac{d^2\pi_B^r(R_1,R_2)}{dR_1dR_2} & \frac{d^2\pi_B^r(R_1,R_2)}{(dR_1)^2} \end{bmatrix}$$

$$H(R_1, R_2) = \begin{bmatrix} [(w_{e2} - w_{ex2} - S_{s2}) * \{f(R_2)\}] & 0 \\ 0 & 0 \end{bmatrix}$$

In order to prove that $H(R_1, R_2)$ is negative semi-definite, we have to derive that

$$A_1 < 0$$

$$A_2 \geq 0$$

Consider A_1, we have,

$$A_1 = [(w_{e2} - w_{ex2} - S_{s2}) * \{f(R_2)\}]$$

It is noted that ($w_{ex2} + S_{s2} > w_{e2}$) and therefore, $A_1 < 0$.

Consider A_2, we have,

$$A_2 = [(w_{e2} - w_{ex2} - S_{s2}) * \{f(R_2)\}] * 0 - 0$$

$$A_2 = 0$$

Hence, we can conclude that the Hessian matrix of retailer's profit function is negative semi-definite and the retailer's profit function $\pi_B^r(R_1, R_2)$ is a concave function.

4.2.3 Total Profit Functions

From the analyses of scenario A and scenario B, the total profit of the retailer, the supplier 1 and the supplier 2 can be determined as the cumulative profits of stage 1 and stage 2 as derived in the sub-scenarios when disruption does not occur and when disruption occurs. If p is the probability that disruption occur at supplier 1 the total profit functions of the retailer, the supplier 1 and the supplier 2 can be derived as in equations (4.35), (4.36) and (4.37), respectively.

$$\pi^r(R_1, R_2) = (1-p) * [\pi_A^r(R_1, R_2)] + p * [\pi_B^r(R_1, R_2)] \tag{4.35}$$

$$\pi^{s1}(C_1) = (1-p) * [\pi_A^s(C_1)] + p * [\pi_B^s(C_1)\ ] \tag{4.36}$$

$$\pi^{s2}(C_2) = (1-p) * [\pi_A^s(C_1)] + p * [\pi_B^s(C_1)] \tag{4.37}$$

We proved the concavity of profit function of retailer for scenario A and scenario B in propositions 4.1 and 4.2. The total profit function of the retailer derived in equation (4.35), is the sum of these functions. Therefore, it is also a concave function. Hence, the optimal reserved capacities of the retailer (R_1, R_2) can be determined uniquely.

In details, R_1 and R_2 will be the unique solutions of $\frac{d\pi^r}{dR_1} = 0$ and $\frac{d\pi^r}{dR_2} = 0$, respectively, i.e.,

$$0 = (1-p) * [(w_{ex1} - w_{e1} - w_{r1}) + (w_{e1} - w_{e2} - S_{s1} + S_{s2})F(R_1) + (w_{e2} - w_{ex1} - S_{s2})\{F(R_1 + R_2)\}] + p * [-w_{r1} + S_s] \tag{4.38}$$

and

$$0 = (1-p) * [(w_{ex2} - w_{e2} - w_{r2}) + (w_{e2} - w_{ex1} - S_{s2})\{F(R_1 + R_2)\} + (w_{ex1} - w_{ex2}) * \frac{(1-p)*(w_{ex1} - c_{p1} - c_{c1}) - p*[c_{c1}\ ]}{(1-p)*(w_{ex1} - c_{p1})}] + p * [(w_{e2} - w_{ex2} - S_{s2}) * \{F(R_2)\} + (w_{ex2} - w_{e2} - w_{r2})] \tag{4.39}$$

To find the optimal solutions of R_1 and R_2, the following iterative procedure is used.

Iterative procedure:

Initialize the procedure by giving $F^{(0)}(R_1 + R_2) = a,\ (0 < a < 1)$, then find $(R_1 + R_2)^{(0)}$

Set $i = 1$

- Step 1: Find $F^{(i)}(R_1)$ from $F^{(i-1)}(R_1 + R_2)$ using equation (4.38).

  Determine ${R_1}^{(i)}$ from $F^{(i)}(R_1)$
- Step 2: Find $F^{(i)}(R_2)$ from $F^{(i-1)}(R_1 + R_2)$ using equation (4.39).

  Determine ${R_2}^{(i)}$ from $F^{(i)}(R_2)$
- Step 3: If $\left|{R_1}^{(i)} + {R_2}^{(i)} - (R_1 + R_2)^{(i-1)}\right| < \varepsilon$, then

  Stop

Otherwise

Determine $F^{(i)}(R_1 + R_2)\ \ from\ R_1{}^{(i)} + R_2{}^{(i)}$

$(R_1 + R_2)^{(i)} = R_1{}^{(i)} + R_2{}^{(i)}$

$i = i + 1$

Go back to step 1.

The optimal constructed capacity of supplier 1 and supplier 2 will be determined using the following propositions.

Proposition 4.3: *The profit function of supplier 1, i.e., π^{s_1} is a concave function, and hence, the optimal constructed capacity of supplier 1 can be determined uniquely as*

$$C_1 = F^{-1}\left[\frac{p*[c_{c1}\,]+(1-p)*(w_{ex1}-c_{p1}-c_{c1})}{(1-p)*(w_{ex1}-c_{p1})}\right] - R_2$$

Proof of proposition 4.3: From the profit function of the supplier 1, we have

$$\frac{d\pi^{s_1}}{dC_1} = (1-p)*[-c_{c1} + \left[w_{e1}*R_1 + w_{ex1}*((R_2+C_1)-R_1-R_2) - c_{p1}*((R_2+C_1)-R_2)\right]f(R_2+C_1) + \left[w_{e1}*R_1 + w_{ex1}*(C_1-R_1) - c_{p1}*C_1\right]f(C_1+C_2) - \left[w_{e1}*R_1 + w_{ex1}*(C_1-R_1) - c_{p1}*C_1\right]f(C_1+R_2) + \int_{C_1+R_2}^{C_1+C_2}\frac{d}{dC_1}\left[w_{e1}*R_1 + w_{ex1}*(C_1-R_1) - c_{p1}*C_1\right]f(x)dx - \left[w_{e1}*R_1 + w_{ex1}*(C_1-R_1) - c_{p1}*C_1\right]f(C_1+C_2) + \int_{C_1+C_2}^{\infty}\frac{d}{dC_1}\left[w_{e1}*R_1 + w_{ex1}*(C_1-R_1) - c_{p1}*C_1\right]f(x)dx] + p*[-c_{c1}\,]$$

$$= (1-p)*[-c_{c1} + \left[w_{e1}*R_1 + w_{ex1}*(C_1-R_1) - c_{p1}*C_1\right]f(R_2+C_1) + \left[w_{e1}*R_1 + w_{ex1}*(C_1-R_1) - c_{p1}*C_1\right]f(C_1+C_2) - \left[w_{e1}*R_1 + w_{ex1}*(C_1-R_1) - c_{p1}*C_1\right]f(C_1+R_2) + (w_{ex1}-c_{p1})\int_{C_1+R_2}^{C_1+C_2}f(x)dx - \left[w_{e1}*R_1 + w_{ex1}*(C_1-R_1) - c_{p1}*C_1\right]f(C_1+C_2) + (w_{ex1}-c_{p1})\int_{C_1+C_2}^{\infty}f(x)dx] - p*[c_{c1}\,]$$

$$= (1-p)*[(w_{ex1}-c_{p1}-c_{c1}) - (w_{ex1}-c_{p1})*\{F(C_1+R_2)\}] - p*[c_{c1}\,]$$

Also, we have

$$\frac{d^2\pi^{s_1}}{dC_1{}^2} = -(1-p)*(w_{ex1}-c_{p1})*\{f(C_1+R_2)\}$$

It is noted that $(w_{ex1} > c_{p1})$,therefore, $\frac{d^2\pi^{s_1}}{dC_1{}^2} < 0$. So, π^{s_1} is a concave function, and hence, the optimal solution of C_1 exists uniquely.

The optimal solution of C_1 can be determined from $\frac{d\pi^{s_1}}{dC_1} = 0$. Hence,

$\{F(C_1 + R_2)\} = \frac{p*[c_{c1}]+(1-p)*(w_{ex1}-c_{p1}-c_{c1})}{(1-p)*(w_{ex1}-c_{p1})}$

Therefore,

$C_1 = F^{-1}\left[\frac{p*[c_{c1}]+(1-p)*(w_{ex1}-c_{p1}-c_{c1})}{(1-p)*(w_{ex1}-c_{p1})}\right] - R_2$

Proposition 4.4: *The profit function of supplier 2, i.e.,* π^{s_2} *is a concave function.*

Proof proposition of 4.4: From the profit function of the supplier 2, we have

$\frac{d\pi^{s2}}{dC_2} = (1-p) * [-c_{c2} + [w_{e2} * R_2 + w_{ex2} * (C_1 + C_2 - R_2 - C_1) - c_{p2} * (C_1 + C_2 - C_1)]f(C_1 + C_2) - [w_{e2} * R_2 + w_{ex2} * (C_2 - R_2) - c_{p2} * C_2]f(C_1 + C_2) + \int_{C_1+C_2}^{\infty} \frac{d}{dC_2}[w_{e2} * R_2 + w_{ex2} * (C_2 - R_2) - c_{p2} * C_2]f(x)dx] + p * [-c_{c2} + \{w_{e2} * R_2 + w_{ex2} * (C_2 - R_2) - c_{p2} * C_2\}f(C_2) + [w_{e2} * R_2 + w_{ex2} * (C_2 - R_2) - c_{p2} * C_2] * \{-f(C_2)\} + [w_{ex2} - c_{p2}] * \{1 - F(C_2)\}]$

$= (1-p) * [-c_{c2} + [w_{e2} * R_2 + w_{ex2} * (C_2 - R_2) - c_{p2} * C_2]f(C_1 + C_2) - [w_{e2} * R_2 + w_{ex2} * (C_2 - R_2) - c_{p2} * C_2]f(C_1 + C_2) + (w_{ex2} - c_{p2}) * \{1 - F(C_1 + C_2)\}] + p * [-c_{c2} + [w_{ex2} - c_{p2}] * \{1 - F(C_2)\}]$

$= (1-p) * (w_{ex2} - c_{p2} - c_{c2}) - (w_{ex2} - c_{p2}) * F(C_1 + C_2) + p * [w_{ex2} - c_{p2} - c_{c2}] - [w_{ex2} - c_{p2}] * F(C_2)]$

Also, we have

$\frac{d^2\pi^{s_2}}{dC_2{}^2} = -(1-p) * [(w_{ex2} - c_{p2}) * f(C_1 + C_2)] - p * [[w_{ex2} - c_{p2}] * f(C_2)]$

It is noted that $(w_{ex2} > c_{p2})$ and therefore, $\frac{d^2\pi^{s2}}{dC_2{}^2} < 0$. Hence, π^{S_2} is a concave function.

From the proposition 4, the optimal solution of C_2 exists uniquely by solving $\frac{d\pi^{s_1}}{dC_1} = 0$, i.e.,

$0 = (1-p) * (w_{ex2} - c_{p2} - c_{c2}) - (w_{ex2} - c_{p2}) * F(C_1 + C_2) + p * [w_{ex2} - c_{p2} - c_{c2}] - [w_{ex2} - c_{p2}] * F(C_2)]$

(4.40)

To find the optimal solution for C_2, the following iterative procedure is used.

Iterative procedure:

Initialize the procedure by giving $F^{(0)}(C_1 + C_2) = b,\ (0 < b < 1)$, then find $(C_1 + C_2)^{(0)}$

Set $i = 1$

- Step 1: Find $F^{(i)}(C_2)$ from $F^{(i-1)}(C_1 + C_2)$ using equation (4.40).

  Determine ${C_2}^{(i)}$ from $F^{(i)}(C_2)$

  $(C_1 + C_2)^{(i)} = C_1 + {C_2}^{(i)}$
- Step 2: If $\left|(C_1 + C_2)^{(i)} - (C_1 + C_2)^{(i-1)}\right| < \varepsilon$, then

  Stop

  Otherwise

  $F^{(i)}(C_1 + C_2) = F((C_1 + C_2)^{(i)})$

  $i = i + 1$

  Go back to step 1.

4.3 Numerical Experiments

To examine the applicability of the proposed capacity reservation contract model, various numerical experiments were conducted, and the results of a base case will be firstly presented in this section. The data related to various costs/contract parameters of the base case are given as: w_s= 400, S_r= 135, w_{r1}= 20, w_{e1}, = 70, w_{ex1}= 105, c_{c1}= 5, c_{p1}= 55, S_{s1}= 55, w_{r2}= 22, w_{e2}= 72, w_{ex2}= 125, c_{c2}= 5, c_{p2}= 55, S_{s2}= 35, S_s= 30, p=0.05. It is noted that the following conditions must hold true, w_{ex1}+$S_{s2} > w_{e2}$; $w_{ex1} < w_{ex2}$; $w_{ex1} > w_{e1}$; $w_{ex2} > w_{e2}$; $w_{e1} < w_{e2}$. It is assumed that the demand follows a normal distribution with mean 1000 and standard deviation 200. In this section we present the numerical results for a base case with predefined input parameters. The effects of various cost and contract parameters will be examined.

From the above input parameters, the following results are achieved.

Reserved capacity set by the retailer for supplier 1, R_1 = 640

Reserved capacity set by the retailer for supplier 2, R_2 = 203

Constructed capacity of supplier 1, C_1 = 1059

Constructed capacity of supplier 2, C_2 = 342

With the above results, the profit of all members are as follows,

Profit of the retailer ($) = 289899

Profit of supplier 1 ($) = 23966

Profit of supplier 2 ($) = 7562

4.4 Sensitivity Analyses

The following sections will present sensitivity analyses with respect to different input parameters to assess their impact on decision variables and the profits of all involved parties. The focus is mainly on the effects of contract parameters related to the backup supplier, the one that has been incorporated into the contract model to help enhance flexibility and to provide redundancy. Discussions on the applicability of the proposed contract model in the contract negotiation process will also be discussed.

4.4.1 Effect of Unit Shortage/Penalty Cost (S_r)

This section will analyze the impact of the unit shortage cost, and the findings are presented in Table 4.1.

Table 4.1

Sensitivity Analysis w.r.t. Unit Shortage Cost

S_r	Capacities				Profits		
	R_1	R_2	C_1	C_2	Retailer	Supplier 1	Supplier 2
120	640	203	1059	342	290417	23966	7562
125	640	203	1059	342	290244	23966	7562
130	640	203	1059	342	290072	23966	7562
135	640	203	1059	342	289899	23966	7562
140	640	203	1059	342	289727	23966	7562
145	640	203	1059	342	289554	23966	7562
150	640	203	1059	342	289381	23966	7562

The results shown in Table 4.1 indicate that the shortage cost does not influence the decision variables or the profits of the two suppliers. This outcome is logical as the reserved and constructed capacities depend solely on the contract parameters

(w_r, w_e, w_{ex}). Nonetheless, the profit of the retailer decreases when the penalty cost rises, which is a comprehensible trend.

4.4.2 Effect of Unit Reservation Price at Supplier 2 (w_{r2})

This section will analyze the impact of the unit price for reserving products at supplier 2, and the findings are presented in Table 4.2.

Table 4.2

Sensitivity Analysis w.r.t. the Unit Price for Reserving Products at Supplier 2

w_{r2}	Capacities				Profits		
	R_1	**R_2**	**C_1**	**C_2**	**Retailer**	**Supplier 1**	**Supplier 2**
21	167	684	579	796	298012	10497	23245
21.5	549	300	963	438	291793	21190	10746
22	640	203	1059	342	289899	23966	7562
22.5	689	149	1113	288	288812	25581	5737
23	724	109	1154	247	287997	26831	4327

According to Table 4.2, when the unit price for reserving products from supplier 2 increases, it becomes more costly for the retailer to reserve products from that supplier. Consequently, the retailer will decrease the quantity reserved to supplier 2 and increase the quantity reserved to supplier 1. This variation in reserved capacities leads to an increase in the constructed capacity of supplier 1 and a corresponding decrease in the constructed capacity of supplier 2. These changes resulted in an increase in the profit of supplier 1 and a decrease in the profit of supplier 2. Moreover, this change in reservation price leads to a decrease in the profit of the retailer.

4.4.3 Effect of Unit Exercise Price at Supplier 2 (w_{e2})

This section will analyze the impact of the unit exercise price at supplier 2, and the findings are presented in Table 4.3.

Table 4.3

Sensitivity Analysis w.r.t. the Unit Exercise Price at Supplier 2

w_{e2}	Capacities				Profits		
	R_1	**R_2**	**C_1**	**C_2**	**Retailer**	**Supplier 1**	**Supplier 2**
71	166	683	580	795	297975	10538	23224
71.5	550	297	965	435	291729	21275	10658
72	640	203	1059	342	289899	23966	7562
72.5	686	153	1110	291	288883	25478	5849
73	719	116	1147	254	288140	26613	4569

Table 4.3 indicates that when the exercise price at supplier 2 increases, it becomes more costly for the retailer to exercise units from that supplier. Consequently, the retailer will shift its reservation towards supplier 1, where the exercise price is lower. This change leads to an increase in the reserved and constructed capacities at supplier 1, while the reserved and constructed capacities at supplier 2 decrease. As a result, there is an increase in the profit of supplier 1. On the other hand, the decrease in reserved capacity and constructed capacity at supplier 2 results in a decrease in his profit. This change in unit exercise price also lead to a decrease in the profit of the retailer.

4.4.4 Effect of Unit Construction Cost at Supplier 2 (C_{c2})

This section will analyze the impact of the unit construction cost at supplier 2, and the findings are presented in Table 4.4.

Table 4.4

Sensitivity Analysis w.r.t. the Impact of the Unit Construction Cost at Supplier 2

C_{c2}	Capacities				Profits		
	R_1	**R_2**	**C_1**	**C_2**	**Retailer**	**Supplier 1**	**Supplier 2**
3	640	203	1059	787	299379	23966	8528
4	640	203	1059	426	292092	23966	7939
5	640	203	1059	342	289899	23966	7562
6	640	203	1059	297	288466	23966	7244
7	640	203	1059	265	287256	23966	6964

From the results in Table 4.4, when the unit construction cost at supplier 2 increases, it becomes less appealing for supplier 2 to construct a high capacity. This leads to a decrease in the constructed capacity and profit of supplier 2, while the reserved capacity of the retailer to supplier 2 remains the same. However, the retailer may encounter more shortages, resulting in a decrease in his profit. Furthermore, it is observed that the reserved and constructed capacities at supplier 1 are not affected, leading to an unchanged profit for supplier 1.

4.4.5 Effect of Unit Production Cost at Supplier 2 (C_{p2})

This section will analyze the impact of the unit production cost at supplier 2, and the findings are presented in Table 4.5.

Table 4.5
Sensitivity Analysis w.r.t. the Unit Production Cost at Supplier 2

C_{p2}	Capacities				Profits		
	R_1	**R_2**	**C_1**	**C_2**	**Retailer**	**Supplier 1**	**Supplier 2**
40	640	203	1059	411	291732	23966	10540
45	640	203	1059	385	291083	23966	9540
50	640	203	1059	362	290484	23966	8547
55	640	203	1059	342	289899	23966	7562
60	640	203	1059	322	289306	23966	6584
65	640	203	1059	303	288683	23966	5613
70	640	203	1059	284	288009	23966	4650

According to Table 4.5, if the unit production cost at supplier 2 increases, the constructed capacity of supplier 2 will decrease. This leads to a decrease in the profits of both supplier 2 and the retailer. Nevertheless, the reserved quantity of the retailer to supplier 2 remains unchanged. For supplier 1, any changes in the unit production cost at supplier 2 will not impact the reserved and constructed quantities as well as the profit of supplier 1.

4.4.6 Effect of Unit Penalty Cost for not Exercising Reserved Capacity at Supplier 2 (S_{s2})

This section will analyze the impact of the unit penalty cost for not exercising the reserved capacity at supplier 2, and the findings are presented in Table 4.6.

Table 4.6

Sensitivity Analysis w.r.t. the Unit Penalty Cost for not Exercising Reserved Capacity at Supplier 2

S_{s2}	Capacities				Profits		
	R_1	R_2	C_1	C_2	Retailer	Supplier 1	Supplier 2
27	612	250	1013	388	290940	22574	9024
29	618	239	1024	377	290687	22903	8684
33	632	216	1047	354	290168	23596	7957
35	640	203	1059	342	289899	23966	7562
37	649	190	1072	329	289619	24359	7138
40	664	169	1093	307	289169	25007	6429

Table 4.6 shows that if the unit penalty cost for not exercising the reserved capacity at supplier 2 increases, the retailer will reduce the reserved capacity from supplier 2 and reserve more from supplier 1, where the penalty cost is lower. This change in reserved capacity leads to an increase in the constructed capacity at supplier 1 and a decrease in the constructed capacity of supplier 2. Consequently, both the retailer and the supplier 2's profits decrease. Conversely, the increase in the reserved capacity at supplier 1 will result in an increase in the constructed capacity and profit for supplier 1.

4.4.7 Effect of Price for Exercising Extra Units at Supplier 2 (w_{ex2})

This section will analyze the impact of the unit price for exercising extra units at supplier 2, and the findings are presented in Table 4.7.

Table 4.7

Sensitivity Analysis w.r.t. the Unit Price for Exercising Extra Units at Supplier 2

w_{ex2}	Capacities				Profits		
	R_1	R_2	C_1	C_2	Retailer	Supplier 1	Supplier 2
115	752	75	1188	175	286328	27903	2880
120	707	128	1135	247	287945	26236	4838
125	640	203	1059	342	289899	23966	7562
130	378	473	789	625	295016	16349	16866
135	56	795	467	908	298658	7400	27786

Table 4.7 indicates that if the price for exercising extra units at supplier 2 increases, the retailer will become more inclined to reserve capacity from supplier 2. This increase in reserved capacity results in an increase in both the constructed capacity and profit of supplier 2. Moreover, the increase in reserved capacity at supplier 2 will lead to decreases in reserved capacity and constructed capacity at supplier 1, and hence, his profit as well.

4.4.8 Effect of Probability of Disruption at Supplier 1 (p)

This section will analyze the impact of the probability of disruption at supplier 1, and the findings are presented in Table 4.8.

Table 4.8

Sensitivity Analysis w.r.t. the Probability of Disruption at Supplier 1

p	Capacities				Profits		
	R_1	R_2	C_1	C_2	Retailer	Supplier 1	Supplier 2
0.01	719	109	1148	159	299344	28492	4028
0.03	687	149	1110	234	293702	26383	5537
0.05	640	203	1059	342	289899	23966	7562
0.08	394	461	806	774	285327	15901	16764
0.1	173	684	586	917	280947	9677	24382

From the results observed in Table 4.8, as the probability of disruption at supplier 1 rises, the retailer will become more inclined to reserve capacity from supplier 2. The rise in the reserved capacity at supplier 2 leads to a corresponding increase in the constructed capacity and profit of supplier 2. However, the profit of the retailer decreases as he reserves more from supplier 2 which is more expensive. In addition, the reserved and constructed capacities at supplier 1 will also be reduced which leads to a decrease in his profit as a consequence.

4.5 Response Surface Analysis

Table 4.9 summarizes the effects of individual contract parameters related to backup supplier on the profit functions of the retailer, the main supplier, and the backup supplier.

Table 4.9
Behavior of Profit Functions when Contract Parameters Increase

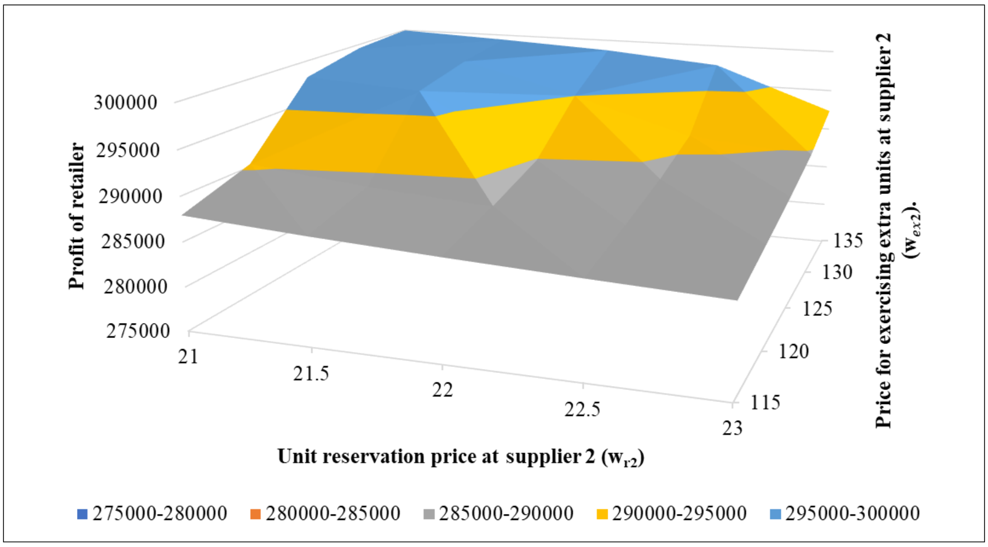
Parameter	Retailer's profit	Main supplier's profit	Backup supplier's profit
$\boldsymbol{w_{r2}}$	↓	↑	↓
$\boldsymbol{w_{e2}}$	↓	↑	↓
$\boldsymbol{S_{s2}}$	↓	↑	↓
$\boldsymbol{w_{ex2}}$	↑	↓	↑

*(↑: Increase in profit , ↓: decrease in profit)

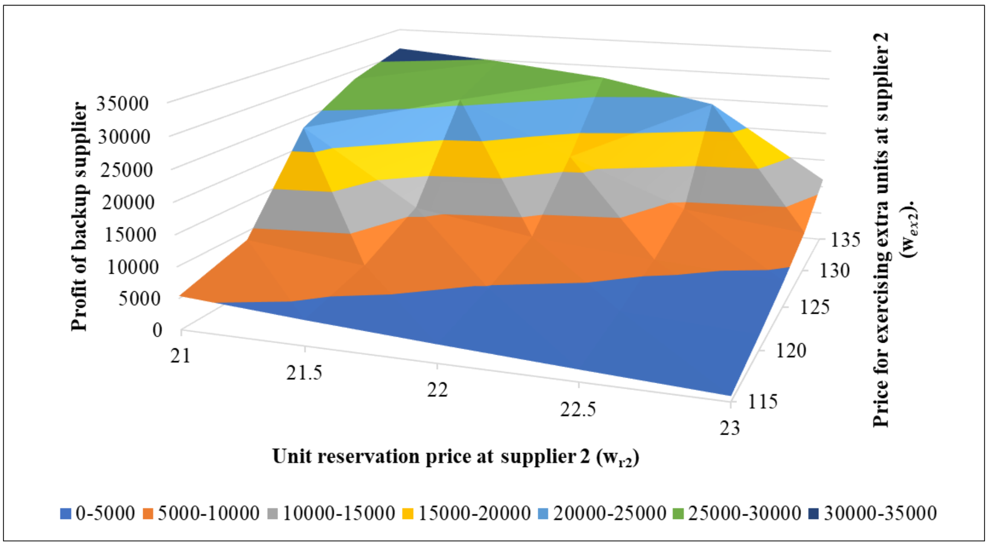
From Table 4.9, we can see that only the increase in w_{ex2} will lead to an increase in profit of the retailer who is the leader in the proposed contract model. To help the retailer and the backup supplier to make appropriate decisions during the contract negotiation process, the combined effects of w_{ex2} and other contract parameters need to be taken into consideration. Figures 4.1, 4.2 and 4.3, show the response surfaces of the retailer's profit and backup supplier's profit with respect to changes in w_{ex2} together with w_{r2}, w_{e2}, or S_{s2}.

Figure 4.3

Retailer's Profit and Backup Supplier's Profit w.r.t. w_{ex2} *and* w_{r2}



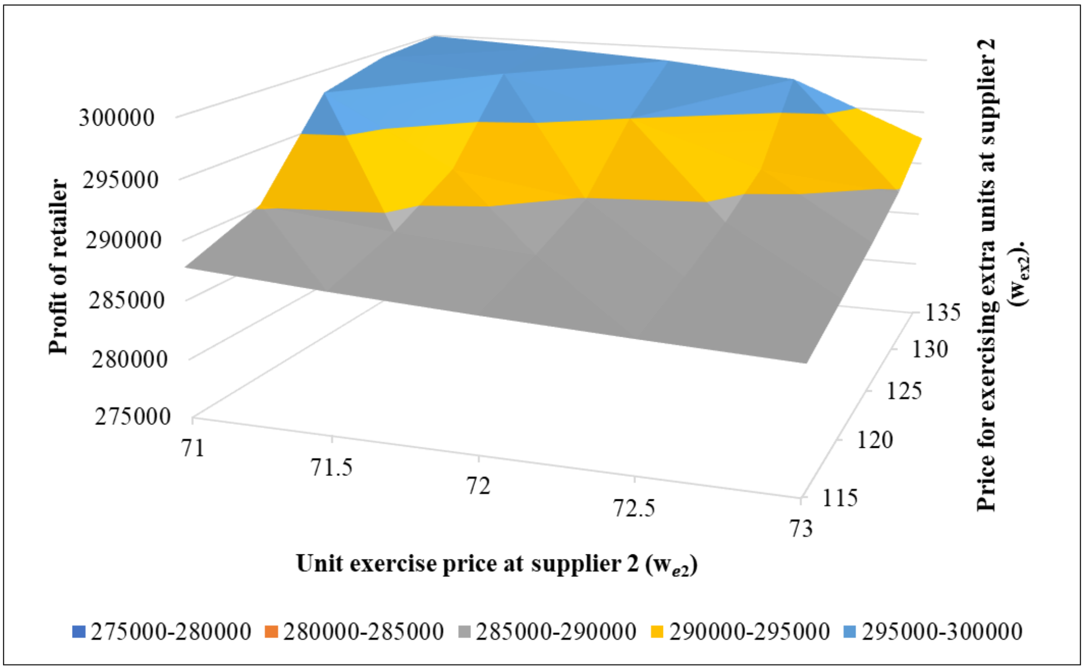
(a) Retailer's profit



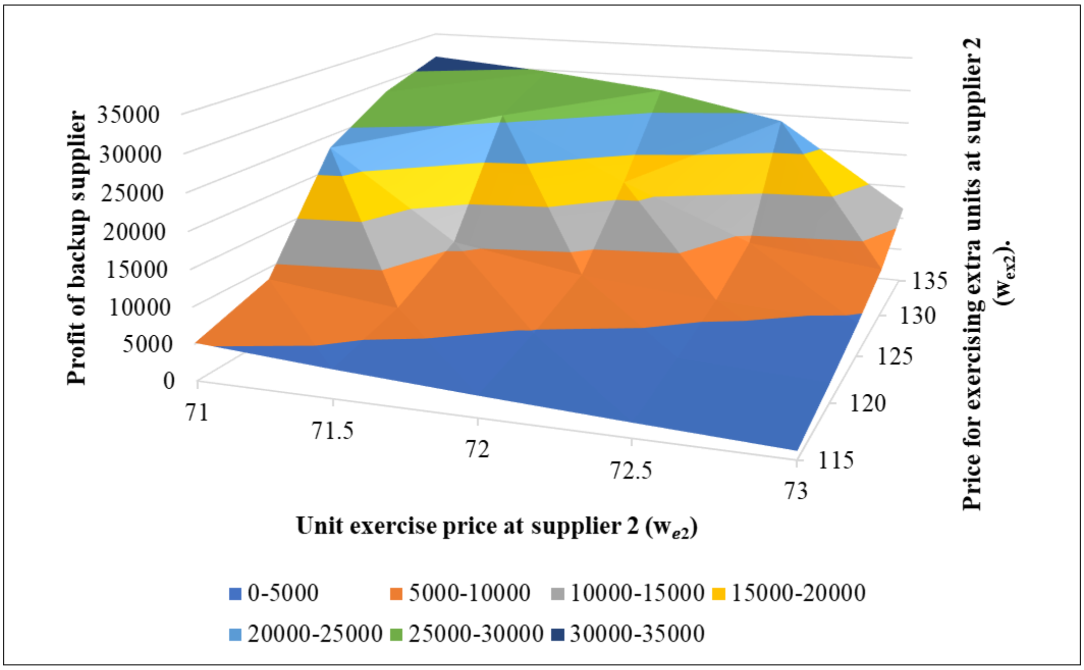
(b) Backup supplier's profit

Figure 4.4

Retailer's Profit and Backup Supplier's Profit w.r.t. w_{ex2} and w_{e2}



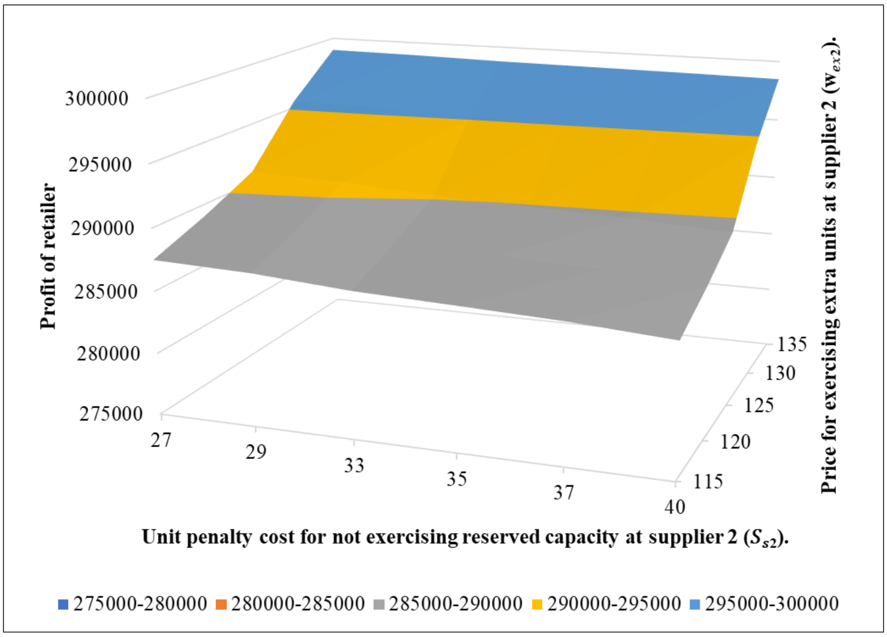
(a) Retailer's profit



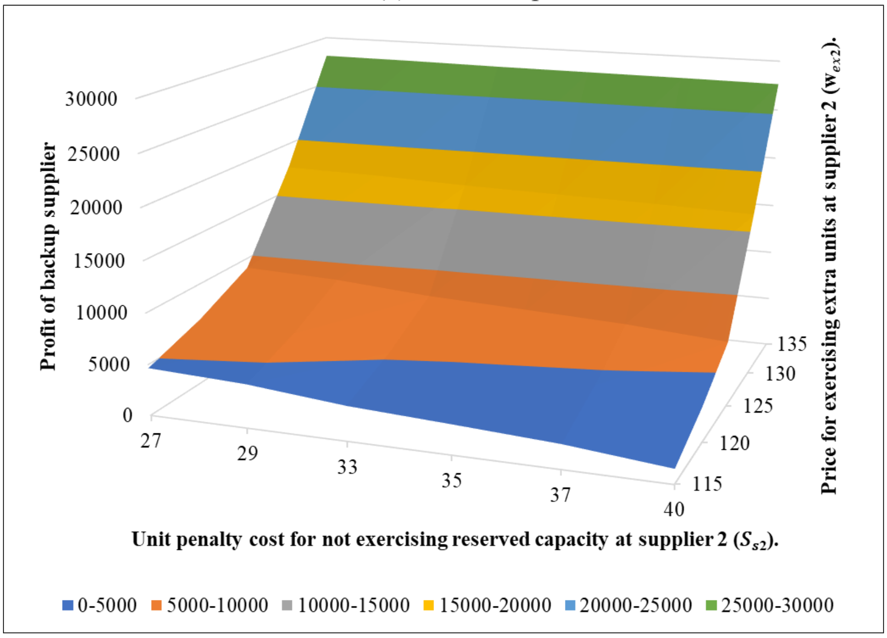
(b) Backup supplier's profit

Figure 4.5

Retailer's Profit and Backup Supplier's Profit w.r.t. w_{ex2} and S_{s2}



(a) Retailer's profit



(b) Backup supplier's profit

From the response surfaces, the retailer and the backup supplier can determine the corresponding contour plots that give them the minimum expected profits. The values of the contact parameters on these contour plots will be helpful for both parties in the contract negotiation process.

CHAPTER 5
MATHEMATICAL MODEL DEVELOPMENT OF DUAL RETAILER AND SINGLE SUPPLIER MODEL

5.1 Model Description

This chapter examines a supply chain that includes a single supplier with limited capacity. The supplier provides products to the two retailers located in different geographical areas, without competing with each other. During the first stage, each retailer i will reserve R_i quantity with the supplier, and supplier constructs capacity C accordingly. In the second stage, when retailer i realizes the demand x_i, he will order x_i units from the supplier. In an environment with high demand uncertainty, the retailers may make incorrect decisions in the first stage. Consequently, when demand is realized, they may place an order that is higher or lower than the reserved capacity to the supplier. In practice, the retailer may exaggerate the reserved capacity to encourage the supplier to invest more in capacity building. On the other hand, the supplier may not build sufficient capacity to avoid inventory risk if they lack confidence in the retailer's reservation level. Without a contract mechanism to coordinate the supply chain, the retailers and the supplier may make incorrect decisions regarding the reserved capacities and the constructed capacity, respectively. We assume that demand must be satisfied, so if the supplier is disrupted, he will look for additional capacity from the other suppliers so that the demand is always fulfilled. For the model formulation, the following parameters and variables are used.

i	Set of retailers, where $i = 1,2$.
C	Constructed capacity of the supplier
R_i	Reserved capacity of retailer i
w_{s_i}	Selling price of retailer i ($/unit)
w_{r_i}	Unit price for reserving products at supplier of retailer i ($/unit)
w_{e_i}	Unit exercise price set by supplier for retailer i ($/unit)
w_{ex_i}	Unit price for extra units set by supplier for retailer i ($/unit)
c_c	Unit construction cost at supplier ($/unit)
c_p	Unit production cost at supplier ($/unit)

c_t	Unit cost to buy product from other suppliers ($/unit)
S_{s_i}	Unit penalty cost for not exercising reserved capacity at supplier of retailer *i* ($/unit)
$\pi^r{}_i$	Profit function of the i^{th} retailer ($)
π^s	Profit function of the supplier ($)
x_i	Realized demand of the i^{th} retailer
p	Probability of disruption at the supplier

5.2 Model Development

We assume that the retailers and the supplier adopt the capacity reservation contract following two stages. In the first stage (capacity construction stage), the supplier signs capacity reservation contracts with each i^{th} retailer in which supplier offers the reservation parameters ($w_{r_i}, w_{e_i}, w_{ex_i}$).

5.2.1 Scenario A: When the Supplier is Available

Each retailer *i* signs a reservation contract with the supplier, whereby they pay a fee to reserve R_i units from supplier. The profit function of retailers in this stage is shown in equation (5.1).

$$\pi_{\mathrm{I}}^{r_i} = -w_{r_i} * R_i \qquad (i=1,2) \tag{5.1}$$

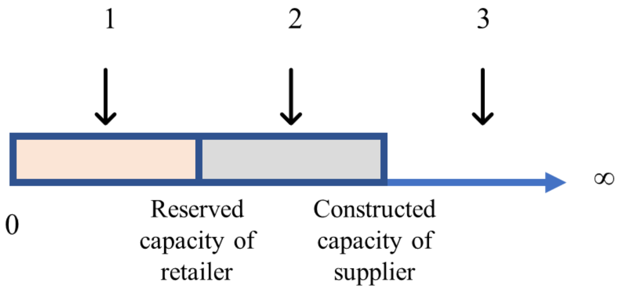
The supplier constructs the capacity as he receives the reserved quantities (R_i) from each retailer. The profit function of supplier in this stage is given in equation (5.2).

$$\pi_{\mathrm{I}}^{s} = \sum_{i=1}^{2}(w_{r_i} * R_i) - c_c * C \tag{5.2}$$

In the second stage, the realised demand at each retailer is 'x_i', and each retailer places order to the supplier accordingly. Due to uncertainty, the realized demand will follow a random distribution. Therefore, numerous scenarios may occur when the retailer *i* realises demand and submits an order to supplier as shown in Figure 5.1. For each retailer there will be 3 scenarios, as described below:

Figure 5.1

Possible Scenarios for Retailer i



We assume that the constructed capacity of the supplier (C) is more than the total reserved capacity of the retailers $(R_1 + R_2)$. With this assumption, the supplier will get an opportunity to sell units at excess price to the retailer when the demand is more than the reserved capacity of the retailers. Table 5.1 represents the scenarios of demands of retailer 1 and retailer 2.

Table 5.1

Scenarios of Demands of Retailer 1 and Retailer 2

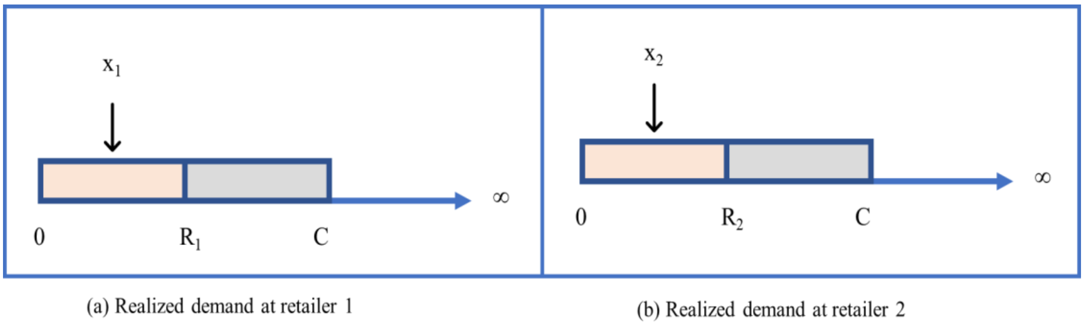
No.	**Demand of retailer**
1	$(0 < x_1 \leq R_1$ and $0 < x_2 \leq R_2)$
2	$(R_1 < x_1 \leq C$ and $0 < x_2 \leq R_2)$
3	$(x_1 > C$ and $0 < x_2 \leq R_2)$
4	$(0 < x_1 \leq R_1$ and $R_2 < x_2 \leq C)$
5	$(R_1 < x_1 \leq C$ and $R_2 < x_2 \leq C)$
6	$(x_1 > C$ and $R_2 < x_2 \leq C)$
7	$(0 < x_1 \leq R_1$ and $x_2 > C)$
8	$(R_1 < x_1 \leq C$ and $x_2 > C)$
9	$(x_1 > C$ and $x_2 > C)$

The profit functions of all members in the above scenarios will be derived in the following sections.

Scenario 1: When $0 < x_1 \leq R_1$ and $0 < x_2 \leq R_2$.

Figure 5.2

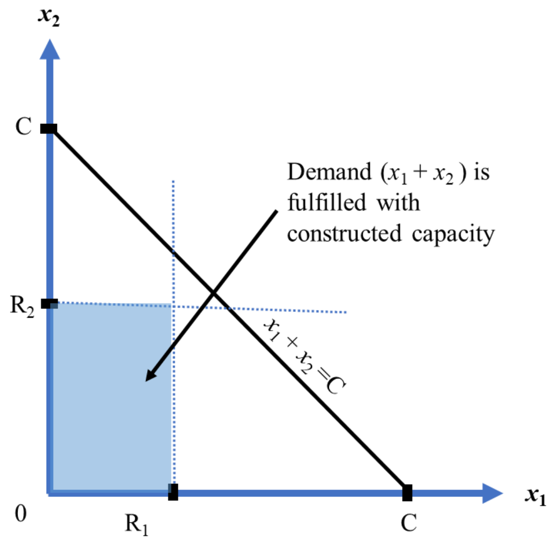
Realized Demand of Retailers in Scenario 1



In this scenario, the demand of retailer 1 and retailer 2 will be fulfilled with the constructed capacity of the supplier. Figure 5.3 shows the domain of the demand of retailers.

Figure 5.3

Plots of Demand of Retailers in Scenario 1



Retailer 1's profit

$$\pi_{\text{II}}^{r_1} = w_{s_1} * x_1 - w_{e_1} * x_1 - S_{s_1} * (R_1 - x_1) \tag{5.3}$$

Retailer 2's profit

$$\pi_{\text{II}}^{r_2} = w_{s_2} * x_2 - w_{e_2} * x_2 - S_{s_2} * (R_2 - x_2) \tag{5.4}$$

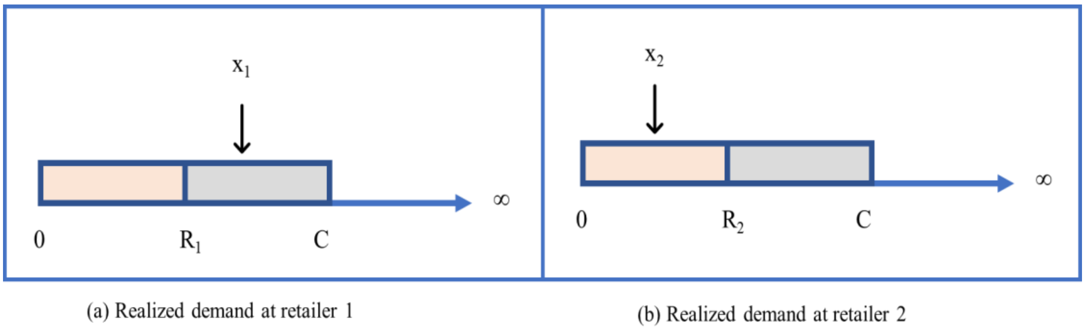
Supplier's profit

$$\pi_{\text{II}}^{s} = w_{e1} * x_1 + S_{s1} * (R_1 - x_1) + w_{e2} * x_2 + S_{s2} * (R_2 - x_2) - c_p * (x_1 + x_2) \tag{5.5}$$

Scenario 2: When $R_1 < x_1 \leq C$ and $0 < x_2 \leq R_2$.

Figure 5.4

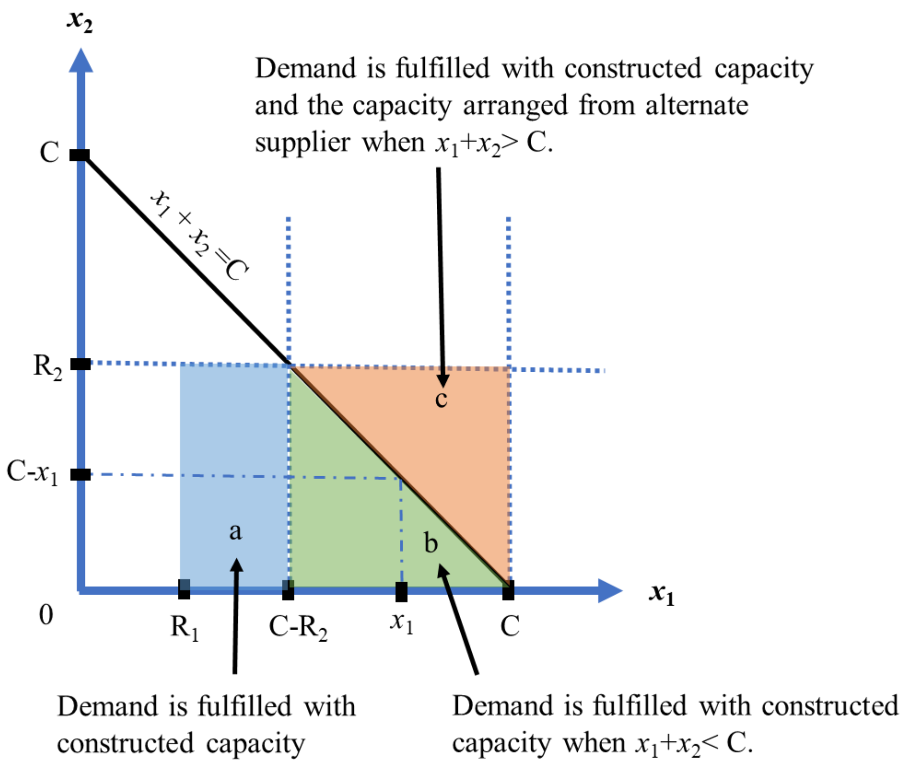
Realized Demand of Retailers in Scenario 2



In this case, 2 sub-scenarios can take place as shown in Figure 5.5.

Figure 5.5

Plots of Demand of Retailers in Scenario 2



Sub scenario 2a: $R_1 < x_1 \leq \mathrm{C} - \mathrm{R}_2$ and $0 < x_2 \leq R_2$ (region a)

The total demand of retailers is less than the constructed capacity of supplier. The demand of retailers will be fulfilled without using the support of other suppliers.

Retailer 1's profit

$$\pi_{\mathrm{II}}^{r_1} = w_{s_1} * x_1 - w_{e_1} * \mathrm{R}_1 - w_{ex_1} * (\mathrm{x}_1 - \mathrm{R}_1) \tag{5.6}$$

Retailer 2's profit

$$\pi_{\mathrm{II}}^{r_2} = w_{s_2} * x_2 - w_{e_2} * x_2 - S_{s_2} * (R_2 - x_2) \tag{5.7}$$

Supplier's profit

$$\pi_{\mathrm{II}}^{s} = w_{e1} * R_1 + w_{ex1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e2} * x_2 + S_{s2} * (R_2 - x_2) - c_p * (x_1 + x_2) \tag{5.8}$$

Sub scenario 2b: $\mathbf{C - R_2 < x_1 \leq C}$ and $\mathbf{0 < x_2 \leq R_2}$ (regions b and c)

In this case, the supplier will try to fulfil the demand with his constructed capacity. And if the demand is more than the constructed capacity, the supplier will fulfil the excess demand from the support of other suppliers.

Retailer 1's profit

$$\pi_{\mathrm{II}}^{r_1} = w_{s_1} * x_1 - w_{e_1} * \mathrm{R}_1 - w_{ex_1} * (\mathrm{x}_1 - \mathrm{R}_1) \tag{5.9}$$

Retailer 2's profit

$$\pi_{\mathrm{II}}^{r_2} = w_{s_2} * x_2 - w_{e_2} * x_2 - S_{s_2} * (R_2 - x_2) \tag{5.10}$$

Supplier's profit

The profit of supplier must be analysed in two cases:

1. If $x_2 < (C - x_1)$: The total demand of the two retailers can be fulfilled from constructed capacity.

Hence,

$$\pi_{\mathrm{II}}^{s} = w_{e1} * R_1 + w_{ex1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e2} * x_2 + S_{s2} * (R_2 - x_2) - c_p * (x_1 + x_2) \tag{5.11}$$

2. If $(C - x_1) < x_2 \leq R_2$: The supplier needs to look for an additional of $(x_1 + x_2 - C)$ units from other suppliers.

Hence,

$$\pi_{II}^{s} = w_{e_1} * R_1 + w_{ex_1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e_2} * x_2 + S_{s_2} * (R_2 - x_2) - c_p * C - c_t * (x_1 + x_2 - C) \quad (5.12)$$

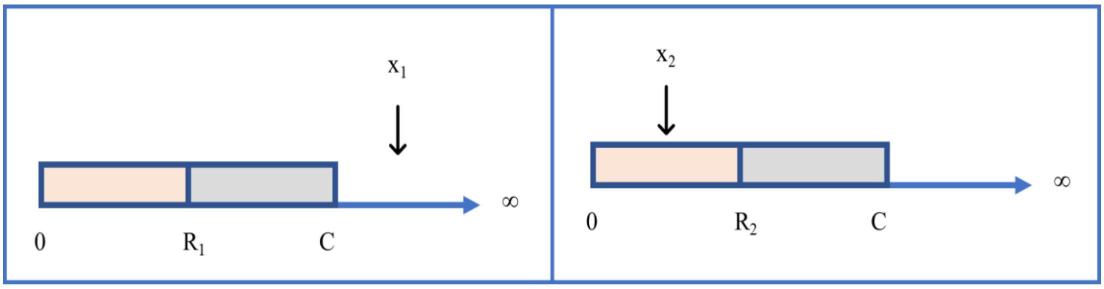
So, the profit of supplier can be expressed as

$$\pi_{II}^{s} = w_{e_1} * R_1 + w_{ex_1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e_2} * x_2 + S_{s_2} * (R_2 - x_2) - c_p * [Min\{(x_1 + x_2, C)\}] - c_t * [Max\{(\mathrm{x}_1 + \mathrm{x}_2 - \mathrm{C}), 0\}] \quad (5.13)$$

Scenario 3: When $x_1 > C$ and $0 < x_2 \leq R_2$.

Figure 5.6

Realized Demand of Retailers in Scenario 3

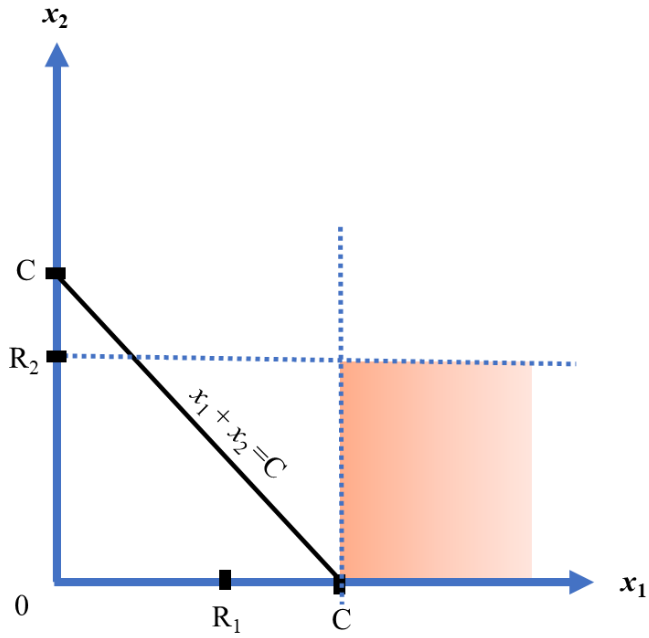


(a) Realized demand at retailer 1 (b) Realized demand at retailer 2

The Figure 5.7 shows the domain of the demand of retailers in this scenario.

Figure 5.7

Plots of Demand of Retailers in Scenario 3



Retailer 1's profit

$$\pi_{\mathrm{II}}^{r_1} = w_{s_1} * x_1 - \mathrm{w}_{\mathrm{e}_1} * R_1 - \mathrm{w}_{\mathrm{ex}_1} * (x_1 - R_1) \tag{5.14}$$

Retailer 2's profit

$$\pi_{\mathrm{II}}^{r_2} = w_{s_2} * x_2 - w_{e_2} * x_2 - S_{s_2} * (R_2 - x_2) \tag{5.15}$$

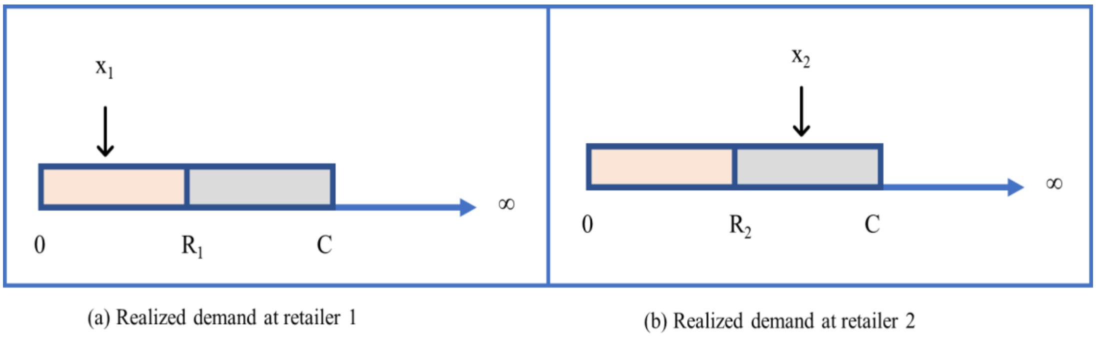
Supplier's profit

$$\pi_{\mathrm{II}}^{s} = w_{e_1} * R_1 + \mathrm{w}_{\mathrm{ex}_1} * (x_1 - R_1) + w_{e_2} * x_2 + S_{s_2} * (R_2 - x_2) - c_p * C - c_t * (\mathrm{x}_1 + \mathrm{x}_2 - C) \tag{5.16}$$

Scenario 4: When $0 < x_1 \le R_1$ and $R_2 < x_2 \le C$.

Figure 5.8

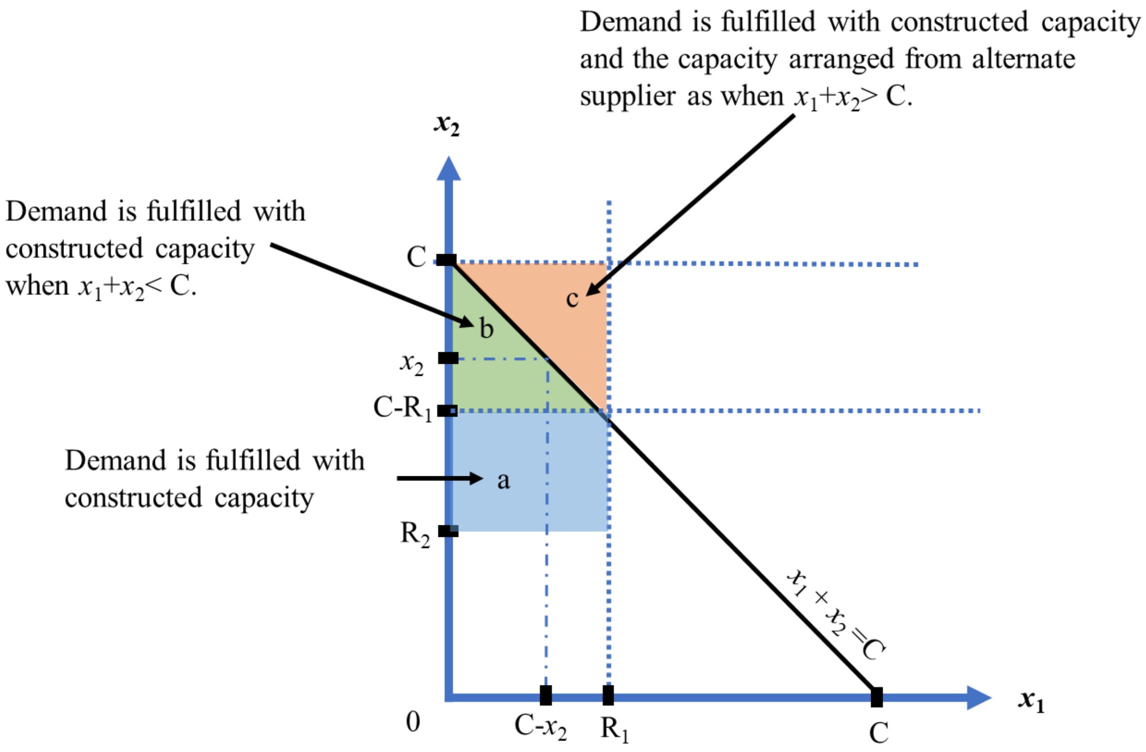
Realized Demand of Retailers in Scenario 4.



In this case, 2 sub-scenarios can take place as shown in Figure 5.9:

Figure 5.9

Plots of Demand of Retailers in Scenario 4



Sub scenario 4a: $0 < x_1 \leq R_1$ and $R_2 < x_2 \leq \mathrm{C} - \mathrm{R}_1$ (region a)

The total demand of retailers is less than the constructed capacity of supplier. The demand of retailers will be fulfilled without using the support of other suppliers.

Retailer 1's profit

$$\pi_{\mathrm{II}}^{r_1} = w_{s_1} * x_1 - w_{e_1} * x_1 - S_{s_1} * (R_1 - x_1) \tag{5.17}$$

Retailer 2's profit

$$\pi_{\mathrm{II}}^{r_2} = w_{s_2} * x_2 - w_{e_2} * \mathrm{R}_2 - w_{ex_2} * (\mathrm{x}_2 - \mathrm{R}_2) \tag{5.18}$$

Supplier's profit

$$\pi_{\mathrm{II}}^{s} = w_{e_1} * x_1 + S_{s_1} * (R_1 - x_1) + w_{e_2} * R_2 + w_{ex_2} * (\mathrm{x}_2 - \mathrm{R}_2) - c_p * (x_1 + x_2) \tag{5.19}$$

Sub scenario 4b: $0 < x_1 \leq R_1$ and $\mathrm{C} - \mathrm{R}_1 < x_2 \leq \mathrm{C}$ (regions b and c)

In this case, the supplier will try to fulfil the demand with his constructed capacity. And, if the demand is more than the constructed capacity, the supplier will fulfil the excess demand form the support of other suppliers.

Retailer 1's profit

$$\pi_{\text{II}}^{r_1} = w_{s_1} * x_1 - w_{e_1} * \text{R}_1 - S_{s_1} * (R_1 - x_1) \tag{5.20}$$

Retailer 2's profit

$$\pi_{\text{II}}^{r_2} = w_{s_2} * x_2 - w_{e_2} * \text{R}_2 - w_{ex_2} * (\text{x}_2 - \text{R}_2) \tag{5.21}$$

Supplier's profit

The profit of supplier must be analysed in two cases:

1. If $x_1 < (C - x_2)$: The total demand of the two retailers can be fulfilled from constructed capacity.

Hence,

$$\pi_{\text{II}}^{s} = w_{e_1} * x_1 + S_{s_1} * (R_1 - x_1) + w_{e_2} * R_2 + w_{ex_2} * (\text{x}_2 - \text{R}_2) - c_p * (x_1 + x_2) \tag{5.22}$$

2. If $(C - x_2) < x_1 \leq R_1$: The supplier needs to look for an additional of $(x_1 + x_2 - C)$ units from other suppliers.

Hence,

$$\pi_{\text{II}}^{s} = w_{e_1} * x_1 + S_{s_1} * (R_1 - x_1) + w_{e_2} * R_2 + w_{ex_2} * (\text{x}_2 - \text{R}_2) - c_p * C - c_t * (x_1 + x_2 - C) \tag{5.23}$$

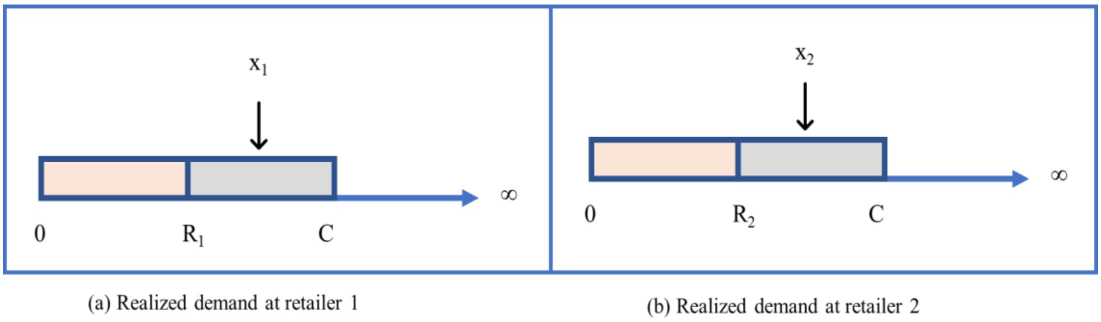
So, the profit of supplier can be expressed as

$$\pi_{\text{II}}^{s} = w_{e_1} * x_1 + S_{s_1} * (R_1 - x_1) + w_{e_2} * R_2 + w_{ex_2} * (\text{x}_2 - \text{R}_2) - c_p * [Min\{(x_1 + x_2, C)\}] - c_t * [Max\{(\text{x}_1 + \text{x}_2 - \text{C}), 0\}] \tag{5.24}$$

Scenario 5: When $R_1 < x_1 \leq C$ and $R_2 < x_2 \leq C$

Figure 5.10

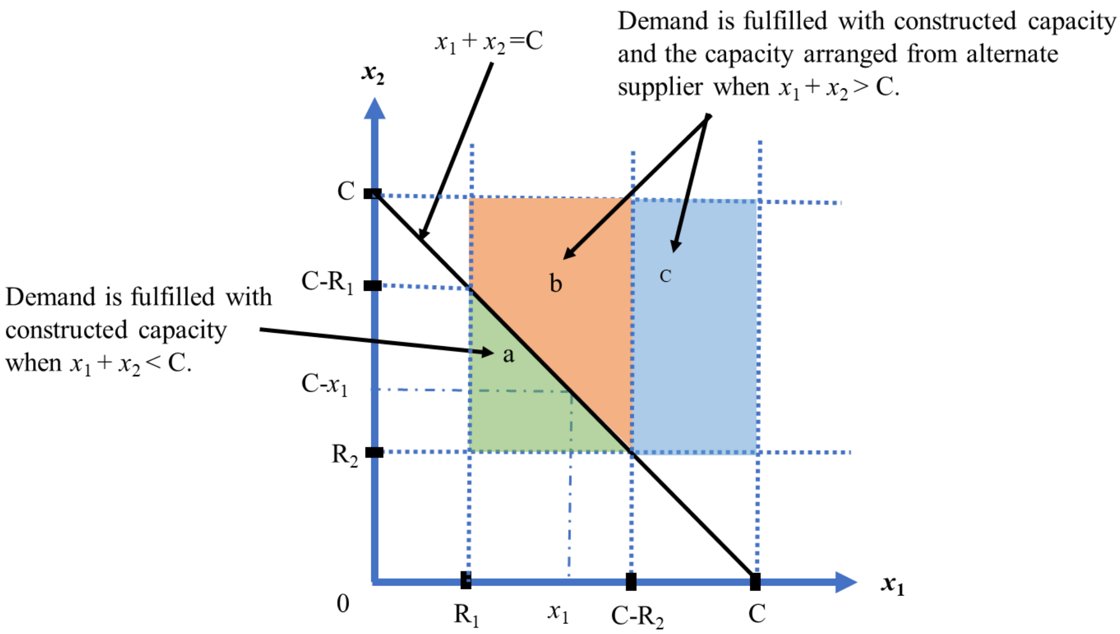
Realized Demand of Retailers in Scenario 5



In this case, 2 sub-scenarios can take place as shown in Figure 5.11.

Figure 5.11

Plots of Demand of Retailers in Scenario 5



Sub-scenario 5a: $R_1 < x_1 \leq \mathrm{C} - \mathrm{R_2}$ and $R_2 < x_2 \leq \mathrm{C}$ (regions a and b)

Retailer 1's profit

$$\pi_{\mathrm{II}}^{r_1} = w_{s_1} * x_1 - w_{e_1} * \mathrm{R}_1 - w_{ex_1} * (\mathrm{x}_1 - \mathrm{R}_1) \quad (5.25)$$

Retailer 2's profit

$$\pi_{\mathrm{II}}^{r_2} = w_{s_2} * x_2 - w_{e_2} * \mathrm{R}_2 - w_{ex_2} * (\mathrm{x}_2 - \mathrm{R}_2) \quad (5.26)$$

Supplier's profit

The profit of supplier must be analysed in two cases:

1. If $R_1 < x_1 \le C - R_2$ and $R_2 < x_2 \le C - x_1$ (region a): The total demand of the two retailers can be fulfilled from constructed capacity.

Hence,

$$\pi_{II}^{s} = w_{e1} * R_1 + w_{ex1} * (x_1 - R_1) + w_{e2} * R_2 + w_{ex2} * (x_2 - R_2) - c_p * (x_1 + x_2) \quad (5.27)$$

2. If $R_1 < x_1 \le C - R_2$ and $C - x_1 < x_2 \le C$ (region b): The supplier needs to look for an additional of $(x_1 + x_2 - C)$ units from other suppliers.

Hence,

$$\pi_{II}^{s} = w_{e1} * R_1 + w_{ex1} * (x_1 - R_1) + w_{e2} * R_2 + w_{ex2} * (x_2 - R_2) - c_p * C - c_t * (x_1 + x_2 - C) \quad (5.28)$$

So, the profit of the supplier is expressed as:

$$\pi_{II}^{s} = w_{e1} * R_1 + w_{ex1} * (x_1 - R_1) + w_{e2} * R_2 + w_{ex2} * (x_2 - R_2) - c_p * [Min\{(x_1 + x_2, C)\}] - c_t * [Max\{(x_1 + x_2 - C), 0\}] \quad (5.29)$$

Sub-scenario 5b: $C - R_2 < x_1 \le C$ and $R_2 < x_2 \le C$ (region c)

Retailer 1's profit

$$\pi_{II}^{r_1} = w_{s_1} * x_1 - w_{e_1} * R_1 - w_{ex_1} * (x_1 - R_1) \quad (5.30)$$

Retailer 2's profit

$$\pi_{II}^{r_2} = w_{s_2} * x_2 - w_{e_2} * R_2 - w_{ex_2} * (x_2 - R_2) \quad (5.31)$$

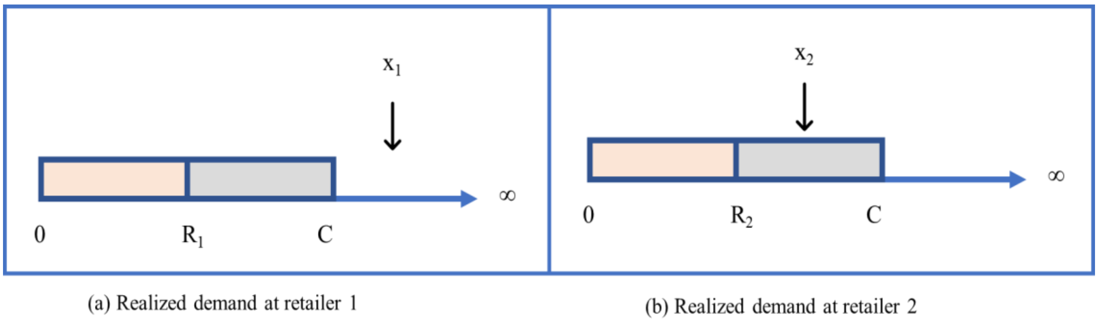
Supplier's profit

$$\pi_{II}^{s} = w_{e1} * R_1 + w_{ex1} * (x_1 - R_1) + w_{e2} * R_2 + w_{ex2} * (x_2 - R_2) - c_p * C - c_t * (x_1 + x_2 - C) \quad (5.32)$$

Scenario 6: When $x_1 > C$ and $R_2 < x_2 \le C$

Figure 5.12

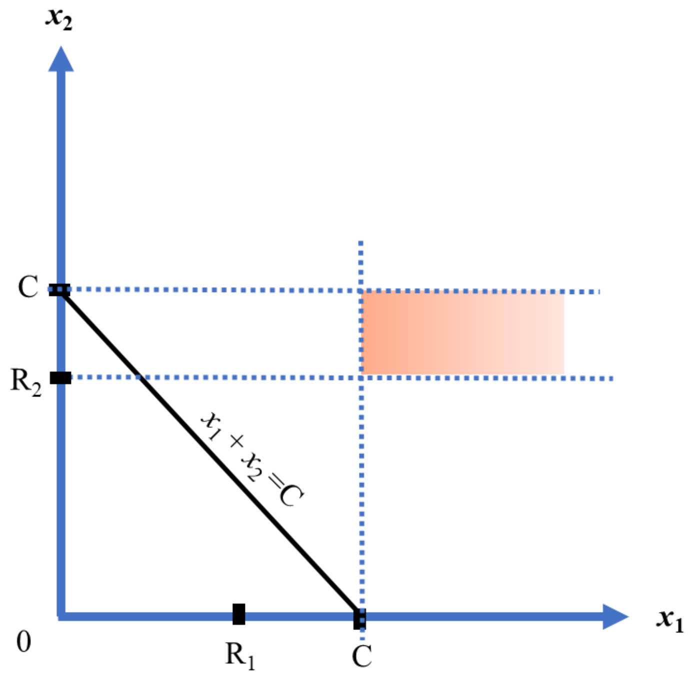
Realized Demand of Retailers in Scenario 6



The Figure 5.13 shows the domain of the demands of retailers in this scenario.

Figure 5.13

Plots of Demand of Retailers in Scenario 6



Retailer 1's profit

$$\pi_{\mathrm{II}}^{r_1} = w_{s_1} * x_1 - w_{e_1} * \mathrm{R}_1 - \mathrm{w}_{\mathrm{ex}_1} * (x_1 - R_1) \qquad (5.33)$$

Retailer 2's profit

$$\pi_{\mathrm{II}}^{r_2} = w_{s_2} * R_2 - \mathrm{w}_{\mathrm{e}_2} * R_2 - \mathrm{w}_{\mathrm{ex}_2} * (x_2 - R_2) \qquad (5.34)$$

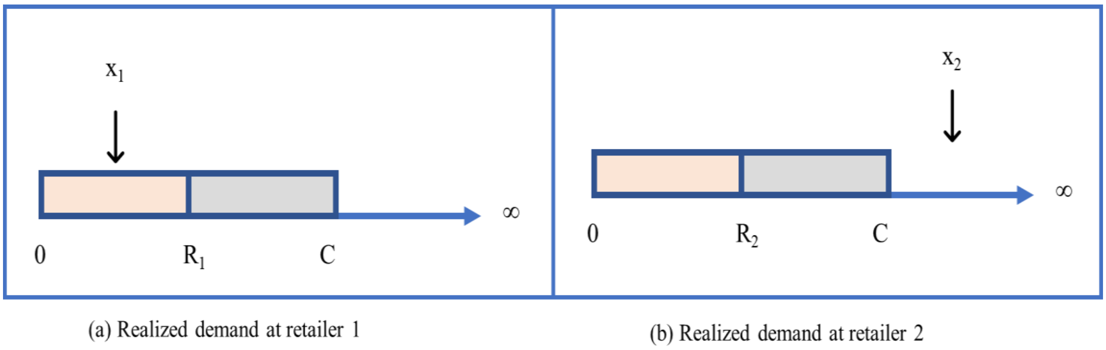
Profit function of the supplier:

$$\pi_{\mathrm{II}}^{s} = w_{e_1} * \mathrm{R}_1 + \mathrm{w}_{\mathrm{ex}_1} * (x_1 - R_1) + \mathrm{w}_{\mathrm{e}_2} * R_2 + \mathrm{w}_{\mathrm{ex}_2} * (x_2 - R_2) - c_p * C - c_t * (\mathrm{x}_1 + \mathrm{x}_2 - C) \quad (5.35)$$

Scenario 7: When 0< $x_1 \leq R_1$ and $x_2 > C$.

Figure 5.14

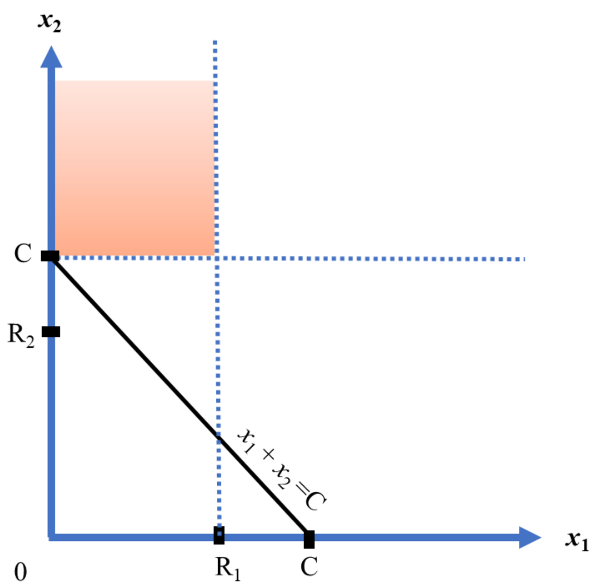
Realized Demand of Retailers in Scenario 7



The Figure 5.15 shows the domain of the demand of retailers in this scenario.

Figure 5.15

Plots of Demand of Retailers in Scenario 7



Retailer 1's profit

$$\pi_{\mathrm{II}}^{r_1} = w_{s_1} * x_1 - w_{e_1} * x_1 - S_{s_1} * (R_1 - x_1) \quad (5.36)$$

Retailer 2's profit

$$\pi_{\mathrm{II}}^{r_2} = w_{s_2} * x_2 - \mathrm{w}_{\mathrm{e}_2} * R_2 - \mathrm{w}_{\mathrm{ex}_2} * (x_2 - R_2) \quad (5.37)$$

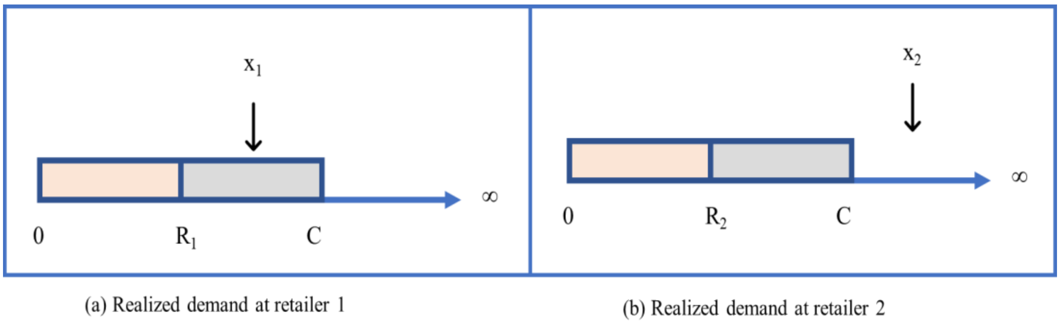
Supplier's profit

$$\pi_{\text{II}}^{s} = w_{e1} * x_1 + S_{s1} * (R_1 - x_1) + \text{w}_{\text{e}2} * R_2 + \text{w}_{\text{ex}2} * (x_2 - R_2) - c_p * C - c_t * (\text{x}_1 + \text{x}_2 - C) \quad (5.38)$$

Scenario 8: When $R_1 < x_1 \leq C$ and $x_2 > C$

Figure 5.16

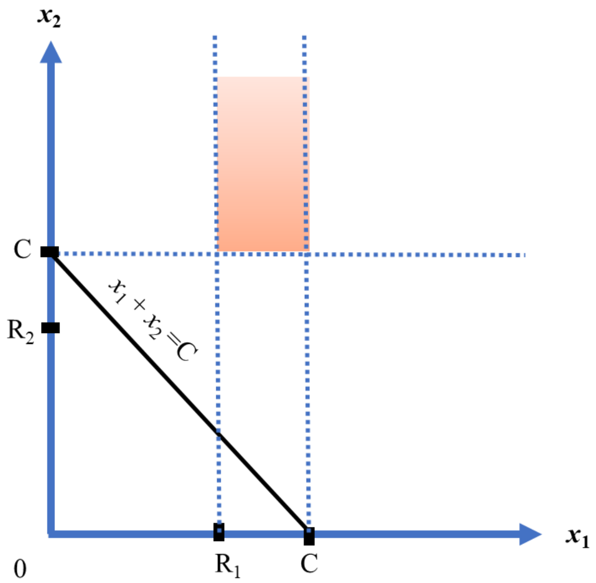
Realized Demand of Retailers in Scenario 8



The Figure 5.17 shows the domain of the demand of retailers in this scenario.

Figure 5.17

Plots of Demand of Retailers in Scenario 8



Retailer 1's profit

$$\pi_{\text{II}}^{r_1} = w_{s_1} * x_1 - w_{e_1} * R_1 - \text{w}_{\text{ex}_1} * (x_1 - R_1) \quad (5.39)$$

Retailer 2's profit

$$\pi_{\text{II}}^{r_2} = w_{s_2} * x_2 - \mathrm{w}_{\mathrm{e}_2} * R_2 - \mathrm{w}_{\mathrm{ex}_2} * (x_2 - R_2) \quad (5.40)$$

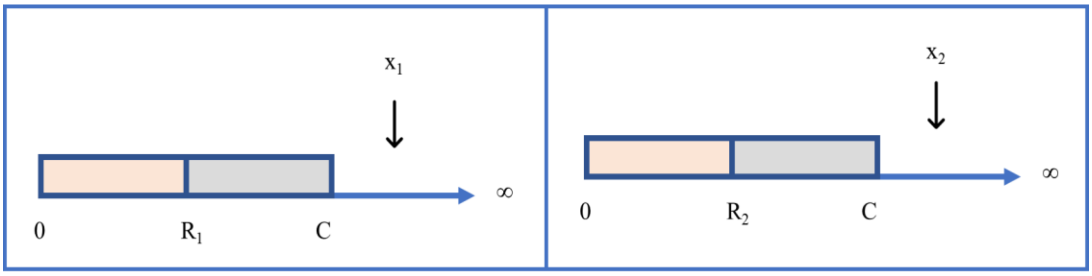
Supplier's profit

$$\pi_{\text{II}}^{s} = w_{e1} * R_1 + \mathrm{w}_{\mathrm{ex}1} * (x_1 - R_1) + \mathrm{w}_{\mathrm{e}2} * R_2 + \mathrm{w}_{\mathrm{ex}2} * (x_2 - R_2) - c_p * C - c_t * (\mathrm{x}_1 + \mathrm{x}_2 - C) \quad (5.41)$$

Scenario 9: When $x_1 > C$ and $x_2 > C$

Figure 5.18

Realized Demand of Retailers in Scenario 9

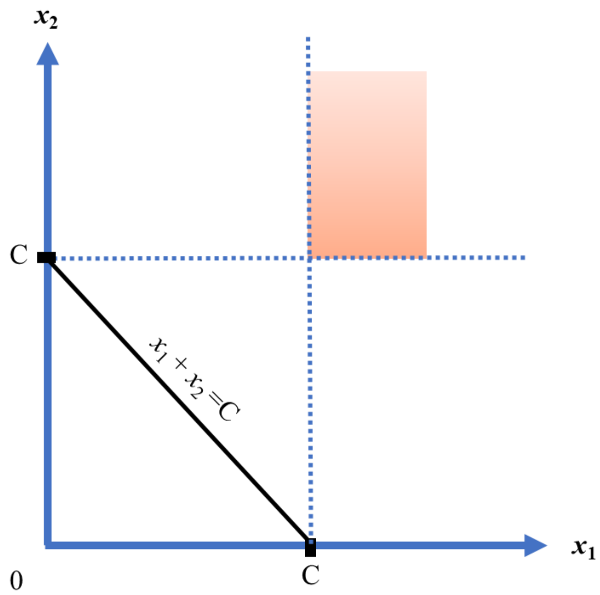


(a) Realized demand at retailer 1 (b) Realized demand at retailer 2

The Figure 5.19 shows the domain of the demand of retailers in this scenario.

Figure 5.19

Plots of Demand of Retailers in Scenario 9



Retailer 1's profit

$$\pi_{\mathrm{II}}^{r_1} = w_{s_1} * x_1 - w_{e_1} * R_1 - \mathrm{w}_{\mathrm{ex}_1} * (x_1 - R_1) \tag{5.42}$$

Retailer 2's profit

$$\pi_{\mathrm{II}}^{r_2} = w_{s_2} * x_2 - \mathrm{w}_{\mathrm{e}_2} * R_2 - \mathrm{w}_{\mathrm{ex}_2} * (x_2 - R_2) \tag{5.43}$$

Supplier's profit

$$\pi_{\mathrm{II}}^{s} = w_{e_1} * R_1 + \mathrm{w}_{\mathrm{ex}_1} * (x_1 - R_1) + \mathrm{w}_{\mathrm{e}_2} * R_2 + \mathrm{w}_{\mathrm{ex}_2} * (x_2 - R_2) - c_p * C - c_t * (\mathrm{x}_1 + \mathrm{x}_2 - C) \tag{5.44}$$

From the above analyses, the overall profit functions of retailer 1, retailer 2 and the supplier can be determined as the cumulative profits of stage 1 and stage 2, which are shown in equations (5.45), (5.46) and (5.47) respectively:

Overall profit of retailer 1

$$\pi^{r_1} = \pi_{\mathrm{I}}^{r_1} + \pi_{\mathrm{II}}^{r_1}$$

So,

$$\pi^{r_1}(\mathrm{R}_1) = -w_{r_1} * R_1 + \int_0^{R_1}\left\{w_{s_1} * x_1 - w_{e_1} * x_1 - S_{s_1} * (R_1 - x_1)\right\} f_{x_1}(x_1) dx_1 + \int_{R_1}^{C}\left\{w_{s_1} * x_1 - w_{e_1} * \mathrm{R}_1 - w_{ex_1} * (\mathrm{x}_1 - \mathrm{R}_1)\right\} f_{x_1}(x_1) dx_1 + \int_{C}^{\infty}\{w_{s_1} * x_1 - w_{e_1} * \mathrm{R}_1 - \mathrm{w}_{\mathrm{ex}_1} * (x_1 - R_1)\} f_{x_1}(x_1) dx_1$$

$$\pi^{r_1}(\mathrm{R}_1) = -w_{r_1} * R_1 + \int_0^{R_1}\left\{w_{s_1} * x_1 - w_{e_1} * x_1 - S_{s_1} * (R_1 - x_1)\right\} f_{x_1}(x_1) dx_1 + \int_{R_1}^{\infty}\left\{w_{s_1} * x_1 - w_{e_1} * \mathrm{R}_1 - w_{ex_1} * (\mathrm{x}_1 - \mathrm{R}_1)\right\} f_{x_1}(x_1) dx_1 \tag{5.45}$$

Overall profit of retailer 2

$$\pi^{r_2} = \pi_{\mathrm{I}}^{r_2} + \pi_{\mathrm{II}}^{r_2}$$

So,

$$\pi^{r_2}(\mathrm{R}_2) = -w_{r_2} * R_2 + \int_0^{R_2}\left\{w_{s_2} * x_2 - w_{e_2} * x_2 - S_{s_2} * (R_2 - x_2)\right\} f_{x_2}(x_2) dx_2 + \int_{R_2}^{C}\left\{w_{s_2} * x_2 - w_{e_2} * \mathrm{R}_2 - w_{ex_2} * (\mathrm{x}_2 - \mathrm{R}_2)\right\} f_{x_2}(x_2) dx_2 + \int_{C}^{\infty}\{w_{s_2} * x_2 - w_{e_2} * \mathrm{R}_2 - w_{ex_2} * (\mathrm{x}_2 - \mathrm{R}_2)\} f_{x_2}(x_2) dx_2$$

$$\pi^{r_2}(\mathrm{R}_2) = -w_{r_2} * R_2 + \int_0^{R_2}\left\{w_{s_2} * x_2 - w_{e_2} * x_2 - S_{s_2} * (R_2 - x_2)\right\} f_{x_2}(x_2) dx_2 + \int_{R_2}^{\infty}\left\{w_{s_2} * x_2 - w_{e_2} * \mathrm{R}_2 - w_{ex_2} * (\mathrm{x}_2 - \mathrm{R}_2)\right\} f_{x_2}(x_2) dx_2 \tag{5.46}$$

Overall profit of the supplier

$$\pi^{s} = \pi_{\mathrm{I}}^{s} + \pi_{\mathrm{II}}^{s} \tag{5.47}$$

So,

$\pi^{s}(C) = \left(w_{r_1} * R_1 + w_{r_2} * R_2 - c_c * C\right) + \int_0^{R_1}\left[\int_0^{R_2}\{w_{e_1} * x_1 + S_{s_1} * (R_1 - x_1) + w_{e_2} * x_2 + S_{s_2} * (R_2 - x_2) - c_p * (x_1 + x_2)\} f_{x_2}(x_2)dx_2\right] f_{x_1}(x_1)dx_1 + \int_{R_1}^{C-R_2}[\int_0^{R_2}\{w_{e_1} * R_1 + w_{ex_1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e_2} * x_2 + S_{s_2} * (R_2 - x_2) - c_p * (x_1 + x_2)\} f_{x_2}(x_2)dx_2] f_{x_1}(x_1)dx_1 + \int_{C-R_2}^{C}[\int_0^{C-x_1}\{w_{e_1} * R_1 + w_{ex_1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e_2} * x_2 + S_{s_2} * (R_2 - x_2) - c_p * (x_1 + x_2)\} f_{x_2}(x_2)dx_2] f_{x_1}(x_1)dx_1 + \int_{C-R_2}^{C}[\int_{C-x_1}^{R_2}\{w_{e_1} * R_1 + w_{ex_1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e_2} * x_2 + S_{s_2} * (R_2 - x_2) - c_p * C - c_t * (x_1 + x_2 - C)\} f_{x_2}(x_2)dx_2] f_{x_1}(x_1)dx_1 + \int_C^{\infty}\left[\int_0^{R_2} w_{e_1} * R_1 + \mathrm{w}_{\mathrm{ex}_1} * (x_1 - R_1) + w_{e_2} * x_2 + S_{s_2} * (R_2 - x_2) - c_p * C - c_t * (\mathrm{x}_1 + \mathrm{x}_2 - C) f_{x_2}(x_2)dx_2\right] f_{x_1}(x_1)dx_1 + \int_0^{R_1}\left[\int_{R_2}^{C-R_1}\{w_{e_1} * x_1 + S_{s_1} * (R_1 - x_1) + w_{e_2} * R_2 + w_{ex_2} * (\mathrm{x}_2 - \mathrm{R}_2) - c_p * (x_1 + x_2)\} f_{x_2}(x_2)dx_2\right] f_{x_1}(x_1)dx_1 + \int_{C-R_1}^{C}\left[\int_0^{C-x_2}\{w_{e_1} * x_1 + S_{s_1} * (R_1 - x_1) + w_{e_2} * R_2 + w_{ex_2} * (\mathrm{x}_2 - \mathrm{R}_2) - c_p * (x_1 + x_2)\} f_{x_1}(x_1)dx_1\right] f_{x_2}(x_2)dx_2 + \int_{C-R_1}^{C}\left[\int_{C-x_2}^{R_1}\{w_{e_1} * x_1 + S_{s_1} * (R_1 - x_1) + w_{e_2} * R_2 + w_{ex_2} * (\mathrm{x}_2 - \mathrm{R}_2) - c_p * C - c_t * (x_1 + x_2 - C)\} f_{x_1}(x_1)dx_1\right] f_{x_2}(x_2)dx_1 + \int_{R_1}^{C-R_2}[\int_{R_2}^{C-x_1}\{w_{e_1} * \mathrm{R}_1 + w_{ex_1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e_2} * R_2 + w_{ex_2} * (\mathrm{x}_2 - \mathrm{R}_2) - c_p * (x_1 + x_2)\} f_{x_2}(x_2)dx_2] f_{x_1}(x_1)dx_1 + \int_{R_1}^{C-R_2}[\int_{C-x_1}^{C}\{w_{e_1} * \mathrm{R}_1 + w_{ex_1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e_2} * R_2 + w_{ex_2} * (\mathrm{x}_2 - \mathrm{R}_2) - c_p * C - c_t * (\mathrm{x}_1 + \mathrm{x}_2 - C)\} f_{x_2}(x_2)dx_2] f_{x_1}(x_1)dx_1 + \int_{C-R_2}^{C}[\int_{R_2}^{C}\{w_{e_1} * \mathrm{R}_1 + w_{ex_1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e_2} * R_2 + w_{ex_2} * (\mathrm{x}_2 - \mathrm{R}_2) - c_p * C - c_t * (\mathrm{x}_1 + \mathrm{x}_2 - C)\} f_{x_2}(x_2)dx_2] f_{x_1}(x_1)dx_1 + \int_C^{\infty}\left[\int_{R_2}^{C}\{w_{e_1} * \mathrm{R}_1 + \mathrm{w}_{\mathrm{ex}_1} * (x_1 - R_1) + \mathrm{w}_{\mathrm{e}_2} * R_2 + \mathrm{w}_{\mathrm{ex}_2} * (x_2 - R_2) - c_p * C - c_t * (\mathrm{x}_1 + \mathrm{x}_2 - C)\} f_{x_2}(x_2)dx_2\right] f_{x_1}(x_1)dx_1 + \int_0^{R_1}[\int_C^{\infty}\{w_{e_1} * x_1 + S_{s_1} * (R_1 - x_1) + \mathrm{w}_{\mathrm{e}_2} * R_2 + \mathrm{w}_{\mathrm{ex}_2} * (x_2 - R_2) - c_p * C - c_t * (\mathrm{x}_1 + \mathrm{x}_2 - C)\} f_{x_2}(x_2)dx_2\}] f_{x_1}(x_1)dx_1 + \int_{R_1}^{C}[\int_C^{\infty}\{w_{e_1} * R_1 + \mathrm{w}_{\mathrm{ex}_1} * (x_1 - R_1) + \mathrm{w}_{\mathrm{e}_2} * R_2 + \mathrm{w}_{\mathrm{ex}_2} * (x_2 - R_2) - c_p * C - c_t * (\mathrm{x}_1 + \mathrm{x}_2 - C)\} f_{x_2}(x_2)dx_2] f_{x_1}(x_1)dx_1 +$

$$\int_C^\infty \left[\int_C^\infty \{w_{e_1} * R_1 + \mathrm{w}_{\mathrm{ex}_1} * (x_1 - R_1) + \mathrm{w}_{\mathrm{e}_2} * R_2 + \mathrm{w}_{\mathrm{ex}_2} * (x_2 - R_2) - c_p * C - c_t * (\mathrm{x}_1 + \mathrm{x}_2 - C)\} f_{x_2}(x_2)dx_2\right] f_{x_1}(x_1)dx_1$$

(5.48)

Proposition 5.1: *The profit function of the retailer i is a concave function and unique solution of R_i exists as*

$$R_i = F_{x_i}^{-1}\left[\frac{(w_{e_i}+w_{r_i}-w_{ex_i})}{(w_{e_i}-w_{ex_i}-S_{s_i})}\right]$$

Proof: From the profit function of the retailer i, we have,

$$\frac{\partial \pi^{r_i}}{\partial R_i} = -w_{r_i} + \frac{\partial}{\partial R_i}\left[\int_0^{R_i}\{w_{s_i} * x_i - w_{e_i} * x_i - S_{s_i} * (R_i - x_i)\} f_{x_i}(x_i)dx_i\right] + \frac{\partial}{\partial R_i}\left[\int_{R_i}^\infty \{w_{s_i} * x_i - w_{e_i} * \mathrm{R_i} - w_{ex_i} * (\mathrm{x}_i - \mathrm{R}_i)\} f_{x_i}(x_i)dx_i\right]$$

$$\frac{\partial \pi^{r_i}}{\partial R_i} = -w_{r_i} + \{w_{s_i} * R_i - w_{e_i} * R_i - S_{s_i} * (R_i - R_i)\} f_{x_i}(R_i) - S_{s_i} * \int_0^{R_i} f_{x_i}(x_i)dx_i - \{w_{s_i} * R_i - w_{e_i} * \mathrm{R_i} - w_{ex_i} * (\mathrm{R}_i - \mathrm{R}_i)\} f_{x_i}(R_i) + \{w_{ex_i} - w_{e_i}\} * \int_{R_i}^\infty f_{x_i}(x_i)dx_i$$

$$\frac{\partial \pi^{r_i}}{\partial R_i} = -w_{r_i} - S_{s_i} * \int_0^{R_i} f_{x_i}(x_i)dx_i + \{w_{ex_i} - w_{e_i}\} * \int_{R_i}^\infty f_{x_i}(x_i)dx_i$$

$$\frac{\partial \pi^{r_i}}{\partial R_i} = -w_{r_i} - S_{s_i} * F_{x_i}(R_i) + (w_{ex_i} - w_{e_i}) * \{1 - F_{x_i}(R_i)\}$$

$$\frac{\partial \pi^{r_i}}{\partial R_i} = (w_{ex_i} - w_{e_i} - w_{r_i}) + (w_{e_i} - w_{ex_i} - S_{s_i}) * \{F_{x_i}(R_i)\}$$

Also, taking the second derivative we have:

$$\frac{\partial^2 \pi^{r_i}}{\partial {R_i}^2} = (w_{e_i} - w_{ex_i} - S_{s_i}) * \{f_{x_i}(R_i)\}$$

It is noted that $(w_{e_i} < w_{ex_i} + S_{s_i})$, therefore $\frac{\partial^2 \pi^{r_i}}{\partial {R_i}^2} < 0$. So, $\pi^{r_i}(R_i)$ is a concave function, and hence, the optimal solution of R_i exists uniquely.

The optimal solution of R_i can be determined from $\frac{\partial \pi^{r_i}}{\partial R_i} = 0$. Hence,

$$0 = (w_{ex_i} - w_{e_i} - w_{r_i}) + (w_{e_i} - w_{ex_i} - S_{s_i}) * \{F_{x_i}(R_i)\}$$

$$R_i = F_{x_i}^{-1}\left[\frac{(w_{e_i}+w_{r_i}-w_{ex_i})}{(w_{e_i}-w_{ex_i}-S_{s_i})}\right]$$

5.2.2 Scenario B: When the Supplier is Disrupted

For the retailers, the profit remains the same as supplier will look for the product from other suppliers to fulfil demand.

For the supplier, we assume that disruptions occur at the start of the 2nd stage (production & selling stage). So, in the second stage, the supplier has to look for support from the other suppliers to fulfil the demand. The profit functions of the supplier in the original nine scenarios when disruption occurs can be derived from the modified expressions of the supplier's profit functions when there is no disruption and are represented in Table 5.2 .

Table 5.2

Profit Functions of the Supplier when Disruption Occurs in the Nine Original Scenarios

No	Demand of retailer	Profit of supplier
1	$(0 < x_1 \leq R_1$ and $0 < x_2 \leq R_2)$	$\pi^s_{\mathrm{II(d)}} = w_{e1} * x_1 + S_{s1} * (R_1 - x_1) + w_{e2} * x_2 + S_{s2} * (R_2 - x_2) - c_t * (x_1 + x_2)$
2	$(R_1 < x_1 \leq C$ and $0 < x_2 \leq R_2)$	$\pi^s_{\mathrm{II(d)}} = w_{e1} * R_1 + w_{ex1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e2} * x_2 + S_{s2} * (R_2 - x_2) - c_t * (x_1 + x_2)$
3	$(x_1 > C$ and $0 < x_2 \leq R_2)$	$\pi^s_{\mathrm{II(d)}} = w_{e1} * R_1 + w_{ex1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e2} * x_2 + S_{s2} * (R_2 - x_2) - c_t * (x_1 + x_2)$
4	$(0 < x_1 \leq R_1$ and $R_2 < x_2 \leq C)$	$\pi^s_{\mathrm{II(d)}} = w_{e1} * x_1 + S_{s1} * (R_1 - x_1) + w_{e2} * R_2 + w_{ex2} * (\mathrm{x}_2 - \mathrm{R}_2) - c_t * (x_1 + x_2)$
5	$(R_1 < x_1 \leq C$ and $R_2 < x_2 \leq C)$	$\pi^s_{\mathrm{II(d)}} = w_{e1} * \mathrm{R}_1 + w_{ex1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e2} * R_2 + w_{ex2} * (\mathrm{x}_2 - \mathrm{R}_2) - c_t * (\mathrm{x}_1 + \mathrm{x}_2)$
6	$(x_1 > C$ and $R_2 < x_2 \leq C)$	$\pi^s_{\mathrm{II(d)}} = w_{e1} * \mathrm{R}_1 + \mathrm{w}_{\mathrm{ex1}} * (x_1 - R_1) + \mathrm{w}_{\mathrm{e2}} * R_2 + \mathrm{w}_{\mathrm{ex2}} * (x_2 - R_2) - c_t * (\mathrm{x}_1 + \mathrm{x}_2)$
7	$(0 < x_1 \leq R_1$ and $x_2 > C)$	$\pi^s_{\mathrm{II(d)}} = w_{e1} * x_1 + S_{s1} * (R_1 - x_1) + \mathrm{w}_{\mathrm{e2}} * R_2 + \mathrm{w}_{\mathrm{ex2}} * (x_2 - R_2) - c_t * (\mathrm{x}_1 + \mathrm{x}_2)$
8	$(R_1 < x_1 \leq C$ and $x_2 > C)$	$\pi^s_{\mathrm{II(d)}} = w_{e1} * R_1 + \mathrm{w}_{\mathrm{ex1}} * (x_1 - R_1) + \mathrm{w}_{\mathrm{e2}} * R_2 + \mathrm{w}_{\mathrm{ex2}} * (x_2 - R_2) - c_t * (\mathrm{x}_1 + \mathrm{x}_2)$
9	$(x_1 > C$ and $x_2 > C)$	$\pi^s_{\mathrm{II(d)}} = w_{e1} * R_1 + \mathrm{w}_{\mathrm{ex1}} * (x_1 - R_1) + \mathrm{w}_{\mathrm{e2}} * R_2 + \mathrm{w}_{\mathrm{ex2}} * (x_2 - R_2) - c_t * (\mathrm{x}_1 + \mathrm{x}_2)$

From Table 5.2, the original nine scenarios can be combined into only four and the profit functions of the supplier in these combined scenarios are presented in Table 5.3.

Table 5.3

Profit Functions of the Supplier in Various Scenarios when Disruption Occurs

No	Demand of retailer	Profit of supplier
1	$(0 < x_1 \le R_1$ and $0 < x_2 \le R_2)$	$\pi^{s}_{\mathrm{II(d)}} = w_{e1} * x_1 + S_{s1} * (R_1 - x_1) + w_{e2} * x_2 + S_{s2} * (R_2 - x_2) - c_t * (x_1 + x_2)$
2	$(R_1 < x_1$ and $0 < x_2 \le R_2)$	$\pi^{s}_{\mathrm{II(d)}} = w_{e1} * R_1 + w_{ex1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e2} * x_2 + S_{s2} * (R_2 - x_2) - c_t * (x_1 + x_2)$
3	$(0 < x_1 \le R_1$ and $R_2 < x_2)$	$\pi^{s}_{\mathrm{II(d)}} = w_{e1} * x_1 + S_{s1} * (R_1 - x_1) + w_{e2} * R_2 + w_{ex2} * (\mathrm{x}_2 - \mathrm{R}_2) - c_t * (x_1 + x_2)$
4	$(R_1 < x_1$ and $R_2 < x_2)$	$\pi^{s}_{\mathrm{II(d)}} = w_{e1} * \mathrm{R}_1 + w_{ex1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e2} * R_2 + w_{ex2} * (\mathrm{x}_2 - \mathrm{R}_2) - c_t * (\mathrm{x}_1 + \mathrm{x}_2)$

So, the profit of the supplier in this scenario can be determined as:

$$\pi_{\mathrm{d}}^{s} = \pi_{\mathrm{I}}^{s} + \pi_{\mathrm{II(d)}}^{s} \tag{5.49}$$

So,

$$\pi_{\mathrm{d}}^{s}(C) = \left(w_{r_1} * R_1 + w_{r_2} * R_2 - c_c * C\right) + \int_0^{R_1}\left[\int_0^{R_2}\{w_{e_1} * x_1 + S_{s_1} * (R_1 - x_1) + w_{e_2} * x_2 + S_{s_2} * (R_2 - x_2) - c_p * (x_1 + x_2)\} f_{x_2}(x_2)dx_2\right] f_{x_1}(x_1)dx_1 + \int_{R_1}^{\infty}\left[\int_0^{R_2}\{w_{e_1} * R_1 + w_{ex_1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e_2} * x_2 + S_{s_2} * (R_2 - x_2) - c_t * (x_1 + x_2)\} f_{x_2}(x_2)dx_2\right] f_{x_1}(x_1)dx_1 + \int_0^{R_1}\left[\int_{R_2}^{\infty}\{w_{e_1} * x_1 + S_{s_1} * (R_1 - x_1) + w_{e_2} * R_2 + w_{ex_2} * (\mathrm{x}_2 - \mathrm{R}_2) - c_t * (x_1 + x_2)\} f_{x_2}(x_2)dx_2\right] f_{x_1}(x_1)dx_1 + \int_{R_1}^{\infty}\left[\int_{R_2}^{\infty}\{w_{e_1} * \mathrm{R}_1 + w_{ex_1} * (\mathrm{x}_1 - \mathrm{R}_1) + w_{e_2} * R_2 + w_{ex_2} * (\mathrm{x}_2 - \mathrm{R}_2) - c_t * (\mathrm{x}_1 + \mathrm{x}_2)\} f_{x_2}(x_2)dx_2\right] f_{x_1}(x_1)dx_1 \tag{5.50}$$

5.2.3 Total Profit Function

From the analyses of scenario A and scenario B, the total profit of the supplier can be determined as the weighted profits of the two scenarios (equations 5.47 and 5.49) in which the weights are the probabilities of occurrence. Hence, the total profit function of the supplier can be derived as in equation 5.51.

$$\pi^{supplier}(C) = (1 - p) * [\pi^{s}(C)] + p * [\pi_{d}^{s}(C)\ ] \tag{5.51}$$

5.3 Numerical Experiments

To examine the applicability of the proposed capacity reservation contract model, various numerical experiments were conducted, and the results of a base case will be firstly presented in this section. The data related to various costs/contract parameters of the base case are given as: w_{s1}= 200, w_{r1}= 20, w_{e1}, = 70, w_{ex1}= 105, S_{s1}= 55, c_c= 5, c_p= 50, c_t= 70, w_{s2}= 210, w_{r2}= 22, w_{e2}= 72, w_{ex2}= 110, S_{s2}= 50, p=0.05. It is assumed that the demand x_1 follows a normal distribution with mean 1000 and standard deviation 200 and demand x_2 follows a normal distribution with mean 1200 and standard deviation 200. In this section we present the numerical results for a base case with predefined input parameters. The effects of various cost and contract parameters will then be examined.

From the above input parameters, the following results are achieved.

Reserved capacity set by retailer 1 for the supplier, R_1 = 807.

Reserved capacity set by the retailer 2 for the supplier, R_2 = 1018.

Constructed capacity of the supplier, C = 2379.

With the above results, the profit of all members are as follows,

Profit of retailer 1 ($) = 105503

Profit of retailer 2 ($) = 134553

Profit of the supplier ($) = 87086

5.4 Sensitivity Analyses

The following sections will present sensitivity analyses with respect to different input parameters to assess their impact on decision variables and the profits of all involved parties. The focus is on the parameters of retailer 1.

5.4.1 Effect of Unit Reservation Price at Retailer 1 (w_{r1})

This section will analyze the impact of the unit reservation price at retailer 1, and the findings are presented in Table 5.4.

Table 5.4

Sensitivity Analysis w.r.t Unit Reservation Price at Retailer

Parameter w_{r1}	**Capacities**			**Profits**		
	R_1	**R_2**	**C**	**Retailer 1**	**Retailer 2**	**Supplier**
16	839	1018	2379	108796	134553	83795
18	824	1018	2379	107133	134553	85457
20	807	1018	2379	105503	134553	87086
22	788	1018	2379	103908	134553	88680
24	767	1018	2379	102353	134553	90236

From the results, the reserved capacity of retailer 1 (R_1) reduces when the unit reservation price increases. This trend is reasonable. As a consequence, when the price of reserving capacity increases at retailer 1, the profit of retailer 1 decreases and the supplier's profit increases. Although, the construction capacity (C) of the supplier remains the same. However, the reserved capacity (R_2) and the profit of retailer 2 remain unchanged as they are not dependent on the unit reservation price at retailer 1.

5.4.2 Effect of Unit Exercise Price at Retailer 1 (w_{e1})

This section will analyze the impact of the unit exercise price at retailer 1, and the findings are presented in Table 5.5.

Table 5.5

Sensitivity Analysis w.r.t Unit Exercise Price at Retailer 1

Parameter w_{e1}	**Capacities**			**Profits**		
	R_1	**R_2**	**C**	**Retailer 1**	**Retailer 2**	**Supplier**
60	865	1018	2379	113644	134553	78782
65	839	1018	2379	109516	134553	83001
70	807	1018	2379	105503	134553	87086
75	736	1018	2379	101618	134553	91018
80	693	1018	2379	98032	134553	94640

From the results, when the exercise price for retailer 1 increases, the reserved capacity (R_1) and the profit of retailer 1 decreases. Although, it is observed that the supplier's constructed capacity (C) remains the same even though the reserved capacity of retailer 1 decreases. The supplier benefits from the increase in the unit exercise price, and hence, the supplier's profit increases. However, the reserved capacity and the profit of retailer 2 remain unchanged as they are not dependent on the unit exercise price at retailer 1.

5.4.3 Effect of Unit Excess Exercise Price at Retailer 1 (w_{ex1})

This section will analyze the impact of the unit excess exercise price at retailer 1 and the findings are presented in Table 5.6**.**

Table 5.6

Sensitivity Analysis w.r.t Unit Excess Exercise Price at Retailer 1

Parameter w_{ex1}	**Capacities**			**Profits**		
	R_1	**R_2**	**C**	**Retailer 1**	**Retailer 2**	**Supplier**
95	693	1018	2379	108032	134553	84534
100	763	1018	2379	106647	134553	85933
105	807	1018	2379	105503	134553	87086
110	839	1018	2379	104516	134553	88078
115	865	1018	2379	103644	134553	88949

From the results, it can be seen that retailer 1 will reserve a higher capacity from the supplier if the unit excess exercise price at retailer 1 increases to avoid purchasing at higher price when the demand is high. The increase in unit excess exercise price at retailer 1 will lead to the decrease in profit of retailer 1, and the increase in profit of the supplier even though his constructed capacity remains the same. However, the reserved capacity and the profit of retailer 2 remain unchanged as they are not dependent on unit excess exercise price at retailer 1.

5.4.4 Effect of Unit Construction Cost at Supplier (c_c)

This section will analyze the impact of the unit construction cost at supplier and the findings are presented in Table 5.7.

Table 5.7

Sensitivity Analysis w.r.t Unit Construction Cost at Supplier

Parameter c_c	Capacities			Profits		
	R_1	R_2	C	Retailer 1	Retailer 2	Supplier
3	807	1018	2483	105503	134553	91944
4	807	1018	2427	105503	134553	89489
5	807	1018	2379	105503	134553	87086
6	807	1018	2335	105503	134553	84729
7	807	1018	2295	105503	134553	82414

The results show that the supplier's constructed capacity (C) decreases when unit construction cost increases as it becomes less appealing for the supplier to construct a high capacity. Due to this, the profit of the supplier decreases. However, the reserved capacities and the profits of both retailers remain unchanged.

5.4.5 Effect of Unit Production Cost at Supplier (c_p)

This section will analyze the impact of the unit production cost at supplier and the findings are presented in Table 5.8.

Table 5.8

Sensitivity Analysis w.r.t Unit Production Cost at Supplier

Parameter c_p	Capacities			Profits		
	R_1	R_2	C	Retailer 1	Retailer 2	Supplier
40	807	1018	2463	105503	134553	107659
45	807	1018	2427	105503	134553	97352
50	807	1018	2379	105503	134553	87086
55	807	1018	2308	105503	134553	76896
60	807	1018	2181	105503	134553	66871

The results in Table 5.8 show that the supplier's constructed capacity (C) decreases when the unit production cost at supplier increases. This trend is reasonable, and due to this, the profit of supplier will decrease. It is noted that the reserved capacities and the profits of both retailers remains unchanged.

5.4.6 Effect of Unit Cost to Buy Product from other Suppliers (c_t)

This section will analyze the impact of the unit cost to buy products from other suppliers and the findings are presented in Table 5.9.

Table 5.9

Sensitivity Analysis w.r.t Unit Cost to Buy Product from other suppliers

Parameter c_t	Capacities			Profits		
	R_1	R_2	C	Retailer 1	Retailer 2	Supplier
60	807	1018	2181	105503	134553	89179
65	807	1018	2308	105503	134553	88050
70	807	1018	2379	105503	134553	87086
75	807	1018	2427	105503	134553	86198
80	807	1018	2463	105503	134553	85352

The results in Table 5.9 show that the supplier's constructed capacity (C) increases when the unit cost to buy product from other suppliers increases. Also, the profit of supplier will decrease. These trends are reasonable. Related to the retailers, the reserved capacities and the profits of both retailers remain unchanged.

5.4.7 Effect of Probability of Disruption at Supplier (p)

This section will analyze the impact of the probability of disruption at supplier and the findings are presented in Table 5.10.

Table 5.10

Sensitivity Analysis w.r.t Probability of Disruption

Parameter *p*	**Capacities**			**Profits**		
	R_1	**R_2**	**C**	**Retailer 1**	**Retailer 2**	**Supplier**
0.01	807	1018	2388	105503	134553	88734
0.03	807	1018	2383	105503	134553	87910
0.05	807	1018	2379	105503	134553	87086
0.07	807	1018	2374	105503	134553	86263
0.1	807	1018	2366	105503	134553	85029

From the results, it can be seen that when the probability of disruption increases, the profit of the supplier decreases. Also, due to high chance of disruption the supplier will build less capacity to avoid loss of capacity when disrupted. Anyway, the retailers will not be affected, and hence. the reserved capacities and the profits of both retailers remain unchanged.

CHAPTER 6
CONCLUSIONS

The focus on capacity reservation contract in this research comes from the fact that many manufacturers, especially in high technology industries, preferred the retailers to reserve the capacity in advance to avoid the risk of having excess capacity at the end of their planning horizon. Besides the fact that building capacity needs long lead time and is capital-intensive, the excess capacity, if exists, may not be utilized due to the high clock speed nature of most high-tech products. Moreover, due to the existence of disruptive events, the supply chains need to be resilient enough to withstand these events and work efficiently. The primary aim of the dissertation was to develop capacity reservation contract models for supply chains facing the risk of disruptions. We proposed three objectives tailored to different supply chain networks, involving both retailers and suppliers. To accomplish these objectives, a systematic approach was undertaken, commencing with a thorough literature review. This review underscored the existing literature on supply chain resilience, capacity reservation contracts, and disruptions, thus guiding the research objectives by pinpointing gaps, challenges, and opportunities in the field.

In the first part of this research, we derived a capacity reservation contract model in a supply chain consisting of a retailer and a supplier. The main target is to maximize the profit of the retailer and the supplier. With the developed model, the reserved capacity of the retailer and the constructed capacity of the supplier can be determined uniquely.

In the second part of this research, we derived a capacity reservation contract model in a supply chain consisting of a retailer, a primary supplier who faces the risk of disruption, and an expensive but reliable backup supplier, as a means to enhance resilience in the supply chain network through redundancy and flexibility which are among the key drivers of supply chain resilience. Using the mathematical model proposed in this part, the reserved capacities of the retailers to the two suppliers and the constructed capacities of the two suppliers can be determined uniquely.

In the last part of this research, we derived a capacity reservation contract model in a supply chain consisting of two retailers and a supplier in which the supplier faces the risk of disruption. In the model derived in this part, the reserved capacities of the retailers to the supplier can be determined uniquely. However, due to the complexity of supplier’s profit function, analytical solution for the constructed capacity of the supplier cannot be derived. Therefore, we used a heuristic technique, i.e., genetic algorithm, to determine the constructed capacity of the supplier.

The methodology employed in this research aimed to derive optimal and unique analytical solutions. By conducting first and second-order tests and verifying that the Hessian matrix is negative or semi-negative definite, we can ascertain the uniqueness of the solution that maximizes profit. We successfully derived the unique solution for retailer's reserved capacities to their suppliers across all mathematical models.

Using backup/multiple sourcing techniques are promising strategies for enhancing supply chain resilience. In the second objective, we introduced a capacity reservation contract model which incorporates backup sourcing. With this mathematical model, we offer a way to guarantee early access to vital resources through capacity reservations, while backup sourcing enables businesses to quickly adjust to disruptions by broadening their pool of suppliers. For implementation in practical scenarios, the response surfaces analysis used in this research can be utilized. In this analysis, the retailer and the backup supplier can determine the corresponding contour plots that give them the minimum expected profits. The proposed contract models developed in this dissertation can be used as effective tools for all parties involved in the contract negotiation process to help determine the combinations of contract parameters in such a way that the optimal expected profits of all members can be achieved.

To enhance resilience and mitigate the impact of disruptions in the future, it is essential to effectively manage supply chain disruptions through a proactive strategy. To enhance resilience, it's crucial to cultivate robust supplier relationships, diversify the supplier base, and establish backup sourcing options. Scenario planning and risk assessment aid in anticipating and preparing for disruptions, while investing in supply chain visibility improves transparency and enables real-time insights. These measures empower organizations to mitigate the impact of disruptions and navigate challenges effectively.

The limitation of this research is that the reserved capacities of the retailers have been considered only as constant values. In reality, the retailers may want to have the flexibility to reserve capacity in a range. This can be a topic for future research. In addition, to deal with flexibility, other contract types such as quantity flexibility contract or bidirectional option contract can be considered for the backup supplier. Another possible future extension of this research is to consider multiple suppliers - multiple retailers' system, where each supplier can serve as a primary supplier for some retailers and a backup supplier for the others.

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