SOURCING AND OUTSOURCING OF MATERIALS AND SERVICES IN CHEMICAL SUPPLY CHAINS

MUKTA BANSAL

NATIONAL UNIVERSITY OF SINGAPORE

2008

SOURCING AND OUTSOURCING OF MATERIALS AND SERVICES IN CHEMICAL SUPPLY CHAINS

MUKTA BANSAL

(B.Tech, HBTI Kanpur, M.Tech, IIT Kanpur)

A THESIS SUBMITTED

FOR THE DEGREE OF PhD OF ENGINEERING

DEPARTMENT OF CHEMICAL AND BIOMOLECULAR ENGINEERING

NATIONAL UNIVERSITY OF SINGAPORE

2008

ACKNOWLEDGEMENTS

This thesis is the result of my PhD work during which I have been accompanied and supported by many people. It is now my great pleasure to take this opportunity to thank them.

My most earnest acknowledgement must go to my supervisor Professor I.A. Karimi, who has been instrumental in ensuring my academic, professional, and moral wellbeing. I have seen in him an excellent advisor who can bring the best out of his students, an outstanding researcher who can constructively criticize research, and a nice human being who is honest, helpful, and fair to others.

I would like to thank my co-supervisor Prof R. Srinivasan for his continuous guidance and support throughout the course of research. His frank and open suggestions shed light into new interesting research topics, sometimes remedying my shortsightedness in my research work.

I sincerely thank Prof. Prahlad Vedakkepat and Prof. A.K. Ray whom constituted and chaired my research panel. I would like to thank all my lab mates for maintaining a healthy, enjoyable and pleasant working environment.

I would like to thank to my spouse, Pradeep Bansal and daughter Tiya, for providing steadfast support in hard times, and for their perpetual love and affection which helped me in coming out of many frustrating moments during my PhD research.

Finally, and most importantly, I would like to thank the almighty God, for it is under his grace that we live, learn, and flourish.

TABLE OF CONTENTS

SUMMARY

Focus on this work is sourcing and outsourcing of materials and services in chemical supply chains. This work is divided into four parts. First, we address the entire chemical supply chain and develop an agent-based platform (MADE) that can be considered as an agent middle-ware to support the development of multi-agent systems and to model the functions and activities within a supply chain. The advantages of MADE is that it reduces development time and simplifies the development of high-performance, robust agent-based systems. MADE can be used for modeling any supply chain. We illustrate the application of MADE by modeling and simulating a refinery supply chain and analyze several case studies. These case studies highlight important issues. One such issue is the timely and cost-intensive procurement and distribution of raw materials. Thus, we investigate in greater detail about the strategies of materials supply with the help of mathematical models.

The second part of this work addresses the strategic and integrated sourcing and distribution of materials in a global business environment for a MNC, which are key planning decisions in many supply chains including the chemical. We propose a comprehensive classification of material supply contracts which is based on several key real-life contract features. We also propose a multi-period mixed-integer linear programming model that not only selects optimal contracts and suppliers for the minimum total procurement cost including the logistics and inventory costs, but also assigns the suppliers and decides the supply distribution to various globally distributed sites of a MNC. Our model is suitable for reviewing the supply strategy and contracts periodically. We made two major assumptions in the above mentioned model. For TQC contracts, we assumed that prices did not vary with time and for PQC contracts,

we assumed the commitment is for a single period. We modify our model to relax these two assumptions.

To compliment our work on materials, the third part addresses the outsourcing of various logistics services. We present a systematic and quantitative decision-making formalism to address the integrated logistics needs of a MNC in a global business environment. The formalism involved a novel representation of logistics activities in terms of a recipe superstructure and a static MILP model based on that to select the optimal contracts that minimize the total logistics cost. It allows the flexibility of selecting partial contracts, which reduces the combinatorial complexity and computation time considerably, along with some reduction in costs under certain assumptions. The model is also able to address in a reactive manner the various dynamic disruptions that normally arise in chemical supply chains.

In the fourth part, we consider the sourcing of materials in a volatile environment. We develop a MILP model to selects the best contracts and suppliers that minimize the total procurement cost in the face of several uncertainties. The model is tested by means of a number of case studies reflecting uncertainty in key parameters such as demand, price, etc. Since our deterministic model is fast even for an industrial scale example, the scenario based approach is used to model uncertainties. Although the handling of uncertainty is demonstrated by considering uncertainties in demand and price, other uncertainties such as logistics cost, penalty, etc can be incorporated in a similar manner.

NOTATIONS

ABBREVIATIONS

LNG	Liquefied Natural Gas
VLCC	Very Large Crude Carriers
MAS	Multi-Agent System
MADE	Multi-Agent Development Environment
PRISMS	Petroleum Refinery Integrated Supply chain Modeler and Simulator
RFQ	Request-For-Quote
RRFQ	Reply-to-Request-For-Quote
SC	Supply Chain
SCM	Supply Chain Management
3PL	3rd Party Logistics provider
AHP	Analytic Hierarchy Process
MILP	Mixed Integer Linear Programming
QC	Quantity Commitment
DC	Dollar Commitment
TQC	Total Quantity Commitment
PQC	Periodic Quantity Commitment
TDC	Total dollar Commitment
PDC	Periodic Dollar Commitment
FLB	Flexibility with Limited Bulk discount
FB	Flexibility with Bulk discount
B	Bulk discount

FLU	Flexibility with Limited Unit discount
FU	Flexibility with Unit discount
U	unit discount

SYMBOLS

Chapter 4

Variables

$C(j)$	amount of crude needed to meet demand in j^{th} procurement cycle
$\tilde{C}(j)$	amount of crude to procure in j^{th} procurement cycle based on forecasted demand
$D(k)$	processing cost for crude k
$E(i)$	forecasted product price for product i
G	crude cut
$H(n)$	shipment of crude on day n
$\tilde{H}(n)$	shipment of crude scheduled to arrive on day n
i	product
j	procurement cycle
k	crude
N	number of products
n	day
$P(k)$	profit of crude k
$Q(i)$	forecasted product quantity for product i
R	transportation cost

$S(n)$ total stock of crude on day n

$\tilde{S}(n)$ planned stock of crude on day n

$T(n, j)$ throughput on day n and for j^{th} procurement cycle

$\tilde{T}(n, j)$ planned throughput for day n and for j^{th} procurement cycle

$\hat{T}(n)$ backlog order for day n

$U(k)$ cost of crude k

$y(i, k)$ yield of product i for crude k

Parameters

A planning horizon

B simulation horizon

F length of procurement cycle

J number of procurement cycles

T_{min} minimum throughput of refinery

T_{max} maximum throughput of refinery

W safety stock

Chapter 5

Subscripts

s plant site

m material

t period

c contract

r price-tier or discount-tier

Superscripts

L lower limit

U	upper limit

Parameters

CL_c	length of contract c in numbers of periods
q^U_{mct}	upper purchase limit of material m under contract c during period t
Q^U_{mc}	upper limit of on the total purchase of material m under contract c
p_{mct}	unit price of material m under contract c during period t
p_{mcr}	unit price of material m under contract c in price-tier r
p_{mcrt}	unit price of material m under contract c in price-tier r during period t
$QL_{mc(r-1)}$	minimum quantity of material m under contract c to qualify for price-tier r
QL_{mcr}	maximum quantity of material m under contract c to qualify for price-tier r
$QL_{mc(r-1)t}$	minimum quantity of material m under contract c to qualify for price-tier r during period t
QL_{mcrt}	maximum quantity of material m under contract c to qualify for price-tier r during period t
π_{mc}	unit penalty for unfulfilled commitment on material m under contract c
π_{mct}	unit penalty for unfulfilled commitment on m under c during t
π_c	percentage penalty for unfulfilled commitment under contract c
π_{ct}	percentage penalty for unfulfilled commitment under contract c during period t
D^U_c	upper purchase limit under contract c
D^U_{ct}	upper purchase limit under contract c during period t
$DL_{c(r-1)}$	minimum purchase value under contract c to qualify for discount-tier r
DL_{cr}	maximum purchase value under contract c to qualify for discount-tier r

$DL_{c(r-1)t}$ minimum purchase value under contract c to qualify for discount-tier r during period t

DL_{crt} maximum purchase value under contract c to qualify for discount-tier r during period t

d_{cr} fractional discount under contract c if purchase value falls under discount-tier r

d_{crt} fractional discount under contract c if purchase value falls under discount-tier range r during period t

LC_{mcst} unit logistics cost for supplying material m under contract c to site s in period t

D_{mst} demand of material m at site s during period t

HC_{mst} unit holding cost for material m at site s during period t

Variables

Binary

ys_{ct} 1 if contract c begins at the start of period t

β_{mcr} 1 if quantity of material m purchased under contract c qualifies for price-tier r

β_{mcrt} 1 if quantity of material m purchased under contract c during period t qualifies for price-tier r

α_{cr} 1 if the total purchase value under contract c qualifies for discount-tier r

α_{crt} 1 if the total purchase value under contract c during period t qualifies for discount-tier r

0-1 Continuous

y_{ct} 1 if contract c is in effect during period t

z_c 1 if contract c is selected

Continuous

q_{mct}	quantity of material *m* bought under contract *c* during period *t*
Q_{mc}	total quantity of material *m* bought under contract *c* during planning horizon
ΔQ_{mcr}	quantity of material *m* bought under contract *c* in price-tier *r*
Δq_{mcrt}	quantity of material *m* bought under contract *c* in price-tier *r* during period *t*
D_c	purchase value for contract *c*
D_{ct}	purchase value for contract *c* during period *t*
ΔD_{cr}	purchase value for contract *c* in discount-tier *r*
ΔD_{crt}	purchase value for contract *c* in discount-tier *r* during period *t*
I_{mst}	inventory of *m* at site *s* at the end of period *t*
S_{mcst}	quantity of *m* supplied to *s* during *t* under contract *c*
PC_{mc}	purchase cost of material *m* bought under contract *c*
PC_{mct}	purchase cost of material *m* bought under contract *c* during period *t*
PC_c	purchase cost under contract *c*
$COST$	total procurement cost

Chapter 6

Subscripts

τ	commitment period

Parameters

CP_c	commitment duration of contract *c* in numbers of periods
$QL'_{mc(r-1)\tau}$	minimum quantity of material *m* under contract *c* to qualify for price-tier *r* during commitment period τ

$QL'_{mcr\tau}$ maximum quantity of material m under contract c to qualify for price-tier r during commitment period τ

Variables

Binary

α_{mcrt} 1 if cumulative quantity of material m purchased under contract c qualifies for price-tier r during period t

$\sigma_{mcr\tau}$ 1 if quantity of material m purchased under contract c qualifies for price-tier r during commitment period τ

$XP_{c\tau t}$ 1 if commitment τ of contract c is in effect during period t

0-1 Continuous

$XF_{c\tau t}$ 1 if commitment τ of contract c begins at the start of period t

$XL_{c\tau t}$ 1 if commitment τ of contract c ends at the end of period t

Continuous

q'_{mct} cumulative quantity of material m bought under contract c up to and including t

$\Delta Q'_{mct}$ differential quantity of material m bought under contract c during t

LQ_{mc} quantity of m by which total quantity bought under contract c falls short of minimum commitment

ΔQQ_{mcrt} quantity of material m bought under contract c in tier r during period t

γ_{mcrt} product of q_{mct} and β_{mcr}

n_c number of commitment periods

$TF_{c\tau}$ time at which commitment τ of contract c begins

$TL_{c\tau}$ time at which commitment τ of contract c ends

$qq_{mc\tau}$	quantity of material m bought under contract c during commitment period τ
$\theta_{mc\tau t}$	product of q_{mct} and $XP_{c\tau t}$
$\Delta qq'_{mcr\tau}$	quantity of material m bought under contract c in price-tier r during commitment period τ

Chapter 7

Subscripts

s	plant site
m	material
t	period
c	contract
r	price-tier
k	hub site
i	demand site
j	production site
n'	form
w	task
u	transport task
v	non-transport task

Superscripts

L	lower limit
U	upper limit

Parameters

CL_c	length of contract c in numbers of periods
R_w	price-tier for task w

p_{wrt} unit price for task *w* in tier *r* during period *t*

QL_{wr} minimum quantity required to qualify for price-tier (*r* +1) under task *w*

Fx_c fixed cost associated with contract *c*

PQ_{mst} demand or production capacity of material *m* at site *s* during period *t*

HC_{mst} unit holding cost for material *m* at site *s* during period *t*

Variables

Binary

ys_{ct} 1 if contract *c* begins at the start of period *t*

α_{wrt} 1 if price tier *r* is in effect for task *w* during *t*

0-1 Continuous

y_{ct} 1 if contract *c* is in effect during period *t*

z_c 1 if contract *c* is selected

Continuous

Q_{wt} quantity on which task *w* is done during period *t*

ΔQ_{wrt} quantity on which task *w* is done in price-tier *r* during period *t*

I_{mst} inventory of *m* at site *s* at the end of period *t*

PC_{wt} logistics cost for task *w* during period *t*

TC total logistics cost

Chapter 8

Superscripts

i scenario

Parameters

α^i probability of scenario *i*

p^i_{mcr} unit price of *m* via contract *c* in price-tier *r* in scenario *i*

D^i_{mst} demand of material *m* at site *s* in scenario *i* during period *t*

Variables

Binary

β^{i}_{mcr}	1 if quantity of material *m* purchased under contract *c* qualifies for price-tier *r* in scenario *i*

Continuous

q^{i}_{mct}	quantity of material *m* bought under contract *c* in scenario *i* during period *t*
Q^{i}_{mc}	total quantity of material *m* bought under contract *c* in scenario *i* during planning horizon
ΔQ^{i}_{mcr}	quantity of material *m* bought under contract *c* in price-tier *r* in scenario *i*
I^{i}_{mst}	inventory of *m* at site *s* in scenario *i* at the end of period *t*
S^{i}_{mcst}	quantity of *m* supplied to *s* in scenario *i* during *t* under contract *c*
PC^{i}_{mc}	purchase cost of *m* bought under contract *c* in scenario *i*
PC^{i}_{mct}	purchase cost of *m* bought under contract *c* in scenario *i* during period *t*
C	total procurement cost

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION

Supply chain is a collection of inter-related entities that combine together to deliver the right quality of products at the right time in a cost efficient manner to the customers. A supply chain (SC) is a network of facilities that perform functions of procurement of materials, transformation of these materials into intermediate and finished products, and distribution of these products to customers (Ganeshan & Harrison, 1995). A typical supply chain is shown in Figure 1.1.

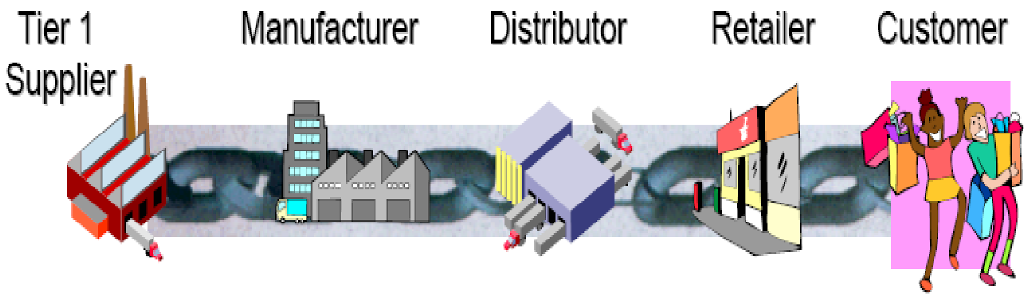

Figure 1.1: A Schematic of a typical Supply chain

The members of a typical supply chain include suppliers of raw materials, suppliers of suppliers, manufacturers, distribution centers, warehouses, and customer centers. Supply chains are global in nature comprising of complex interactions and flows between tens, even hundreds and thousands of companies and facilities geographically distributed across regions and countries (Gaonkar & Viswanadham, 2004). Supply chain results from cooperation among independent and heterogeneous companies, who have the aim of pursuing economic advantages. Supply Chain Management means transforming a company's "supply chain" into an optimally efficient, customer satisfying process. Supply chain management was introduced as a business practice to achieve operational efficiency, and cut costs, while maintaining quality.

The chemical industry is one of the world's largest manufacturing industries, producing more than 50,000 chemicals and formulations. Starting from raw materials such as oil, coal, gas, water, air and minerals, the chemical industry produces a vast array of substances that form the basis for almost every other manufacturing activity. It operates on a global scale; it exists in nearly every country in the world, and contributes 7% of global income and accounts for 9% of international trade.

Supply chains in the electronics, automobile and other industries have received much attention in the literature. Although some of the work on these industries can be partly extended to the chemical industry, supply chains in the chemical and process industry have distinctive features and require special attention. As an example, consider a petroleum refinery supply chain.

1.1 Petroleum Refinery Supply Chain

Figure 1.2 shows a schematic of a typical petroleum refinery supply chain. Refining is a complex process that transforms crude oil into valuable products such as gasoline, heating oil, and jet fuel, as well as petrochemical intermediates, which are further processed to produce fertilizers, plastics, synthetic fibers, detergents, etc. A refinery supply chain begins with the production of crude oil and liquefied natural gas (LNG) from either ground fields or offshore platforms. After pretreatment and storage, these are transported via Very Large Crude Carriers (VLCCs) and LNG tankers to various refineries around the world. The petroleum refinery converts these into a variety of intermediate bulk chemicals that are used as feedstock in petrochemical plants as well as fuels for aviation, ground transport, electricity generation, etc. Thus, the supply chain has at least three distinct centers of manufacturing, namely the oil/gas fields & platforms, the petroleum refineries, and the petrochemical plants. Each of these manufacturing entities is in turn surrounded by a host of logistics services for storage, transportation, distribution, packaging, etc.

Oil products are distributed to customers via various modes that depend on the distance, the nature of products, and demand quantities. The main oil products leave the refinery in bulk loads. Large consumers like petrochemical manufacturers may be supplied directly from the refinery via pipelines, rail, road, or sea. Smaller customers are generally supplied via storage and distribution centers known as terminals or depots. These disparate entities make the task of supplying the right product and the right quantity to the right customer at the right time with the right quality and service a very complex endeavor.

The long refinery supply chain that spans the globe suffers from long transportation times (for example, it takes four-six weeks to ship crude oil from the Middle East to a refinery in Asia). Further, the price of crude oil, the basic raw material for the refinery, is very volatile even on a daily basis; the demands and the prices for the products are also highly variable. These confound production planning, scheduling and supply chain management. As one example, higher than forecasted demand for products can lead to market opportunities for the refiner that can be exploited if adequate stock of crude is available at hand; however a lower than forecasted demand would lead to high inventory costs that can significantly erode refinery profits. Determining the safety stock levels for crude oil is therefore tricky. Similarly, numerous products and their variants can be produced from a crude by suitably utilizing the complex manufacturing process consisting of a highly interconnected system of reactors, separators and blenders. However, the yields of the different products from different crudes are different as are the operating costs for each combination. Given forecasted demands and prices for the products, the process of determining the right mix of crudes has to account for these as well as the landed cost of the crude that includes the purchase cost as well as the costs involved in moving it to the refinery. The fluctuation in the costs, demands and prices on a daily-basis necessitates frequent and speedy re-evaluations of numerous supply chain alternatives. Each evaluation should account for the complex relationships between the raw materials, operating units, and products to arrive at a feasible and optimal solution.

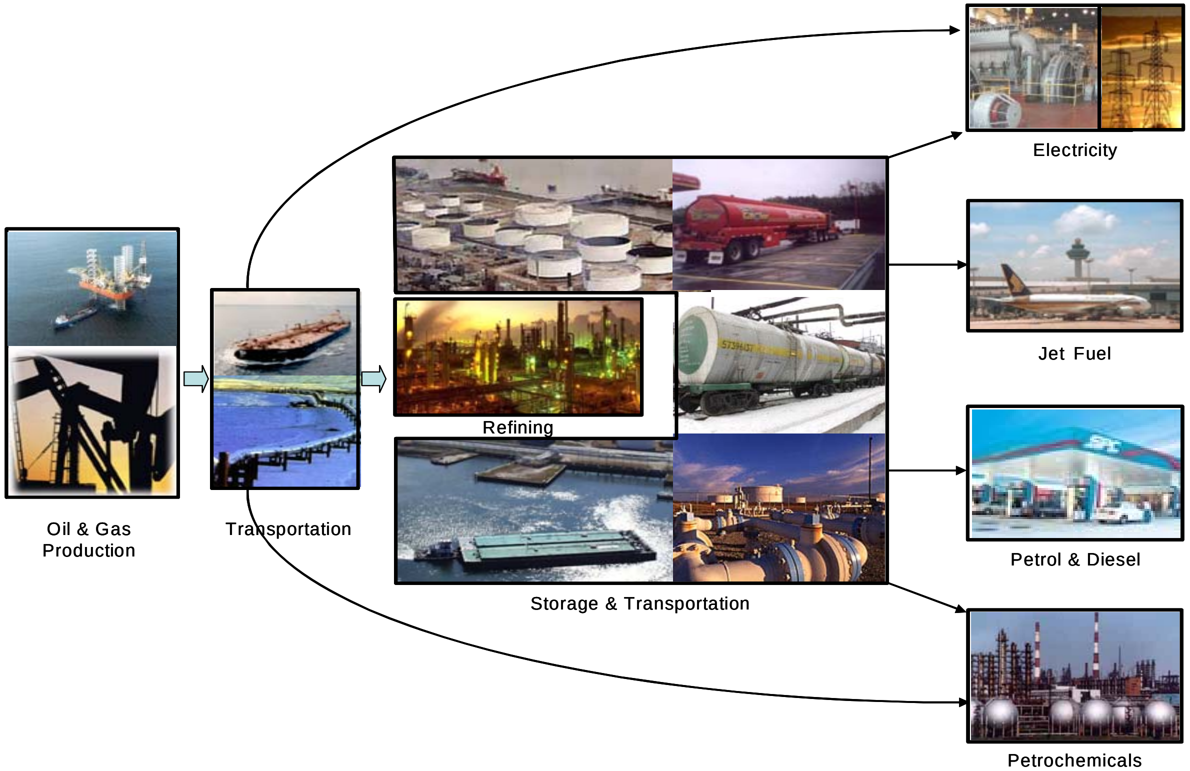

Figure 1.2: Schematic of petroleum refinery supply chain

1.2 Distinguishing Features of Chemical Supply Chains

It is evident from the above example that, while chemical supply chains show some similarity with other supply chains, they have many unique features as well. These can be summarized as due to:

1. Complex Nature of Chemical Industry

A primary feature of chemical supply chains is the huge variety of non-discrete, immiscible, incompatible, non-substitutable, huge-volume products, each of which has its own unique characteristics. The concepts of “discrete parts” and “assembly” do not exist in chemical manufacturing. The industry is highly capital-intensive with long and divergent supply chains with recycle loops that simply do not exist in other supply chains. The industry is the biggest consumer of itself and many of its businesses are high-volume and low-margin. Huge inventories that are critical to the continuity and profitability; need for safety-first; sociopolitical uncertainties, and environmental regulations; and extensive trading are other key features of the chemical industry that set them apart from the other manufacturing industries.

2. Fluctuations in Oil Price:

Volatility in crude oil poses a tremendous challenge to manage the chemical supply chain. OPEC, the Organization of Petroleum Exporting Countries, has significant influence on the price of crude oil as its members control a great portion of the world’s oil supply. The price of oil strongly influences the price of petrochemical products. The efficiency of chemical supply chain is dependent on the fluctuations in oil prices. The variations in the oil price may disrupt the supply chain.

3. Intricate Manufacturing Process:

The manufacturing complexity of the chemical industry and the hazardous nature of chemicals pose a challenge to the efficient management of the supply chain. Chemical process manufacturing plants are expensive to build and maintain and are designed for specific production modes. Due to these factors, manufacturing plant is not flexible to reconfigure according to the dynamics of supply chain.

4. Complex Transportation Process and Large Inventory:

The chemical industry transports huge amounts of chemicals all over the world. They are transported by either land or sea with maritime transport as the workhorse. This makes the transportation process very slow. Further, the hazardous nature and huge volumes of chemicals necessitate the use of highly expensive and sophisticated transport equipment and storage facilities that require complex and expensive cleaning procedures and maintenance, and result in long lead times. The slow transportation induces high in-transit inventory, which have to be accounted for during inventory management. Logistics costs in the chemical industry could be as high as 20% of the purchase cost (Karimi et al., 2002). Variability of transport times make necessary to have safety stock at the company ends to ensure that customer services would not be affected by any disruptions of in-transit inventory.

5. Environmental Regulations:

As most chemicals are hazardous, there are stringent regulatory compliances imposed on transporting it on land and sea. Environmental regulations relate to pollution during manufacturing and transport. In an effort to protect the environment, specific standards exist for packaging, labeling, distribution and transport of chemicals. For example, certification of vessels is a widely prevalent requirement.

1.3 Important Issues in Chemical Supply Chain Management

Due to the above mentioned features of chemical supply chain, there are important issues in managing chemical supply chain. One of the important issues is sourcing and outsourcing in chemical supply chains. Strategic sourcing is a process for systematically analyzing and developing optimal strategies for buying goods and services to support organizational mission. Outsourcing is buying a product or service from outside the organization rather than producing or providing it within the organization. There are two types of sourcing and outsourcing decisions in supply chains: (1) goods and (2) services.

1.3.1 Global Supply and Distribution of Raw Materials

Raw material purchases comprise a major portion of the total production costs in many companies. Automobile manufacturers spend 60% of their revenues on material purchases, food processors spend 70%, and oil refineries spend 80% (Chaudhry et al., 1991). Purchased materials and services represent up to 80% of total product costs for high technology firms (Burton, 1988). Coal purchases for large electric utilities, such as TVA, approach $1 billion annually (Bender et al., 1985). The percentages of sales revenues spent on materials vary from more than 80% in the petroleum refining industry to only 25% in the pharmaceutical industry (Krajewski and Ritzman, 1999). Clearly, it is vital for companies to reduce their material purchase costs.

Globalization is offering new opportunities and global competition is forcing companies to seek ways of reducing purchase costs. Many companies, especially the chemical companies, often prefer long-term contracts with their raw material suppliers. Such a supply contract is an agreement between a buyer (company) and a supplier for a fixed duration, which stipulates certain terms, conditions, and commitments. Negotiating the best supply contracts with each supplier and selecting the right contracts with the right suppliers are crucial tasks. Shah (2005) identifies the negotiation of long-term supply contracts as a typical supply chain problem.

One motivation for a supply contract is to share the risks arising from various uncertainties in demand, supply, delivery, inventory, price, exchange rate, etc. in the business environment. Contracts often specify fixed amounts of materials that the supplier agrees to deliver at various times in future at some agreed prices. These prices are not necessarily fixed; for instance, the price of liquefied natural gas (LNG) in most supply contracts is pegged to the price of crude oil. Fixed or pegged prices, contracts reduce price uncertainty to some extent. In addition, contracts increase supply reliability and may save costs for the buyer. Many contracts stipulate purchase commitments, which guarantee orders for the suppliers and reduce demand and inventory uncertainty for the supplier.

A company's goal is to fulfill the demands of raw materials over time at all its plant sites. This can be done in two ways. One is to sign contracts with one or more suppliers. The other is to buy from the spot market. While a long-term contract generally offers reliability, it may also force a price that is higher or lower than that in the open market. Thus, to reduce its costs, a company could use a combination of both ways to fulfill its raw material needs. However, contracts come in various shades of price, reliability, flexibility, duration, lead-time, quality, capacity, commitment, discount, terms and conditions, product bundling, etc. Striking an optimum balance among these factors and the option of spot market is not always easy and hence selecting the right combination of contracts can often be a challenging problem.

Another important sourcing decision in chemical supply chain is logistics.

1.3.2 Chemical Logistics

There are two types of outsourcing: outsourcing of physical goods/materials and outsourcing of services (intangible). Outsourcing of services is more challenging than outsourcing of goods as it involves acquiring a process rather than goods or materials.

Services can include logistics, transportation, training, accounting, warehousing, etc. Logistics services differ from other services as buyer is not affected by the service but also his customers where the impact is direct. Logistics service is very critical in chemical supply chains as it can break or make the supply chain and logistics costs in the chemical and related industries are among the highest in asset-intensive supply chains. Having managed the intra-plant logistics well for years, the companies are now looking for ways to lower the costs of enterprise-wide logistics by increasingly outsourcing a variety of logistics services to third-party logistics (3PL) firms globally.

The definition of logistics – "the flow of material, information, and money between consumers and suppliers" (Frazelle, 2002) emphasizes the link between logistics performance and customer satisfaction. Whether it is a chemical company that manages its own logistics, or a third party logistics provider (3PL) that manages it for the chemical company, the ultimate cost of logistics directly affects the cost effectiveness of global chemical supply chains (Jetlund et al., 2004). According to Karimi et al. (2002), "Often an overlooked component of the chemical business, a critical examination of logistics practices can result in substantial savings". While logistics is an issue of increasing importance to almost all industries, it is of most relevance to the chemical industry, as various types of chemical and related industries have some of the highest logistics costs. For instance, the $1.5 trillion chemical industry spends $160 billion annually on logistics, and has among the highest average supply chain costs (12% of revenues, compared to 10% for pharmaceuticals companies & 9% for automotive manufacturers) according to Mark Kaiser, the CEO of Cendian Corporation (Hoffman, 2002). Logistics costs can vary from 3.6% of the purchase price for a best-in-class (BIC) site to 20% at the other extreme (Karimi et al., 2002).

Today, logistics is much more than transportation alone; it includes many other services.

Many companies prefer long-term contracts with the providers due to the uncertainties and complexity of logistics services. A logistics service contract is an agreement between a company and a 3PL for a fixed duration that comprises certain terms and conditions. Contracts differ in features such as service, carrier, transport mode, equipment, reputation, speed, freight, pricing, flexibility, lead time, terms, conditions, duration, etc. In such a scenario, selecting logistics contracts and 3PLs is a complex problem that has received little attention in the literature.

Continuous change, uncertainty, and intense competitive interactions are the norms in today's volatile business environment. Uncertainties in price, availability, demand, production costs, etc. complicate the task of a supply chain manager to meet customer demand on time. Hence, it is necessary to consider the impact of uncertainties in supply chain design and operation.

1.3.3 Uncertainties

In a perfect SC, all the partners of the supply chain can synchronize their activities and business processes leading to greater efficiencies and profits for everyone. A real supply chain operates in an uncertain environment (Lababidi et al., 2004). Sales routinely deviate from forecasts, components are damaged in transit, production yields fail to meet plan, and shipments are held up in customs (Gaonkar & Viswanadham, 2004).

Uncertainty plays an important role in the modern supply chains (Xu et al., 2003). In the prevailing volatile business environment, with ever changing market conditions and customer expectations, it is necessary to consider the impact of uncertainties involved in the supply chain (Gupta & Maranas, 2000). Deterministic planning and scheduling models may yield unrealistic results as they fail to capture the effect of demand variability on the tradeoff between lost sales and inventory holding costs (Gupta & Maranas, 2000). Failure to incorporate a stochastic description of the product demand could lead to either unsatisfied customer demand and loss of market share or excessively high inventory holding costs (Petkov & Maranas, 1997).

1.4 Research Objective

This work focuses on supply chain management in chemical industry. The objectives of this work are to develop a platform to simulate chemical supply chain and develop models to help a chemical company (the buyer) in procuring materials and managing chemical logistics. As mentioned earlier, uncertainty is an important factor in characterizing supply chain, so these models are extended to deal with various price and demand uncertainties.

1.5 Outline of the Thesis

This thesis has nine chapters. Chapter 2 provides a detailed literature review. In Chapter 3, we develop a multi-agent platform called MADE (Multi-Agent Development Environment) which is specially designed for chemical supply chain applications. The MADE illustrates an easy to use framework to model the functions and activities within a supply chain. Then, we illustrate the application of MADE by modeling and simulating a refinery supply chain in Chapter 4.

Chapter 5 addresses the Global Supply and distribution of raw materials for a chemical supply chain. We propose a relatively comprehensive classification of material supply contracts and propose a multi-period mathematical programming model that selects optimal contracts for the minimum total procurement cost in the face of several practical considerations. In Chapter 6, we describe how our basic model can be modified to relax some of the assumptions in the earlier model.

In Chapter 7, we present a novel approach to represent logistics tasks in terms of recipes and recipe superstructures. Using this representation, we develop a mixed-integer linear programming formulation to fulfill the logistics needs of a global enterprise in terms of 3PL contracts and in-house execution. The goal is to obtain the contracts, and thus the 3PLs, that serve the total needs of a company in an integrated manner and with the minimum cost.

In Chapter 8, we model the selection of material suppliers and supply contracts for a multinational chemical company's globally distributed sites in an integrated manner under various demand and price uncertainties. We formulate the problem as a multi-period mixed integer linear programming (MILP) model with the goal of minimizing total procurement cost.

Finally, we end with conclusions and recommendations for future study in Chapter 9.

CHAPTER 2. LITERATURE REVIEW

Supply chain management has gained much attention in recent years as businesses feel the pressure of increased competition. In the following sections, we review the literature related to important issues in supply chains.

2.1 Design of Supply Chain

The design of a supply chain is a strategic decision addressing the location and capacities of production units and distribution centers, transportation links between them, as well as the modes of transportation. Supply chain design is a difficult task because (1) the sub-systems are intrinsically complex, (2) there are many interactions among the sub-subsystems, and (3) external factors such as demand uncertainties intricately affect performance. Dynamic modeling of the supply chain is an essential requirement for such studies. Perea, Grossmann, Ydstie & Tahmassebi (2000) apply ideas of process dynamics and control for supply chain management. Their model accounts for the flow of information and materials and provides insights into trade-offs between various performance indicators. Tsiakis et al. (2001) considered the design of a multi-product, multi-echelon supply chain network comprising of a number of manufacturing sites at locations fixed a priori, a number of warehouses and distributions centers at locations to be selected from a set of choices, and fixed customer zones. The design problem is modeled as a mixed-integer linear program whose objective is to minimize the total annualized cost of the network, taking into account both infrastructure and operating costs. Uncertainty in product demand is handled using a scenario-planning approach where a set of scenarios are constructed representative of both optimistic and pessimistic situations.

Papageorgiou et al. (2001) describe an optimization-based approach to addresses a related problem commonly faced by the pharmaceutical industry – selecting one or products to be introduced from a set of potential products and jointly planning site production capacity. The overall problem is formulated and solved using a mixed-integer linear programming (MILP) model that considers many aspects specific to the pharmaceutical sector such as product lifetime constraints, scale-up, and qualification. Guillén et al. (2005) consider the design of a supply chain consisting of several production plants, warehouses and markets, and the associated distribution systems. Uncertainty in the production scenario is represented as a set of scenarios with given probabilities of occurrence. The design problem is then formulated as a multi-objective optimization to maximize profit and customer satisfaction while minimizing the financial risk. Pareto optimal design alternatives that represent the trade-off among the different objectives are generated rather than a unique solution.

Complex interaction between entities and the multi-tiered structure of supply chains obviate analytical models that can accurately capture the dynamics of entire supply chains. Agent-based systems are a promising alternative to supply chain modeling and simulation. Now, we describe agents, multi-agent system (MAS), and previous works done on MAS.

2.2 Agents

The introduction of multi-agent systems has brought us opportunities for the development of complex software that serves as a platform for advanced distributed applications. A multi-agent system (MAS) is a distributed and concurrent system that consists of a number of intelligent agents (Woolridge, 2002). These agents interact with one another and exhibit the following properties (Woolridge, 2002):

- Reactivity: Ability to respond to changes that occur in their environment
- Social Ability: Ability to interact i.e., cooperate, co-ordinate, and negotiate with other agents to meet their objectives
- Pro-activeness: Ability to take initiative to satisfy their objectives
- Autonomy: Ability to operate alone and have control over its actions.

Reactive agent is often called as event-driven agent and proactive agent is often called as goal-driven agent. The interaction among agent is normally through sending and receiving messages. Agents distinguish different types of messages and use complex protocols, such as Contract Net or Task Sharing protocol to collaborate or negotiate. An agent may be static or mobile. If the agent is mobile, it is able to transfer to other machines along with its associated data. These qualities make agents ideal for modeling and analysis of supply chains, where collaboration, intelligence, and mobility are essential.

The agent paradigm is a natural metaphor for supply chain management since the entities or companies of supply chain have the same characteristics as the agents. Let's consider them one by one.

Reactivity- The entities of supply chain react according to the changes in market. Market acts like an environment for companies. They always keep a tab on market and their competitors and respond to changes that occur in it.

Social Ability: The entities of supply chain have to communicate with each other so that they can coordinate their activities and work together to fulfill the common goal of meeting customer needs with the right product, at the right time, at the right place and in a most cost effective manner.

Pro-activeness: In spite of having a common goal of meeting customer demand in a most cost effective way, every entity of a supply chain have aim of maximizing their own profits and they take initiative to satisfy their objectives.

Autonomy: Entities carries out their task itself without the interference of other entities and have control on their actions.

Further, agent-based technologies support concurrent and distributed decision-making that is also an integral element of supply chain management (Bond & Gasser, 1988). Agent-based approaches are also versatile and can easily capture qualitative and transactional events in the supply chain in addition to the quantitative aspects that traditional modeling approaches are best suited for. The development of agent-based systems offers a new and exciting paradigm for development of complex software that can serve as the platform for advanced distributed applications. Agent-based systems offer the high-level software abstractions needed to manage complex applications. Agent-based Systems views supply chain as composed of a set of intelligent agents (companies), each responsible for one or more activities and communicating with other agent (companies) in planning and executing their responsibilities. As there are several similarities between a company in a supply chain and an agent, the Multi-Agent System paradigm can be a valid approach for modeling supply chain. Parunak et. al. (1998) summarizes the domain of supply networks and illustrated how supply chain network can be modeled both with agents and equations. Agent-based model consists of a set of agents where agents encapsulate the behavior of the individuals and execution consists of emulating the behavior of the agents. Equation based model consists of a set of equations and execution consists of evaluating them. They have compared both approaches and concludes that agent-based model have significant advantage in supply chain modeling. Complex interaction between entities and the multi-tiered structure of supply chains obviate analytical models that can accurately capture the dynamics of entire supply chains. Unfortunately, an agent-based approach is not the panacea. It has some disadvantages also. Parunak, 1996 compares this approach with traditional approaches in Table 2.1.

Table 2.1: Agent-based vs. Conventional Technologies [Parunak, 1996]

Issue	**Autonomous Agents**	**Conventional**
Model	Economics, Biology	Military
Issues favouring conventional systems		
Theoretical Optima?	No	Yes
Level of Prediction	Aggregate	Individual
Computational Stability	Low	High
Issues favouring autonomous agents		
Match to reality	High	Low
Requires central data?	No	Yes
Response to change	Robust	Fragile
System reconfigurability	Easy	Hard
Nature of software	Short, simple	Lengthy , complex
Time required to schedule	Real time	Slow

All the above mentioned advantages of agent-based systems show the relevance to use agents in supply chain management.

Agent-based approaches have therefore received some attention in the chemical supply chain context as well. Flores, Wang & Goltz (2000) describe an ongoing effort in developing an integrated framework for supporting supply chain management of process industries. Retailers, warehouse, plants, and raw material are modeled as a network of co-operative agents, each performing one or more supply chain functions. Julka, Srinivasan and Karimi (2002a; b) propose a unified, flexible and scalable framework for modeling, monitoring and managing supply chains. Their framework has two basic elements: object modeling of supply chain flows and agent modeling of supply chain entities. Their framework uses three classes of agents: (1) emulation; (2) query and (3) project agents. Emulation agents model the supply chain entities such as manufacturers, logistics providers, etc. Query agent handle queries from the user and assist in supply chain analysis. Project agent performs the tasks needed to perform the study or solve the problem. Aldea et al. (2004) present case studies illustrating the application of multi-agent systems to diverse problems in the chemical process industry.

An agent toolkit is a development environment that provides modelers (agent builders) with a sufficient level of abstraction to allow them to implement intelligent agents with desired attributes, features and rules (Serenko & Detlor, 2002). In the last few years, several toolkits have been developed with special attention to interoperability and compatibility. Some of them are JADE, JATlite, Zeus, FIPA-OS, CAPNET, AgentBuilder, etc.

JADE (Java Agent Development Environment) is used to develop multi-agent systems (MASs) and can be considered middle-ware that complies with the FIPA specifications. JADE also contain useful set of graphical tools that support the debugging and deployment phases. The agent platform can be distributed across machines (that does not need to share the same OS) and the configuration can be controlled via a remote GUI. JADE is developed in Java language and comprises various java packages.

JATlite (Java Agent Template Lite) is a package of programs written in Java language that allows users to quickly create new software agents that communicate robustly over the internet. Agents send and receive messages, transfer files with FTP, and generally exchange information with other agents on the various computers where they are running.

Zeus offers a library of software component s and tools that facilitate fast and friendly design, development, and deployment of multi-agents. It consists of three main components: agent library, agent code generator and visual environment for capturing user's specifications.

FIPA-OS is another software framework to develop agent systems developed by Nortel. It is built utilizing Java technology. The FIPA-OS toolkit provides a group of classes that are used in agent development, as well as a graphical testing environment.

CAPNET (Component Agent Platform based on .NET) has been developed in the C# language using Microsoft's .NET framework. This platform uses several technologies available in .NET and window platform such as Web Services (WS), remoting, asynchronous call-backs, delegates, XML, database connectivity, etc. It consists of a run-time environment that supports MAS deployment, development environment in the form of agent templates, programming tools and a component gallery and some connectors to enable the integration with enterprise applications.

AgentBuilder is an integrated tool suite for constructing intelligent software agents-based on two major components - the Toolkit and the Run-Time System. The Toolkit includes tools for managing the agent-based software development process, analyzing the domain of agent operations, designing and developing networks of communicating agents, defining behaviours of individual agents, and debugging and testing agent software. The Run-Time System includes an agent engine that provides an environment for execution of agent software. Agents usually communicate through KQML messages; however, the developer has the option to define new communication commands that suits his particular needs. All components of AgentBuilder are implemented in Java (source: http://www.agentbuilder.com).

Sycara et al. (1996) developed a reusable, multiagent computational environment called RETSINA (Reusable Task Structure-based intelligent Network Agents) to address issues of distributed information gathering in an open world environment. Retsina has three types of agents: (1) Interface agent interacts with the user by receiving user specifications and delivering results. (2) Task agent supports decision making by formulating problem-solving plans and carrying them out through querying and exchanging information with other agents. (3) Information agent provides intelligent access to heterogeneous collection of information sources. Agent communicates through KQML. The agent architecture in RETSINA is divided into - Planning module in which the agent take input a set of goals and produces a plan that satifies these goals. The agent planning process is based on a hierarchical task network (HTN) planning formalism, Communication and coordination module in which agent accepts and interprets messages from other agent in KQML and Scheduling module in which agent schedules each of the plan steps.

The Foundation for Intelligent Physical Agent (FIPA) reference model has emerged as a standard for developing agent platforms (APs). The APs reference model of the FIPA has four components: Agents, Directory Facilitator (DF), Agent Management System (AMS), and Message Transport System (MTS). The DF and AMS are special types of agents that support the management of other agents, while the MTS provides a message delivery service.

Barber et al. (2003) discusses infrastructure for design, deployment and experimentation of multi-agent systems and illustrated it with Sensible Agent Testbed. The analysis of Sensible Agent Testbed development shows the functional specification and implementation decision process for multi-agent system architecture and testing infrastructure. Co-ordination among agents is a very important aspect of multi-agent systems. Cicirello and Smith (2004) present a new approach for coordination in which wasp colonies coordinate individual activities and allocate task to meet the collective needs of the nest. They focus on the problem of configuring parallel multi-purpose machine in a factory to best satisfy product demand over time.

Agents use a model of wasp task allocation behavior, coupled with a model of wasp dominance hierarchy formation, to determine which new jobs should be accepted into the machine's queue. Swaminathan, Smith & Sadeh (1998) provides a flexible and reusable modeling and simulation framework using Multi-Agent approach that enables rapid development of customized decision support tools for supply chain management. Agents represent supply chain entities, e.g. customers, retailers, manufacturers, and transporters. These agents use different interaction protocols and help in simulation of material, information, and cash flows. These interaction protocols are in the form of messages of various classes. Message handlers are associated with each message class and consider the agent receiving the message, to decide upon the message processing semantics. The agents use various control policies to manage inventory, procure components, and determine optimal transportation routes. Their framework can be utilized while making decisions by developing different simulation models for alternative configurations and evaluating them while using the same set of input parameters. Kimbrough, Wu & Zhong, (2002) model an electronics supply chain managed by artificial agents. They investigate whether artificial agents can do better than the humans when playing the MIT beer game. In the game, each agent tries to achieve the goal of minimizing long term system wide total inventory cost in ordering from its immediate supplier. The agents are able to track demand, discover the optimal policies (where they are known), and find good policies under complex scenarios where analytical solutions are not available. Liang and Huang (2006) develop a multi-agent system to simulate a supply chain where agents operate companies with different inventory systems. Agents are coordinated to control inventory and minimize the total cost of a supply chain by sharing information and forecasting knowledge. Agents in the supply chain use genetic algorithm (GA) to forecast the demand. Janssen (2005) designed a multi-agent system which improve supply chain management and evaluate the business value. He presents the semi-cooperative architecture and evaluates the benefits using agent-based simulation. He found that the multi-agent system increases the level of flexibility in the supply chain and enables supply chain members to become more responsive which is a positive impact on the ordering lead-time, human processing time, the inventory levels and number of stock-outs. Fox et. al. (2000) presents agent-based supply chain architectures which is capable of supporting complex cooperative work and the management of perturbation caused by stochastic events in the supply chain.

With this detailed description about supply chain modeling using multi-agent systems, the past work in the area of supplier selection and procurement of raw materials, which is one of the cost-intensive processes in supply chain, is discussed in the next section.

2.3 Supplier Selection

A common approach for purchase decisions is to evaluate and select suppliers first, before allocating order quantities among the selected suppliers. Weber et al. (1991) reviewed, annotated, and classified 74 articles related to vendor selection criteria and analytical methods, which have appeared since 1966. It is interesting to note that 47 of the 74 articles or 64% discussed more than one criteria and Dempsey (1978) alone discussed 18 criteria. Net price, delivery, and quality were discussed in 61, 44, and 40 articles respectively. Weber et al. (1991) grouped quantitative approaches for vendor selection into three general categories, namely linear weighting models, mathematical programming models, and statistical/probabilistic approaches. Only ten articles discussed the use of mathematical models for supplier selection. Of these, eight used single-objective models based on linear programming, mixed-integer programming, goal programming, etc. The most common objective was to minimize total purchase costs. Only two (Buffa and Jackson (1983); Sharma et al., 1989) used multi-objective optimization. While Buffa and Jackson (1983) used quality, price, and delivery as criteria, Sharma et al., (1989) used price, quality, lead-time, demand, and budget considerations.

Linear weighting models are the most common approach. They assign a weight to each criterion using a method such as analytical hierarchical procedure and compute a total score for each vendor by summing up the vendor's weighted performance on the criteria. AHP is a decision-making method for prioritizing alternatives in the face of multiple criteria. Saaty (1980) used AHP to enable decision makers to represent the interaction of multiple factors in complex and unstructured situations. Nydick et al., (1992) used AHP to address supplier selection specifically with quality, price, delivery, and service as evaluation criteria. The AHP approach, as used by Nydick et al., (1992) consists of the following five steps:

1. Identify the criteria for evaluating supplier proposals,
2. Perform pairwise comparisons of the relative importance of the criteria in selecting the best supplier, and compute the priorities or weights of the criteria based on this information,
3. Develop measures that describe the extent to which each supplier achieves the criteria,
4. Using the information from step 3, do pairwise comparisons of the suppliers, and compute their priorities,
5. Using the results of steps 2 and 4, compute the hierarchies of suppliers.

Mohanty et al., (1993) also proposed an AHP framework for evaluating suppliers. According to them, the evaluation of suppliers is an unstructured decision-making problem due to the complex nature and structure of the supply management process, lack of information and quantifiable data, large search space for the decision maker, and a multitude of factors that are often conflicting and complementary. An advantage of the AHP over other multicriteria decision-making (MCDM) methods is that AHP is able to incorporate tangible as well as intangible factors especially where the subjective judgments of different individuals constitute an important part of the decision process. Easy accessibility, user interface by specifying various attributes, minimal data requirements, and easy communicability are other advantages.

Relatively fewer publications have used the mathematical programming approach for supplier selection. Kasilingam et al., (1996) proposed a mixed-integer linear programming (MILP) model to select vendors and determine order quantities for multiple items. They considered stochastic demand, quality, purchase and transport costs, fixed cost for vendor selection, impact (cost) of poor quality parts, and lead-time requirements. They used chance constraints to address stochastic demand. Ghodsypour et al., (2001) presented a multi-objective MINLP model for a single item, which used cost and quality as objectives for supplier selection. They included costs of storage, transportation and ordering. Chaudhry et al., (1991) illustrated the use of integer goal programming for allocating order quantities among suppliers using multiple criteria. In goal programming, the criteria are ranked in the order of priority, and goals with higher priority goals are maximized before those with lower priorities. Karpak et al., (2001) presented an alternative decision support system, termed visual interactive goal programming (VIG). VIG helps improve supplier selection decisions of materials/purchasing teams by allowing them to evaluate trade-offs among their goals interactively and graphically.

Some efforts have tried to combine mathematical programming and AHP. For instance, Ghodsypour et al., (1998) proposed an integration of AHP and linear programming for one product to consider both tangible and intangible factors in choosing the best suppliers and distributing the optimum order quantities among them. They aimed to maximize the total value of purchasing, which they defined as the product of supplier rating and order quantity (from that supplier). They used Expert Choice (EC) software and Microsoft Excel Solver for AHP and LP respectively.

The above works addressed the sourcing strategy in terms of supplier selection. Another approach is to address the same in terms of contract selection. Tsay et al., (1999) reviewed supply chain contracts and classified the literature in terms of contract clauses such as specification of decision rights, pricing, minimum purchase commitments, quantity flexibility, buyback or return policies, allocation rules, lead-times, and quality. Sykuta (1996) examined the role of future contracts in the context of a firm's overall contracting activities, and presented alternative forms of contracting. He identified four types of purchasing strategies; namely spot market, forward contracts, long-term contracts, and future contracts. Both spot purchases and forward contracts are transaction-specific. While the former involves an exchange of goods and payment at present conditions, a forward contract involves a future exchange of goods and payment at the terms set today. Sykuta (1996) viewed future contracts as a form of synthetic storage. They lower the cost of contracting for advance supplies by providing the flexibility of a spot contract with the advanced coordination features of a forward contract. A long-term contract, on the other hand, specifies the terms for a series of repeated transactions and involves repeated exchanges of goods and payments over set contract duration.

Anupindi & Bassok (1999) stated the key objective of supply contracts to be the coordination between a supplier and buyer, and described various types of supply contracts. They argued that two main streams of contract research exist, one on the analysis and the other on the design of contracts. Martínez-de-Albéniz et al., (2005) developed a general rule-based framework for selecting supply contracts in which portfolios of contracts can be analyzed and optimized in a multi-period environment. They considered portfolios of option, long-term, and flexibility contracts. In an option contract, the buyer pre-pays a relatively small fraction of the product price up-front in return for a commitment from the supplier to reserve capacity up to a certain level. Option contracts reduce inventory risks. In flexibility contract, a fixed amount of supply is committed, but the amount to be deliver and paid for can differ by no more than a given percentage determined upon signing the contract. Martínez-de-Albéniz et al., (2005) derived conditions to determine when a particular contract option is relatively attractive compared to other options or the spot market. Chen et al., (2001) considered supply contracts in which the buyer commits to procure certain quantities of item/s from the supplier over a predetermined period. After the quantity specified in the commitment has been purchased, any additional units can be purchased on the as-ordered basis. Such contracts offer guaranteed orders to the suppliers and transfer inventory risk from the supplier to the buyer. To encourage the buyer to commit to greater quantities, the supplier usually provides a quantity-discount price schedule that offers prices that decrease with increasing commitment.

A penalty contract requires the supplier to pay a penalty, if it cannot fulfill an order. Frascatore et al., (2008) examine long-term and penalty contracts in a two-stage supply chain with stochastic demands. Their results indicate that the suppliers tend to create a capacity below the optimal supply chain level and manufacturers can induce them to create higher capacity by using long-term and penalty contracts. They showed that such collaboration increases the profit potentials of both manufacturers and supply chain. Park et al., (2006) presented an MILP approach to model different types of contracts that a company may sign with its suppliers (for raw materials) and customers (for final products). They considered contracts with fixed prices, discounts after certain amounts, bulk discounts, and fixed durations. The considered both short-term and long-term planning for contracts. They concluded that modeling contracts with customers would be more useful when considering stochastic problems, as contracts can help reduce uncertainties.

An aspect of supply contracts, which has received limited attention, is product bundling. Some suppliers offer discounts for buying combinations of materials to attract buyers. Rosenthal et al., (1995) examined relationships among different bundling scenarios and found that the most general scenario is the one in which free items are given to the buyer when sufficient quantities are purchased. While the idea of offering free items makes sense in the consumer market, equivalent ideas using additional discounts can also exist in the chemical industry.

Till now, we discussed work related to sourcing and outsourcing of materials. Another important outsourcing and cost intensive process in chemical supply chains is logistics. Today, logistics is much more than transportation alone; it includes many other services. We have discussed this in detail in chapter 1. In the following part, we describe work related to logistics.

2.4 Logistics

"It is remarkable that an industry that is built around the management of process and materials flows in plants has been slow to grasp the principle of organizational processes and logistics flows. But based on the success of such methods in other sectors, this is the future; …" – Braithwaite, (2002). This clearly indicates the state of the chemical industry in paying attention to supply chain logistics. Logistics is the glue that binds the entities of a supply chain (Karimi et al., 2005). According to the Council of Logistics Management (Lambert, 2001), "Logistics is that part of the supply chain process that plans, implements, and controls the efficient, effective flow and storage of goods, services, and related information from the point-of-origin to the point-of-consumption in order to meet customer requirements". Although a functional silo within most companies and a tactical issue, it is a bigger concept and a strategic issue that deals with the management of material and information flows across the supply chain (Lambert, 2001). Logistics is likely to be a key frontier of competition in the future (Bhatnagar et al., 1999). As mentioned in the inaugural issue 2004 of Logistics & SCM, "More than US$3 trillion was spent on global logistics last year. This represents almost 12% of the world's gross domestic product. But inefficiencies in the global logistics network are estimated to be close to US$600 billion" (De Souza, 2004). According to a recent survey (Kearney, 2000) of over 200 European companies, logistics costs represent 7.7% of sales revenue on an average.

Lieb and Randall (1996) showed that the most frequently outsourced logistics services are warehouse management/operations, shipment consolidation, carrier selection, logistics information systems, rate negotiation, and fleet management/operations with the significant expansion of services including product assembly/installation, product returns, and customer spare parts**.** According to Koen

Cardon, the Managing Director of Katone Natsie Sembcorp Singapore Pte Ltd (De Souza, 2004), “Our customers require services that go far beyond conventional logistics. We are becoming part of their integrated production process and are able to optimize their supply chain and product flows by processing or repackaging the products”. In a survey conducted in the USA by Sink et al. (1996) some of the important services for outsourcing were identified to be transportation, warehousing, inventory management, order processing, information systems, and packaging. The logistics function is a key facilitator in the cross-functional effort towards supply chain integration (Harrington, 1995a).

Outsourcing of logistics activities to third party service providers is widely prevalent in Asia-Pacific, Europe, North America, and Australia (Bhatnagar et al., 1999). Razzaque and Chang (1998) surveyed the outsourcing of logistics functions. The primary drivers for outsourcing logistics are the need to focus on core competence (Andersson, 1997), the globalization of business (Byrne, 1993; Foster and Muller, 1990; Rao et al., 1993; Sheffi, 1990; Trunick, 1989), and the need to reduce operating costs and improve customer service (Sink and Langley, 1997). Outsourcing is a viable strategy, as it enables the management to leverage its resources, spread its risks, and concentrate on issues critical to survival and future growth (Sink and Langley, 1997). The concept of third-party logistics (3PL) has generated considerable interest in the American industry during the past several years. It involves the outsourcing of logistics activities that have traditionally been performed within an organization. Increasing corporate emphasis on supply chain management (SCM) has led many companies to consider the use of third-party services. Lieb and Randall (1996) conducted a survey in May-July 1995. The survey involved 500 largest American manufacturing companies as identified by Fortune magazine and focused on the companies, services, benefits, and obstacles related to the use of 3PL services. 55% percent of the respondents used 3PL services as compared to 37% and 38% in 1991 and 1994 respectively. According to the survey, companies using 3PL services reap benefits such as cost reduction, improved expertise, access to data, improved operations, greater flexibility, and improved customer service. Understandably, the chemical multi-nationals are also increasingly outsourcing a variety of their logistics services to 3PL firms worldwide (Figure 2.1) to reduce logistics costs and focus on the core competency of chemical manufacturing.

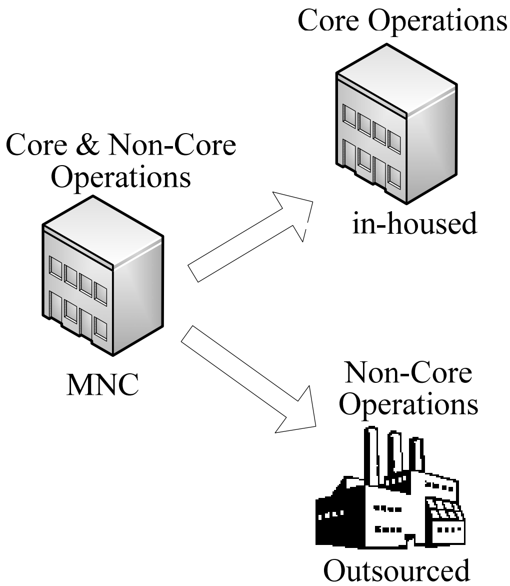

Figure 2.1: Business operations, competencies, and outsourcing

Outsourcing of services differs from that of manufacturing, since the services are intangible, heterogeneous, inseparable, and perishable (Zeithaml et al., 1985), and they impact customer satisfaction (Razzaque and Chang, 1998) directly. The fundamental difference between them is that the former involves acquiring a process rather than parts or materials (Maltz and Ellram, 1997). While logistics services also have the above characteristics, they differ from a large part of the services described in the service literature. For instance, logistics services mainly involve business-to-business relationships, where not only the buyer is the critical stakeholder, but also his customers who can be directly affected by bad service (Andersson and Norman, 2002). Tay et al. (2005) divided the services required by chemical companies into three broad categories, namely tank storage, land logistics, and integrated logistics. Integrated logistics involves inbound (supply) and outbound logistics (distribution). While the former deals with the flow of raw materials between a chemical company and its suppliers, the latter concerns the movement of finished products from the company to its customers.

As stated by Sink and Langley (1997), 3PL is usually discussed in the context of "contract" logistics, which suggests "a process whereby the shipper and the third part(ies) enter into an agreement for specific services at specific costs over some identifiable time horizon". Using a transaction cost theory perspective, Van Hoek (2000) has verified the expected positive correlation between the offering of supplementary logistics services and the use of detailed contracts. Lieb and Randall (1996) survey shows that of the 3PL contracts in place in 1995, 67% were shorter than 3 years in duration, and only 7% were longer than 5 years. Caliber logistics has signed more than fifty contracts, covering a broad range of services, such as inventory management, warehousing, cross-docking, product assembly, and logistics information systems, since the firm was founded in 1989 (Sink and Langley, 1997). Significant customer relationships have been developed by other leading firms as well, such as Exel Logistics - North America, Caterpillar Logistics Services, Menlo Logistics, UPS Worldwide Logistics, Ryder Integrated Logistics, and TNT Logistics (Sink and Langley, 1997). Tay et al. (2005) addressed the selection of contracts and allocation of tanks to them in a storage terminal to maximize profit. However, the problem of selecting contracts for land and integrated logistics has remained unaddressed. Lieb and Randall (1996) showed that most companies focus on service and cost issues in selecting 3PLs. Pedersen and Gray (1998) found that transport price factors were rated as more important than other transport selection criteria by a high proportion of Norwegian exporters. Menon et al. (1998) examined the effect of firm's competitiveness and external environment on the selection criteria. Based on a survey of logistics executives in the USA, on-time shipments and deliveries, ability to deliver on promises, top management availability, and superior error rates may be better bases for assessment than price, quality, and service.

In the general logistics literature, research has focused mainly on general 3PL provider selection with emphasis on carrier, mode, and freight selection problems. According to Sink and Langley (1997), "Selecting the right source is much more of an art when purchasing services than when purchasing materials". Several authors have defined processes for selecting carriers (Lambert and Stock, 1993) and 3PL providers (Sink and Langley, 1997; Bagchi and Virum, 1998; Menon et al., 1998). Anderson and Norman (2002) described and compared the processes for purchasing logistics services of companies following either the trend towards outsourcing of more advanced logistics services or the trend towards leveraging the internet as a tool in their buying of basic services. The term "advanced logistics services" includes (1) multiple and bundled logistics services; (2) unclear outcome requirements; (3) value-adding; (4) management of activities; and (5) development and engineering solutions. They also mentioned the factors complicating the selection process such as the number of services; the tangibility of service; whether the focus is on handling or value adding; whether the focus is on execution of activities or management, and whether the service is pre-defined and stable. They proposed an 8-step sequential process for the purchase of logistics services: (1) define/specify the service; (2) understand currently bought volume and limitations; (3) simplify/ standardize; (4) conduct market survey; (5)

request for information (RFI); (6) request for proposal (RFP); (7) negotiation; and (8) contracting.

Transportation is a major component of logistics services. Transport modes are the means by which freight is carried. They are of three basic types, depending on over which physical environment the freight travels – land (road, rail and pipelines), water (maritime shipping), and air (aviation). Modes can compete or complement each other in terms of cost, speed, accessibility, frequency, safety, comfort, etc. Although intermodal transport has opened many opportunities for complementarities between modes, there is a huge competition, as companies are now competing over many modes in the transport chain. Numerous papers exist on the transport mode and carrier selection problem. McGinnis (1989) grouped the existing literature on freight transportation choice into four categories, namely, the classic economic model, the inventory-theoretic model, the trade-off model, and the constrained optimization model. The classic economic model evaluates the fixed and variable costs of competing modes, and argues that below a theoretical distance, one mode dominates the other, and vice versa. The inventory-theoretic model considers inventory to optimize the modal choice by considering the trade-off among various costs such as carrying, ordering, safety stock, and shipping. The trade-off model chooses between two modal alternatives by minimizing the sum of transport and non-transport costs. The constrained optimization model minimizes transport costs subject to constraints on product, distribution pattern, and service requirements. Besides these cost-based models, a popular method for carrier selection is the analytic hierarchy process (AHP). AHP is a decision-making method for prioritizing alternatives in the face of multiple criteria. Saaty (1980) used AHP to enable decision makers to represent the interaction among multiple factors in complex and unstructured situations. Bagchi (1989) demonstrated the use of AHP in carrier selection problem based on the following steps: (a) decomposition of the carrier selection problem into a hierarchy, (b) formulation of a relative importance matrix for all levels of the hierarchy, (c) determination of the eigenvector from the relative importance matrices, and (d) selection of the alternative with the highest eigenvalue.

Another extremely important factor characterizing the supply chain problems is the high degree of uncertainty. Supply chains are dynamic and demand, price data, production costs, etc rarely stay unchanged. The uncertainty propagates through the supply chain network from the market at supply side, quantity and quality of raw materials, to production quality and yield, and from the other side to the market economics and customer demands (Lababidi et al., 2004). Now, we briefly describe uncertainties and works related with uncertainties in supply chain.

2.5 Uncertainties in Supply Chain

Davis (1993) has given a good description of the uncertainties that occur throughout the entire supply chain network. He considers uncertainty arising from suppliers, manufacturing, and customers. According to Liu and Sahinidis (1997), it is usually difficult to foretell prices of chemicals, market demands, and availabilities of raw materials, etc., in a precise fashion. Zimmermann (2000) identifies the sources of uncertainty as lack of information, complexity of information, conflicting evidence, ambiguity, and measurement errors. Handling uncertainty in an efficient and effective way is becoming more and more important to the success of supply chain management (Xu et al., 2003). A number of works have devoted to studying supply chain management under uncertain environments. There are mainly two primary approaches to address uncertainty i.e., probabilistic approach and scenario planning approach

(Tsiakis et al., 2001). Scenario planning attempts to capture uncertainty by representing it in terms of a moderate number of discrete realizations of the stochastic quantities, constituting distinct scenarios (Mulvey et al., 1997). Probabilistic models consider the uncertainty aspects of the supply chain treating one or more parameters as random variables with known probability distributions (Sridharan, 1995).

Tsiakis et al. (2001) considered the design of multiproduct, multi-echelon supply chain networks under uncertainty in product demands using a scenario-based planning approach. The decisions to be determined include the number, location, and capacity of warehouses and distribution centers to be set up, the transportation links that need to be established in the network, and the flows and production rates of materials. The authors developed a large-scale mixed-integer linear programming model and presented a case study using a European supply chain network involving 14 products, 18 customer locations, 6 distribution center locations, and 3 demand scenarios. Lababidi et al. (2004) used a two-stage stochastic linear program with fixed recourse, also known as the scenario analysis technique, to develop an optimization model for the supply chain of a petrochemical company operating under uncertain operating and economic conditions. They used a two-stage method to solve the stochastic model. In the first stage, decisions are made regarding the production volumes of different products for every planning period. In the second stage, decisions are made regarding the volume shipped to the distribution center, demand losses, backlog orders, and product inventories. The model is tested by number of case studies reflecting uncertainty in key parameters like demand and market prices. Santoso et al. (2005) proposed sampling strategy, the sample average approximation (SAA) scheme, with an accelerated Benders decomposition algorithm to solve supply chain design problems with continuous distributions for the uncertain parameters, and hence an infinite number of scenarios.

The applicability of the scenario-based approach is limited by the fact that it requires the forecasting all possible outcomes of the uncertain parameter. In cases where a natural set of discrete scenarios cannot be identified and only a continuous range of potential scenarios can be predicted, probabilistic approach is used (Gupta & Maranas, 2003). Another drawback of this technique is that the number of scenarios increases exponentially with the number of uncertain parameters, leading to an exponential increase in the problem size (Gupta & Maranas, 2000). A substantial decrease in the size of the problem is usually achieved at the expense of introducing nonlinearities into the problem through multivariate integration over the continuous probability space (Gupta & Maranas, 2000).

Gupta and Maranas (2000) modeled uncertain demand via a normal probability function and proposed a two-stage solution framework for multisite midterm planning. Supply chain decisions are classified into production and logistics decisions. In their approach, production decisions are made before the demand is known (first stage) while the logistics decisions are delayed. The latter are made in the second stage to handle evolving uncertainty in the product demand. Later, Gupta et al. (2000) extended this customized solution procedure to include probabilistic constraints for enforcing desired customer demand satisfaction levels. They used a chance-constraint programming approach in conjunction with a two-stage stochastic programming methodology to capture the trade-off between customer demand satisfaction and production costs.

Most of the models are based on the assumption that “all” activities of SC are governed by a “global” organizer neglecting multiple perspectives that individual activities are often governed by separate supply chain components which have their own, often conflicting, objectives. To address this, Ryu et al. (2004) presented a bilevel programming framework for supply chain planning problems under uncertainty. A BiLevel Programming Problem (BLPP) refers to an optimization problem that is constrained by another optimization problem. It is used to address industrial situations involving several groups, having own objectives, which are inter-connected in a hierarchical structure (Ryu et al., 2004).

Petrovic et al. (1998) used fuzzy sets to handle uncertain demands and external raw material problems and further considered uncertain supply deliveries in a later work (Petrovic et al., 1999). Giannoccaro et al. (2003) also apply fuzzy set theory to model the uncertainties associated with both market demand and inventory costs. Chen and Lee (2004) proposed fuzzy decision-making method for the optimization of multi-echelon supply chain networks with uncertain sales prices.

Xu et al. (2003) and Qi et al. (2004) presented an alternate model, disruption management, to approach the demand uncertainty. Generally, disruption management studies the situation where an operational plan has to be made before the uncertainty is resolved, and deviation costs occurred for revising the operational plan in its execution period with the resolution of the uncertainty (Xu et al., 2003). According to Qi et al. (2004), formulating a good plan based on certain probability assumptions is important, but realistically, it is not possible for the decision-maker to anticipate all contingencies.

We now define the scope and objectives of this research.

2.6 Scope of Research

As discussed, agent approach is suitable for modeling the behavior of supply chains as it can capture the dynamics and complexity of the supply chain. To develop multi-agent applications, there is an urgent need for frameworks, methodologies and toolkits that support the effective development of multi-agent systems.

Hence, the first part of this work focuses on the development of multi-agent platform called MADE (Multi-Agent Development Environment) which is specially designed for chemical supply chain applications. The goal of MADE is to simplify the development of agent applications and provide the agent software developer with an integrated environment for quickly and easily constructing intelligent agents and agent-based software. We illustrated the application of MADE by modeling and simulating a refinery supply chain. Software agents are used to emulate the entities such as procurement, sales, operations, storage and logistics department of the refinery as well as the suppliers, logistics service providers, and oil exchanges.

In the second part of this work, we focus on the sourcing and outsourcing involved in chemical supply chains. In this work, we address the sourcing of goods and services in terms of contract selection. Strategic sourcing contracts offer several advantages and are common practice in many industries, especially the chemical industry. We propose a relatively comprehensive classification of material supply contracts. We address the contract selection problem from the perspective of a multinational company with globally distributed manufacturing facilities, who is considering several suppliers offering different types of contracts and some acting as spot market suppliers.

The above work is related to the sourcing of materials. We develop a model for decisions involved in outsourcing of logistics. We present a systematic framework for managing chemical logistics in an integrated manner. We present a novel approach to represent logistics tasks in terms of recipes and recipe superstructures. Using this representation, we develop a mixed-integer linear programming formulation to fulfill the logistics needs of a global enterprise in terms of 3PL contracts and in-house execution.

The above works ignore the uncertainties associated with prices and demands but these deterministic models can be extended to solve for stochastic scenarios. The above deterministic models are fast even for an industrial-scale example. This is a desirable feature, because it needs to be solved repeatedly for a real-life stochastic scenario, in which several cost/price parameters are uncertain. Thus, we extend our work of sourcing of materials by considering demand and price uncertainties. An efficient deterministic model enables us to use a scenario-based approach to represent uncertainties in demands and purchase prices.

CHAPTER 3. MADE A Multi-Agent Platform for Supply Chain Management

As there are several similarities between a company in a supply chain and an agent, the Multi-Agent System paradigm can be a valid approach for modeling supply chain. To develop multi-agent applications, there is an urgent need for frameworks, methodologies and toolkits that support the effective development of multi-agent systems. Hence, we develop multi-agent platform called MADE ((Multi-Agent Development Environment).

In this chapter, we describe MADE which is specially designed for chemical supply chain applications. MADE can be considered as an agent middle-ware that is an efficient agent platform and supports the development of multi-agent systems. The MADE provides an easy to use framework to model the functions and activities within a supply chain. Section 3.1 provides an overview of the Multi-Agent Development Environment (MADE), a special-purpose modeling environment developed using Gensym's G2 Expert System shell (http://www.gensym.com/documents/g2_datasheet.pdf). MADE contains the essential building blocks for modeling supply chains. Models, simulators, and decision support systems for any supply chain can therefore be developed without significant programming effort. We end with concluding remarks and discussions.

3.1 MADE

MADE is an integrated environment to design, develop, debug, simulate and deploy agents. It supports the development of scalable multi-agent applications capable of running in a single machine or on a distributed network. This agent platform is itself a distributed system since it can run in different machines with one of them acting as a front end.

3.1.1 Architecture of MADE

The architecture of MADE shown in Figure 3.1 contains 3 main layers: 1) SCAgents 2) Administrative Services and 3) Message Passing. The first layer provides the functionality of the MAS by creating SCAgents. The administrative services manage the Yellow Pages and White Pages facilities of the host. Yellow pages maintain the directory of services provided by the agent and white pages keep the list of agent present in the same machine. The service of transport, delivery and reception of messages represent a key point within MADE. Exchange of messages model peer to peer interaction in which agents make requests, provide information, react to events, and so on.

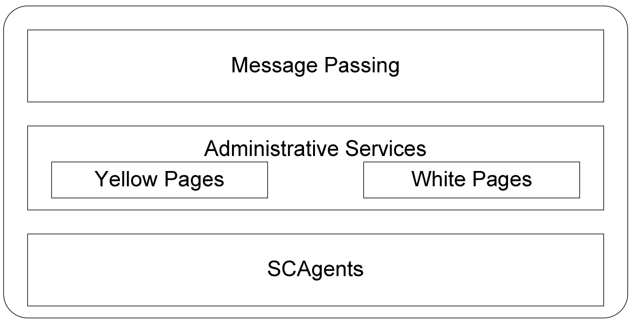

Figure 3.1: Architecture of MADE

MADE offers the following list of features to the developer:

- APIs to create agent and register agents to host. Agent can be dynamically created, deleted, cloned and move across the network. It also provides graphical programming language to design and develop agent behaviour based on grafcets. Parallel task can be executed by agents.

- Yellow Page and White Page Facility whose function is same as Directory Facilitator (DF) and Agent Management System (AMS) of FIPA (Standardization for agent-based systems).
- Distributed agent platform. The agent platform can be split onto several hosts with each host running on different machines and one of them acting as a front end.
- APIs to send/receive messages to/from other agents.
- Graphic user interface for the operation on agents i.e. creating a new agent, and creating Grafcet for agent.

3.1.2 Components of MADE

The main components of MADE are SCAgent, SCMessage, SC-Activity and Host.

SCAgent: A SCAgent is an autonomous, multi-threaded object having the ability to specify characteristics of various supply chain entities. Agent is specialized according to the intended role in supply chain for example, supplier agent, logistics agent, 3PLs etc. The behavior of a SCAgent is described in the form of Grafcets that is embedded inside the agents (explained below). Each SCAgent has a network-wide unique name and communicates with other SCagents through messages. MADE has "White Pages" and "Yellow Pages" facility. The objective of "White Pages" is to maintain a directory of SCAgents present on the same machine registered with the same host. Yellow Pages facility helps SCAgents to find other SCAgents with specific properties. When an agent is registered with the host, it advertises its properties to the Yellow Pages. An agent can query a yellow page to find agent that possess a particular property. The Yellow Pages returns appropriate lists of agents matching the query description or "null" if there is no agent present with that property.

SCMessage: SCAgents communicate with each other by exchanging objects, called SCMessages. All SCMessages share common attributes including the originating (source) SCAgent, departure time, Recipient SCAgent, and time of receipt. In addition, a SCAgent can use customized messages that are subclasses of SCMessage. These subclasses are suitable for representing specific types of supply chain communications such as Request-for-Quote (RFQ). A SCMessage can be sent by one SCAgent to another (including itself) in general, or a specific activity within a SCAgent. MADE does not distinguish between messages send to the agent running on the same machine (means that the sender and the receiver agent are living on the same machine) or on a different machine.

Activity: An activity defines a specific behavior of a SCAgent. At any time, a SCAgent may perform multiple activities of the same or different types (i.e., multi-threaded agents). A SCMessage send to an agent may initiate a new activity or continue a dialog with an ongoing activity. Once an activity is initiated, messages can be sent specifically to it. In MADE, Grafcets are used to specify the activity of SCAgents (David and Alla, 1992). A Grafcet is as a graphical programming language that is widely used for specifying process control actions in the chemical industry. A Grafcet is a graph that consists of two types of nodes – steps and transitions, as shown in Figure 3.2

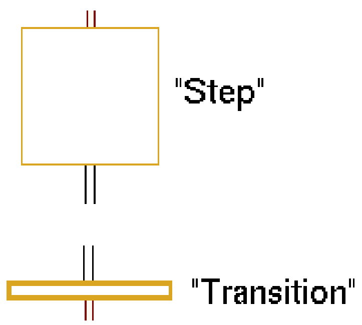

Figure 3.2: Steps and Transitions are used to develop a Grafcet that specifies the activities of a SCAgent

A step represents a state, phase, or mode that can be active or inactive. Associated with a step are actions that are performed when a step is active. In MADE, actions can be specified using G2's full-scale procedural language. Some examples of actions include sending message, calculating profits, selecting operable crudes from a set, etc. A transition signifies a change from one state to another. Each transition represents a condition that is necessary for the change to occur and for execution to move to the next step. An example of a transition condition is "Wait for quotations from at least three suppliers". In MADE, simple transition conditions can be expressed in the form of G2-rules while complex ones can be coded as G2 procedures. The flow of control during the activity of an agent is thus defined by the Grafcet. A Grafcet can contain parallel threads of actions (see below), thus agents can perform parallel tasks. MADE contains standard Grafcet templates for each class of agents; these can be modified by the developer to bestow a specific behavior to a SCAgent. A new activity can be initiated by the receipt of a specific message class as defined in the SCAgent handler.

Agent Handler: The agent handler determines how a SCAgent will respond to messages. The agent handler thus accepts or refuses the message, routes accepted messages to the appropriate activity, and initiates new activities as necessary. Messages that can initiate a new activity are specified in the agent handler by the developer.

Host: Every multi-agent application contains a host. Every agent, when created, registers with the host. The host serves as the post office and is responsible for message delivery. All SCMessages are routed through the host. The host sorts all outstanding messages according to the requested destination time of the message, locates the destination SCAgent and delivers the message to the agent handler of the addressee SCAgent. As described above, the message may be processed by the addressee in one of two ways – it will either start a new activity or continue an ongoing one.

The activities involved in message exchange are illustrated in Figure 3.3 using the example of a Producer and Supplier agent. Producer agent seeks to procure material "A". If the Producer agent knows the identity of a suitable supplier, then it can directly send a purchase-order message to the supplier. If a suitable supplier is not known beforehand, the Producer agent can look up the Yellow Pages directory to find out all supplier agents who sell "A". The Producer can then send some or all of them RFQ messages. All messages will go through the host and would be delivered to the agent handler of the destination agent. This scenario is applicable only when both Producer and Supplier agent are living in the same machine.

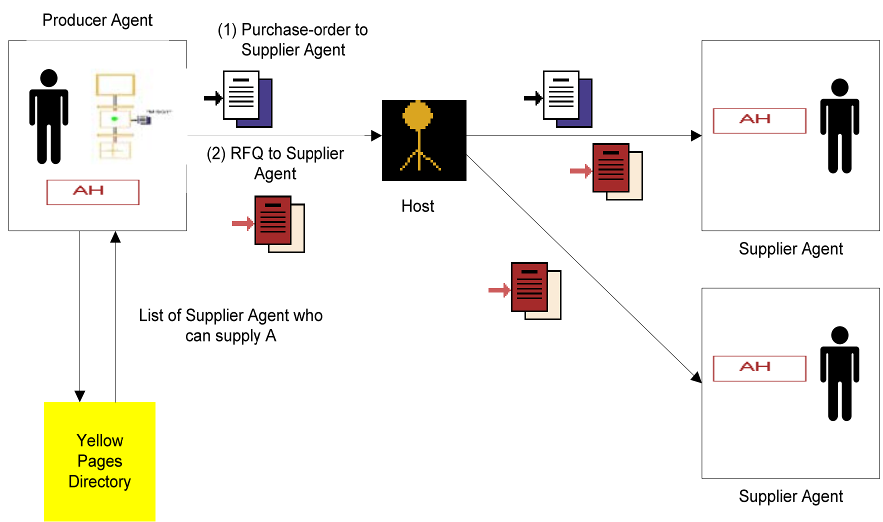

Figure 3.3: Message Passing in MADE

If the two interacting agents i.e. producer and supplier agent are running in different machines then the activities involved in message exchange will be slightly different and is illustrated using Figure 3.4. Producer agents running in Machine "A" want to send a purchase-order to Supplier Agent running in another Machine "B". The message will go through the host of both machines and then delivered to the supplier agent. When the agent want to send a message to another agent, irrespective of whether the agent is running in the same or different machine, the message will always go through host. Host has a list of all the agents on the same network irrespective of whether they are in same or in different machines. If the agent name does not match with the agent name of the message recipient, then the message will be refused. In the other case, there are two scenarios which are already explained that the recipient agent is sitting in the same machine or in different machine on the same network.

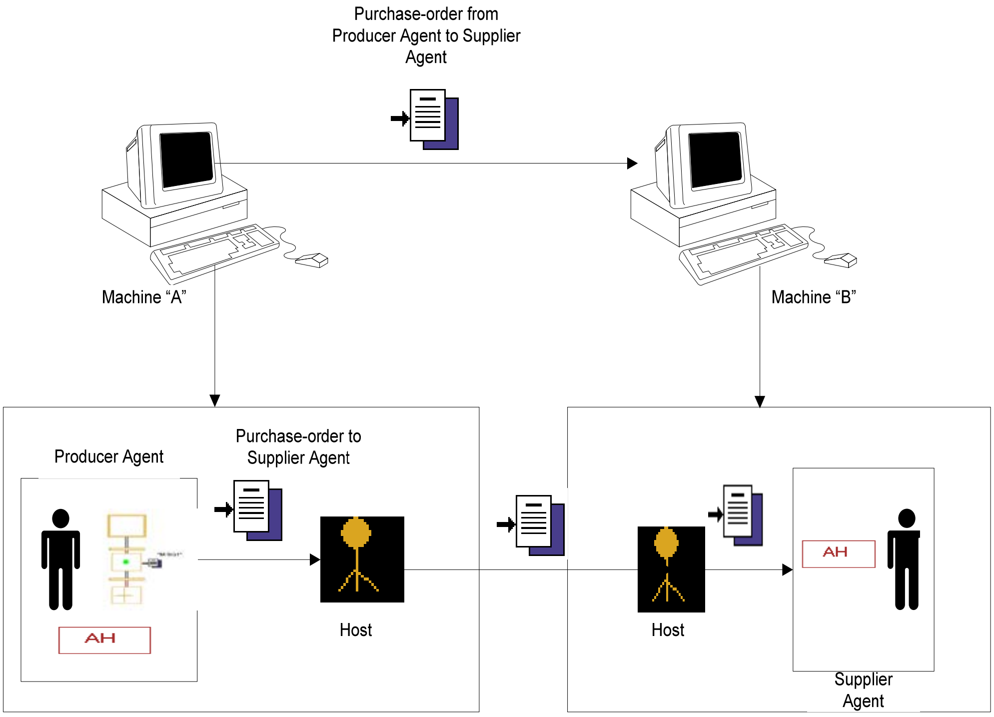

Figure 3.4: Message Passing in MADE between agents running in different machines

MADE-Scheduler: MADE comprises a message scheduler based on discrete-event simulation. Whenever a message to initiate a new activity is received, the scheduler creates a new instance of the SCAgent's Grafcet and starts it execution. Figure 3.5 shows a Grafcet that models the activity of the Supplier in the above example. Whenever a Supplier agent receives a new message, this Grafcet will be instantiated and execution will begin from the main thread at the step marked M. Based on the class of message, the appropriate thread T1 or T2 will be executed. If the message is of class RFQ, then the condition embedded in the first transition of T1 (notated as "Receive RFQ details) will be satisfied and the next step ("Send Quotation") will be executed. Similarly, a message of class Purchase-order will result in the execution of thread T2 and the task to "Send confirmation to procurement" will be performed. The "End of thread" transition signals completion of the activity and execution of the Grafcet instance will be terminated. Any complex, multi-threaded supply chain activity can be modeled using this formalism.

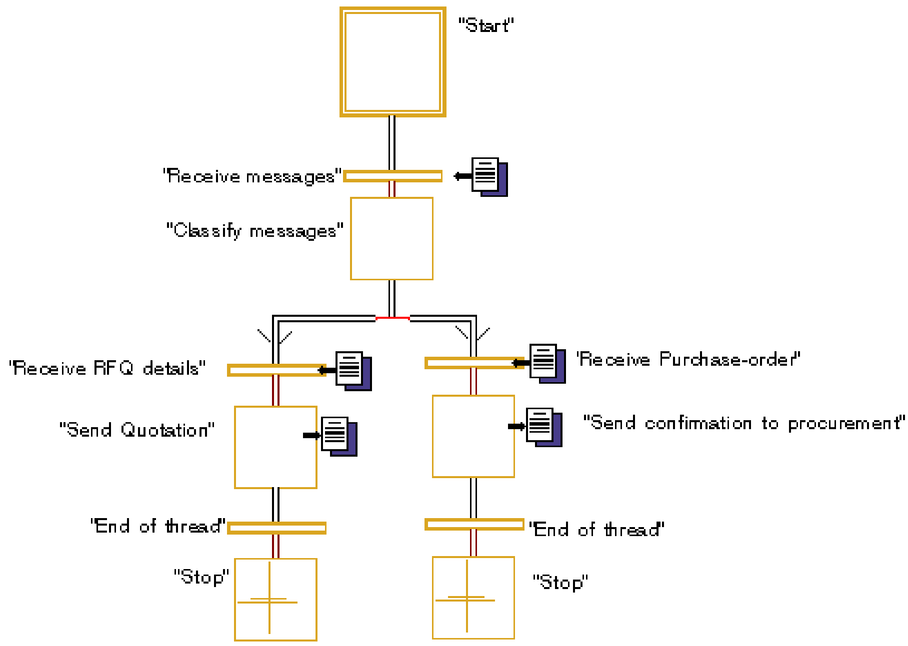

Figure 3.5: Grafcet for Supplier Agent

3.2 Discussion

In this chapter, the MADE multi-agent platform customized for supply chain modeling and simulation is described. MADE is an integrated environment to design, develop, debug, simulate and deploy agents (Srinivasan et al., 2006). It supports the development of scalable multi-agent applications capable of running on a single machine or on a distributed network. The multi-agent approach is suitable for modeling the dynamic behavior of supply chains and it can capture the complexity of globalized, distributed supply chain in a comprehensive and extendable fashion. With MADE, we can create intra- as well as inter-enterprise applications. One such is illustrated in the next chapter, where MADE is used for modeling and simulating a refinery supply chain.

CHAPTER 4. A Multi-Agent Approach to Supply Chain Management in the Chemical Industry

Here, we describe an agent-based model of a refinery's supply chain. Software agents emulate the entities such as procurement, sales, operations, storage and logistics departments of the refinery as well as the suppliers, logistics service providers, and oil-exchanges. These agents model the embedded business policies and thus mimic the different business processes (described later) of the enterprise. Uncertainties are captured by stochastic elements embedded in the agents. The dynamics of the supply chain is emulated by discrete event simulation of the agent-based model. The application of the supply chain model and simulation in decision-making is illustrated here. Different business processes and supply chain configurations are evaluated based on their effect on entity-specific as well as supply chain wide key performance indicators. This enables well-rounded decisions related to both the structure and parameters of the supply chain. In Section 4.1, we describe the salient features of the refinery crude supply chain. The supply chain decision support system called Petroleum Refinery Integrated Supply Chain Modeler and Simulator in MADE (PRISMS-MADE) is developed and presented in Section 4.2. In Section 4.3, we illustrate the application of PRISMS-MADE to support effective supply chain management.

4.1 Refinery Supply Chain Management

Crude procurement is one of the most important supply chain activities in the refinery and has a direct impact on refinery profits. Large buffers of crude degrade the economics of the refinery due to the high inventory cost; insufficient crude would lead to crude stock-out situations that necessitate unit shutdowns – both should therefore be avoided. Further, crude procurement is a complex activity that requires interaction and closed coordination between several departments in the refinery as well as third parties. It therefore serves as a suitable illustration to explore the benefits of agent-based supply chain management. A brief overview of the internal departments of the refinery is given below.

Procurement: Coordinates the crude procurement process. It retrieves crude availability and decides which crude to purchase and in what quantity. To do this, it needs information about crude availability, refinery targets, and logistics.

Sales: Provides product prices and demands, both current and forecasted

Operations: Decides which crude and how much to process every day

Storage: Manages the crude inventory and releases crude to operations.

Logistics: Arranges transport of crude from the oil supplier terminal to the refinery

In addition to the refinery, oil suppliers and third party logistics providers (3PLs) are important players in the refinery supply chain. 3PLs arrange for the transportation of the crude from the oil supplier's terminal to the refinery.

The crude procurement process varies from refinery to refinery; the following is one popular approach. The major events during crude procurement are shown in Figure 4.9. The entire crude procurement process can be divided into three sub-processes: crude selection and purchase; crude transportation, delivery and storage; and crude refining. Each of the sub-processes is explained below.

4.1.1 Crude Selection and Purchase

The crude selection and purchase is normally done at fixed intervals called *procurement cycles*. The purchase of crude is done significantly in advance of the time the crude will be processed – this duration is known as the *planning horizon*, and notated as *A*. The following activities are performed in each procurement cycle:

1. At the beginning of the procurement cycle, the procurement department requests the estimated demands during the *target week* (at the end of the planning horizon) of the various petroleum products from the sales department.
2. The sales department subsequently sends forecasted prices and demands of products to the procurement department.
3. The procurement department also acquires the list of crudes available for purchase in the petroleum exchange. Based on the characteristics of each crude (crude assays and cuts), its price, the forecasted product demands, and their prices, the procurement department calculates the profit margin, (also called the *netback value*, for each crude. The procurement department shortlists the most profitable crudes and sends the list, called the *crude basket*, to the operations department.
4. The operations department confirms the operability of the crudes in the crude basket based on plant constraints and previous experience and returns the *refined crude basket* to the procurement department.
5. The procurement department compiles the pickup location and time for the crudes in the refined crude basket and requests the logistics department for estimates of transportation costs.
6. The logistics department invites various 3PLs to bid for the contract of transporting each crude from its pickup terminal to the refinery. 3PLs bid for

the contracts; their bids contain the transportation costs, demurrage terms and cost, etc.

7. The logistics department processes the bids and transportation cost estimates sent to procurement department based on the best bid.

8. The procurement department calculates the net profit on each crude (including the transportation cost) in the refined crude basket and finally selects the crudes to be purchased. Purchase orders are sent to the supplier. On receiving confirmation from the oil supplier, the logistics department is informed.

9. The logistics department in turn awards the contract for transporting the crude to the lowest cost 3PL. After receiving confirmation from the 3PL, the logistics department forwards the transport details to the procurement and storage departments.

4.1.2 Crude Transportation, Delivery, and Storage

The delivery and storage sub-process are given below:

10. Depending upon the date of pickup, the 3PL dispatches the ship to the pickup terminal.

11. The oil supplier starts loading crude. On completion, the tanker starts its journey to the refinery and informs the storage department of its expected arrival date.

12. The storage department checks the jetty schedule and arranges for the timely unloading of the crude. Demurrage charges may be levied by the 3PL if the tanker has to wait for a long period for the jetty to become available. On arrival at the refinery, the tanker informs the storage department. After berthing and approval from the storage department, crude unloading begins.

4.1.3 Crude Refining

This is the actual processing in the refinery. The refinery is a continuous process that runs 24x7 at a throughput that can be specified daily in the range $[T_{\min} \ \ T_{\max}]$. The task of selecting the mix of crudes to process is carried out daily:

13. The operations department decides the crude mix to run based on the present process conditions, crude stock, and the day's production targets (received from the sales department). It requests the storage department to release the required crude.
14. The storage department releases the required amounts to the operations department and updates the inventory database.

4.2 Agent Modeling of Refinery Supply Chain

The crude procurement process described above can be modeled using the multi-agent paradigm (Julka et al., 2002a; b). The resulting model has been implemented in MADE and a decision support tool called Petroleum Refinery Integrated Supply chain Modeler and Simulator (PRISMS-MADE) developed. In PRISMS-MADE, agents are used to model the departments of refinery as well as the external entities. The hierarchy of SCAgents in refinery supply chain model is shown in Figure 4.1.

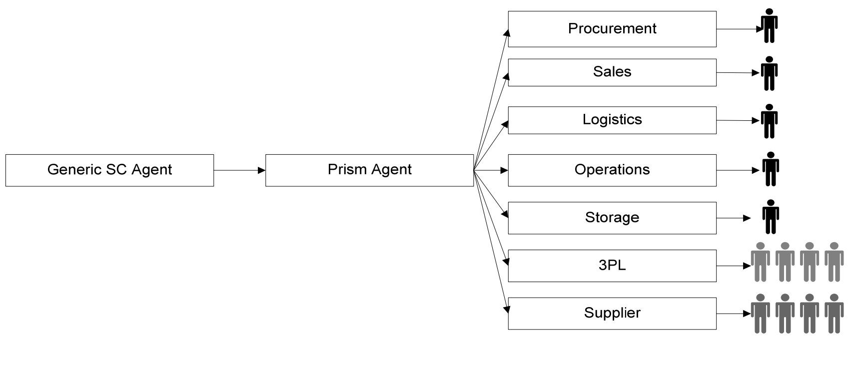

Figure 4.1: Hierarchy of Agent Classes in PRISMS-MADE

The Generic-SCM-Agent is the superior class of all agents in MADE. The Prism Agent is the superior class of all agents in PRISMS-MADE. It has seven subclasses, each customized to reflect the activities of a different entity – the Procurement, Sales, Logistics, Operations, and Storage departments of the refinery and the 3PLs and Supplier. One or more instances of these agent classes are used to model the structure and functioning of the refinery's supply chain. Messages are exchanged between the agents to emulate flow of information and chemicals in the refinery supply chain. Figures 4.2 to 4.8 describe the activities of the different agents involved in crude procurement. The procurement and logistics agents have one thread while the storage, sales, operations, 3PL, and supplier agents are multi-threaded.

The procurement agent receives a message from the clock agent (not described here) at the beginning of each procurement cycle. This message initiates the procurement process for that cycle. As shown in Figure 4.7, the procurement agent sends a message (Message M_P^1) to the sales department asking for the market data, which is the first step in the crude selection and purchase process as explained in Section 4.1. The sales agent has two threads (marked T1 and T2) as depicted in Figure 4.2. Any message requesting for 'market data' will activate thread T1 and the sales agent will respond with the market data (Message M_s^1) to procurement agent, as described in Step 2 of crude selection and purchase. Using this, the procurement agent calculates the profit and amount of crude to procure based on equations 4.1 and 4.2:

$$P(k) = \sum_{i=1}^{N} (y(i,k) * E(i)) - U(k) - D(k) \tag{4.1}$$

$$\tilde{C}(j) = (\sum_{i=1}^{N} Q(i) / G) / N - S + W \tag{4.2}$$

The procurement agent then sends the crude basket to the operations agent (Message M_P^2, Step 3). The operations agent has two threads as shown in Figure 4.4.

The message with the crude basket will activate thread T1 and the operations agent will refine it and return refined crude basket as Message M_o^1 to the procurement agent (Step 4). The procurement agent then requests the logistics agent for transportation costs (Message M_p^3, Step 5) which is provided as Message M_L^2. The procurement agent recalculates the profit including the transportation cost.

$$P(k) = \sum_{i=1}^{N} (y(i,k) * E(i)) - U(k) - D(k) - R \tag{4.3}$$

The procurement agent then selects the crude to purchase and sends the purchase order to supplier (Message M_p^4, Step 8). On receiving the purchase order, the supplier agent, whose Grafcet is shown in Figure 4.3, sends a confirmation (Message M_{SP}^1) to the procurement agent. The latter then sends the purchase details to the logistics agent (Message M_p^5) and waits for the transportation details (Message M_L^4). Finally, the transportation details are forwarded to storage and supplier agents (Message M_p^6).

In addition to the above tasks, some agents have other tasks to be performed on a regular basis. These are spawned by messages from the clock-agent. The sales agent performs the routine task of calculating the actual demands at regular intervals based on customer orders. Similarly, the Operations agent (Figure 4.4) decides the crude mix to run daily based on the crude stock and product demand (Step 13). Equations 4.4 and 4.5 are used in this thread to calculate planned throughput $\tilde{T}$ and actual throughput T in every procurement cycle.

$$\tilde{T}(n,j) = \tilde{C}(j) / F \tag{4.4}$$

$$T(n,j) = \begin{cases} 0 & \text{if } S(n) < T_{\min} \\ \min(C(j)/F + \hat{T}(n-1), S(n), T_{\max}) & \text{otherwise} \end{cases} \tag{4.5}$$

$$\hat{T}(n+1) = \max\left[(T'(n) - T(n)), 0\right] \text{ where } T'(n) = C(j)/F + \hat{T}(n-1) \tag{4.6}$$

The Operations agent sends Message M_O^2 daily to the storage department to release the crude necessary for the day's processing. The storage agent (Figure 4.5) has six threads. On getting Message M_O^2, storage agent releases the crude and updates the stock inventory based on equation 4.7.

$$S(n) = S(n-1) - T(n, j) + H(n) \tag{4.7}$$

The Grafcet of the logistics agent is shown in Figure 4.6. When Message M_P^3 is received from Procurement agent to arrange for transportation, the logistics agent sends a RFQ (Message M_L^1) to the 3PLs registered with it. The 3PL agents reply (see Figure 4.8) with a RRFQ (Message M_{PL}^1) The logistics collates the information from these RRFQ and sends the best price for transportation to the Procurement agent. The logistics agent also sends a message (M_L^3) to the winning bidder, who replies with the transportation details. These are forwarded by the logistics department to the procurement agent via Message M_L^4.

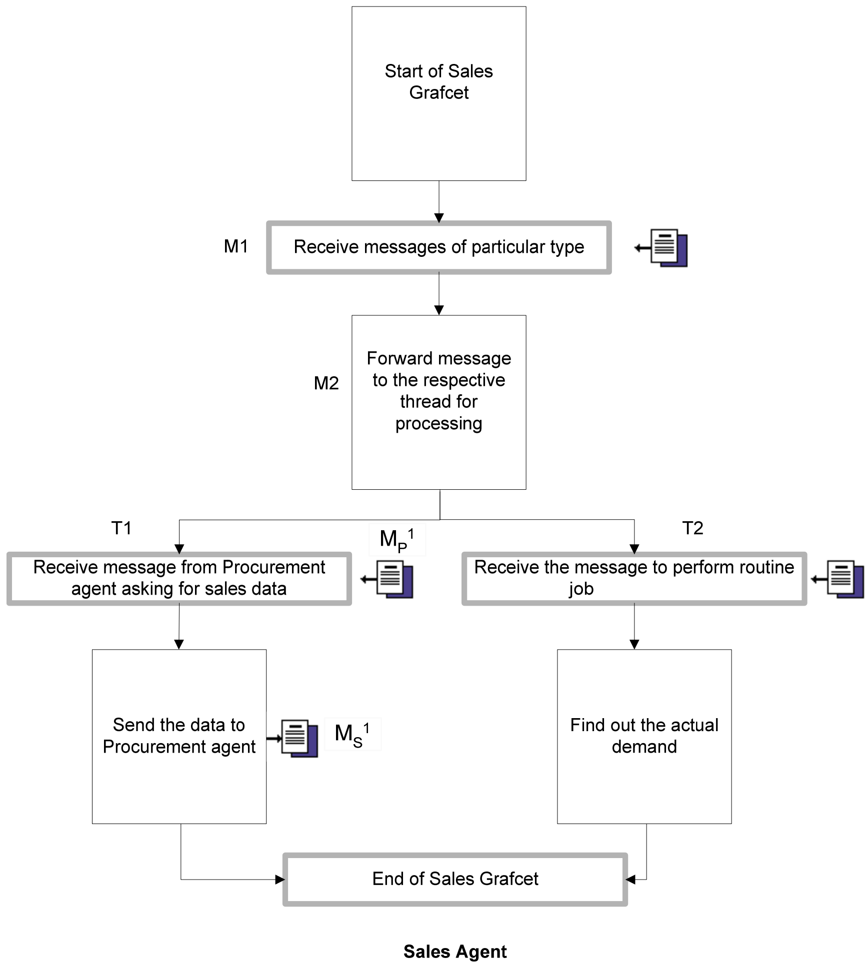

Figure 4.2: Grafcet for Sales agent in PRISMS-MADE

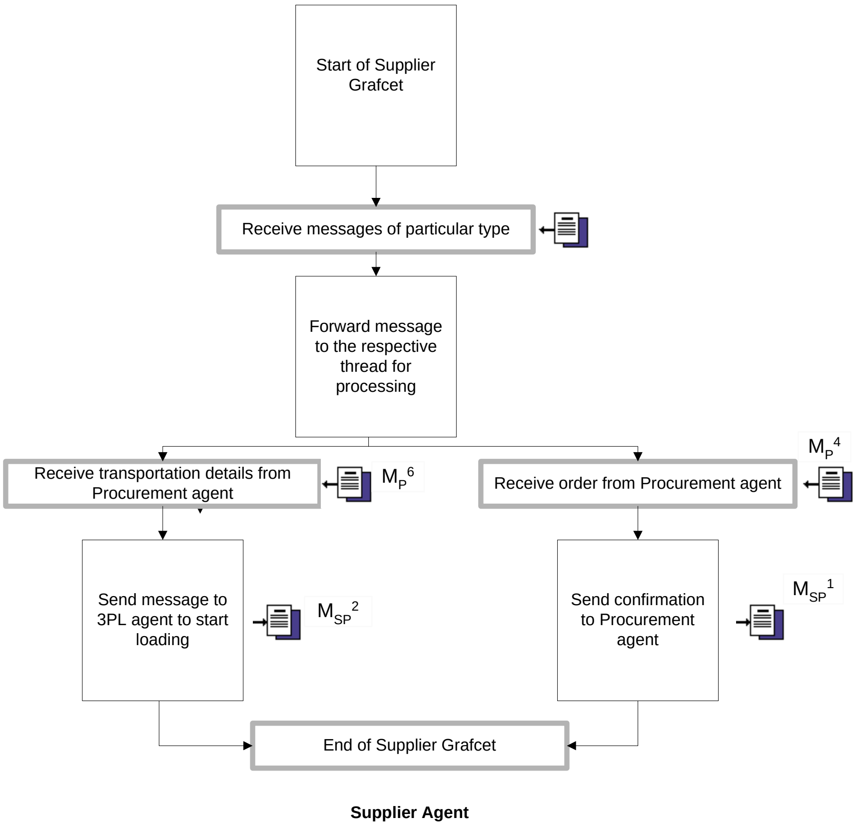

Figure 4.3: Grafcet for Supplier agent in PRISMS-MADE

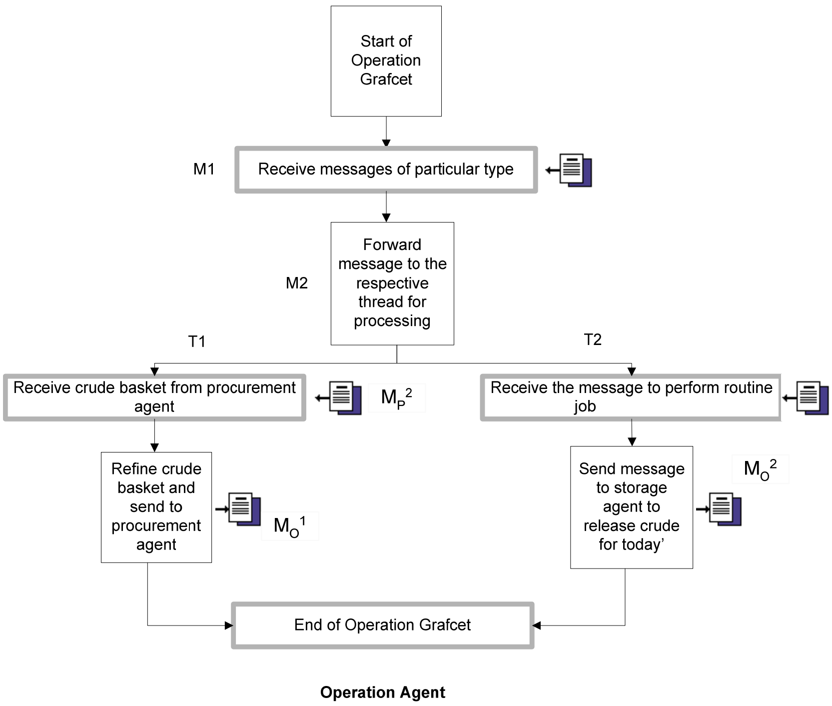

Figure 4.4: Grafcet for Operation agent in PRISMS-MADE

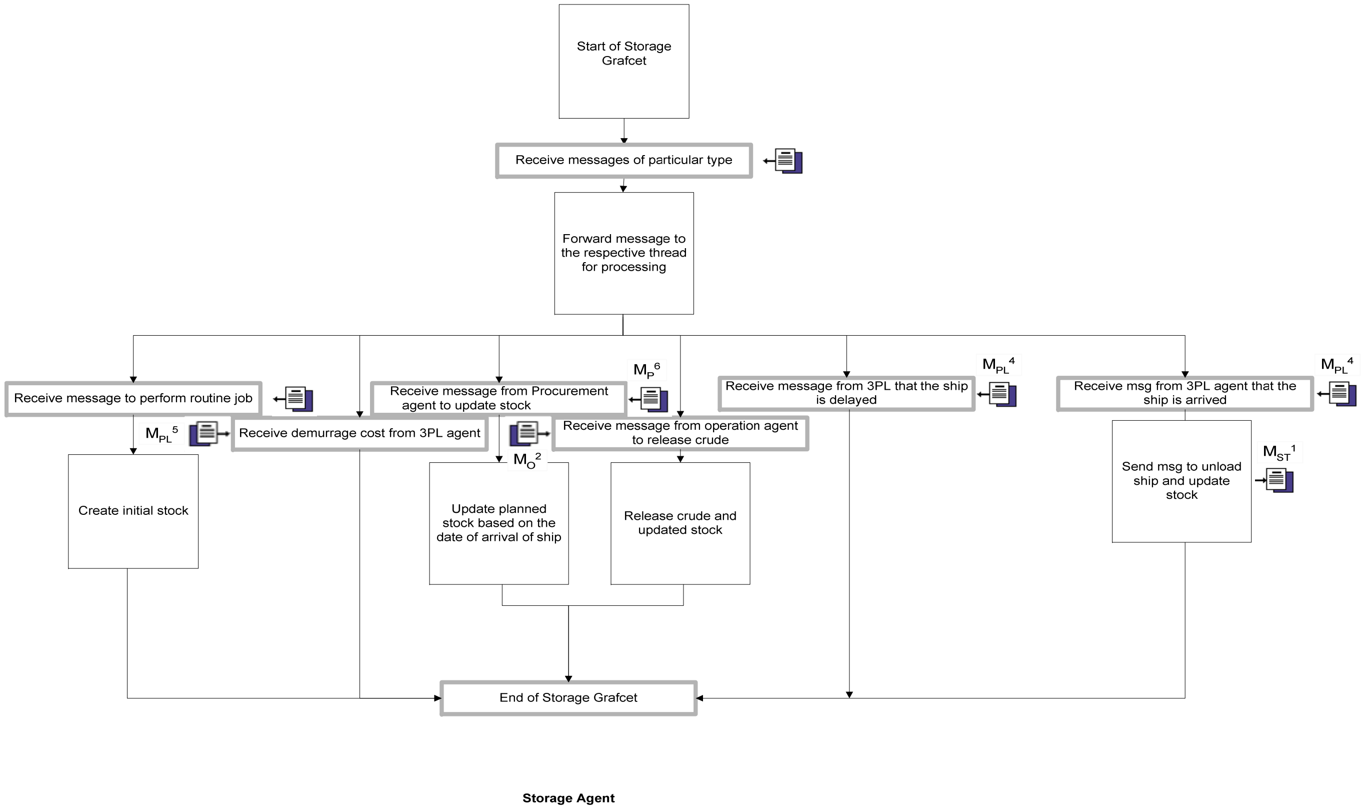

Figure 4.5: Grafcet for Storage agent in PRISMS-MADE

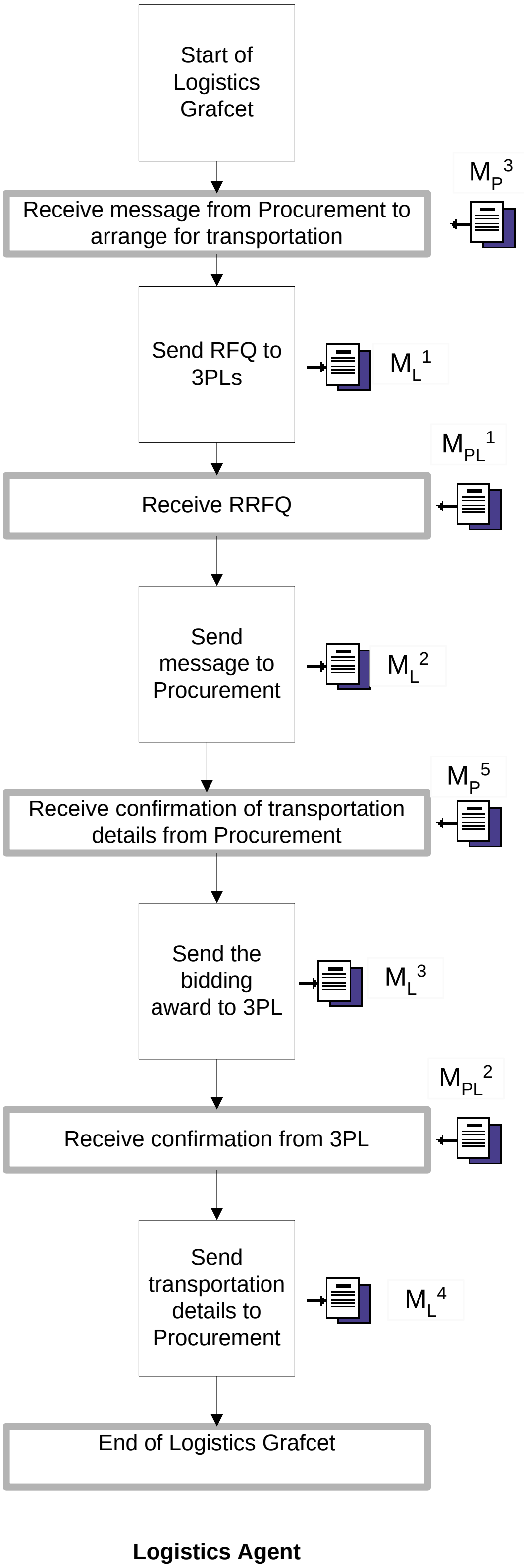

Figure 4.6: Grafcet for Logistics agent in PRISMS-MADE

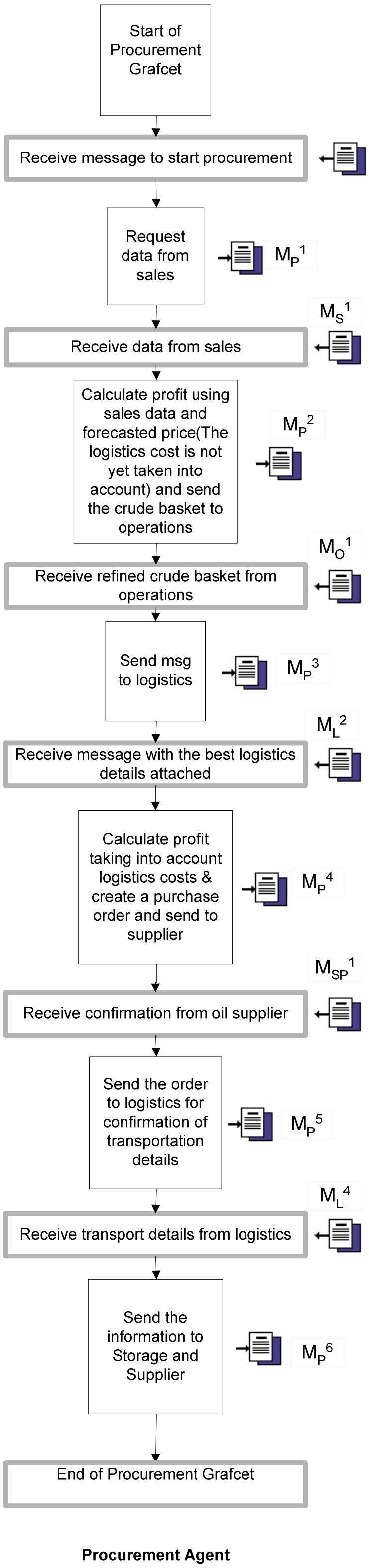

Figure 4.7: Grafcet for Procurement agent in PRISMS-MADE

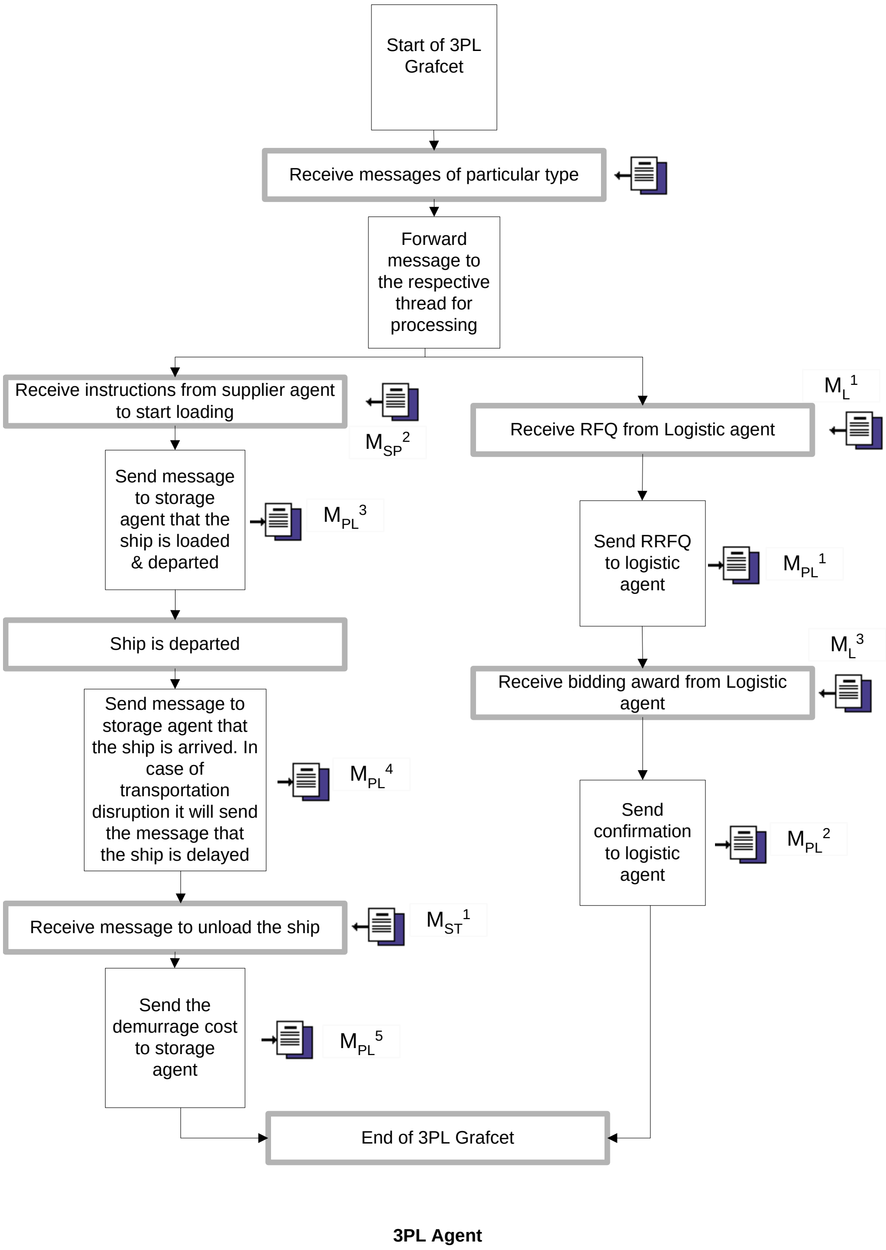

Figure 4.8: Grafcet for 3PL agent in PRISMS-MADE

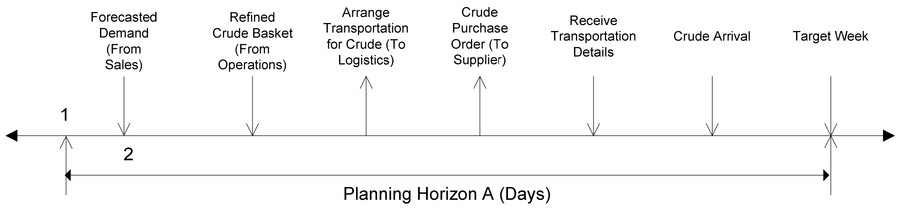

Figure 4.9: Supply Chain Events during a Procurement Cycle

In the next section, we illustrate how this agent-based model of the refinery supply chain can be used for decision support.

4.3 Case Studies

Consider a simplified refinery with the following characteristics:

1. The refinery makes seven products.
2. Only one crude is procured in each procurement cycle.
3. The refinery operates on a pull mechanism, i.e. throughput is calculated based on demand. The Sales agent generates demand forecast and actual demand data stochastically.
4. A safety stock (*W*) of crude is maintained so that inventories do not fall below a pre-specified minimum level.
5. During normal operation, a max of 5% difference may exist between forecasted and actual demand. If the difference is larger, a disruption is considered to have occurred in the supply chain.

The following parameters values are used for the refinery and its supply chain operation:

Minimum throughput of refinery	T_{min}	70 kbbl/day
Maximum throughput of refinery	T_{max}	120 kbbl/day
Planning horizon	A	50 days
Simulation horizon	B	105 days
Length of procurement cycles	F	7 days
Number of procurement cycles	J	10
Safety stock	W	150 kbbl

In the following studies, results are shown from Day 35 of the simulation when the refinery and the supply chain has reached steady state after initialization.

4.3.1 Study 1: Normal Scenario

In this study, the normal operation of the supply chain is illustrated. Figure 4.10 shows the planned stock versus actual stock of refinery for ten procurement cycles. In the first procurement cycle, products have to be delivered on the 50th day. In this cycle, crude is delivered by ship on the 35th and 42nd day, consequently stock levels go up on these days. Inventory level trend down on other days due to production. The same saw-tooth trend occurs in other procurement cycles as well. Table 4.1 shows the projected and actual demand for the first ten procurement cycles. Figure 4.12 plots the crude procured to fulfill the forecasted demand for each procurement cycle. To fulfill the demand for the first procurement cycle 702 kbbl of crude is procured. The actual demand is the same as the planned demand for the first and second procurement cycles. Therefore, the planned and actual inventory profiles match. In subsequent procurement cycles, forecast and real demands differ, resulting in the CDU throughput differing from the original plan (See Figure 4.11). In the 4^{th} – 6^{th} procurement cycles, actual demand is less than the forecasted demand, so the actual throughputs are lower and stocks higher than planned. This effect is carried forward to the 7th procurement cycle. The refinery throughput changes to meet actual demands. Similar responsiveness of the supply chain can be seen in other procurement cycles as well.

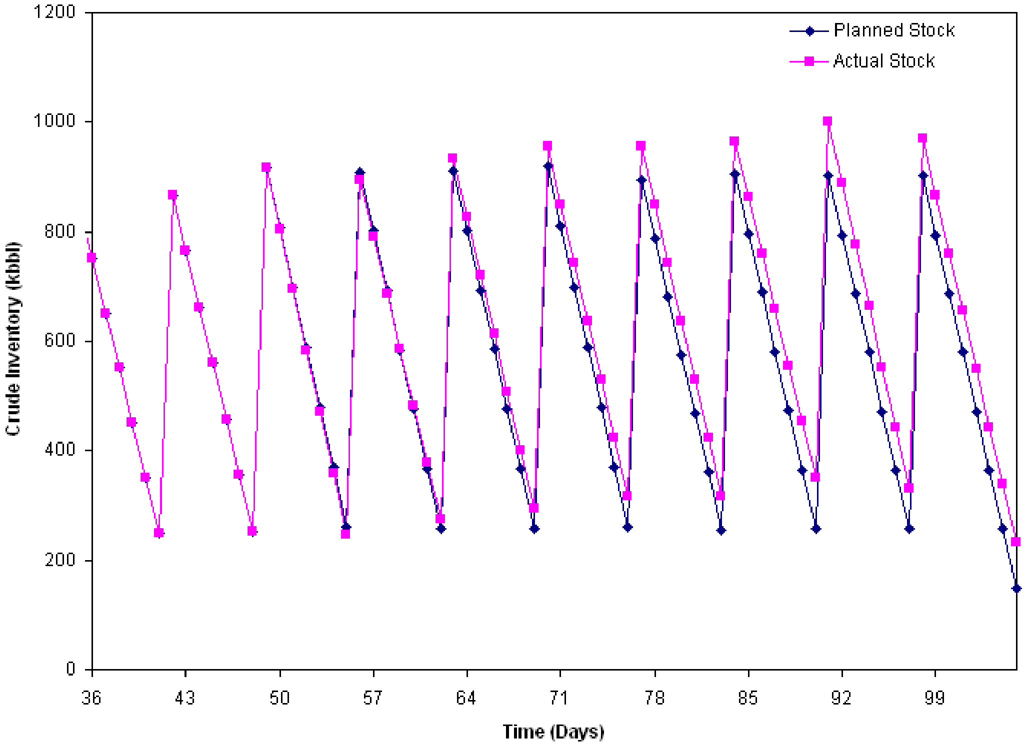

Figure 4.10: Crude Inventory profile over simulation horizon

Table 4.1: Forecasted and actual crude demand in the first 10 procurement cycles

Procurement Cycle	Delivery Date	Crude Procured based on forecasted demand (kbbl)	Crude needed to meet the actual demand (kbbl)
1	50	702	702
2	57	717	717
3	64	768	783
4	71	759	721
5	78	761	745
6	85	769	746
7	92	744	744
8	99	754	717
9	106	752	782
10	113	752	737

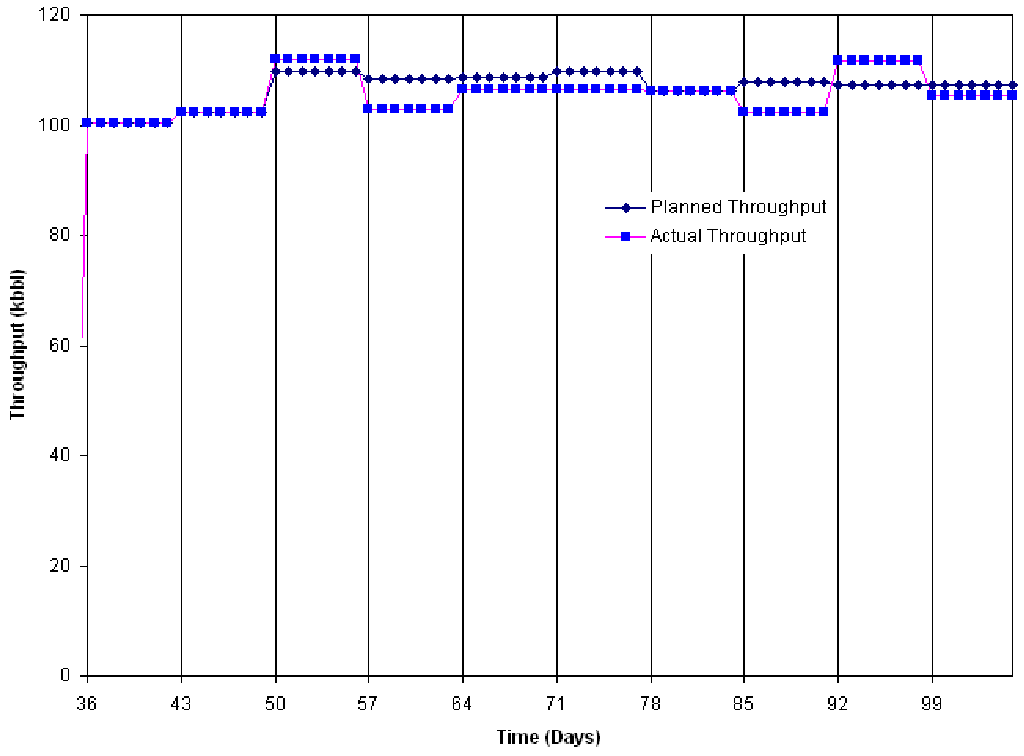

Figure 4.11: Actual versus Planned throughput over simulation horizon

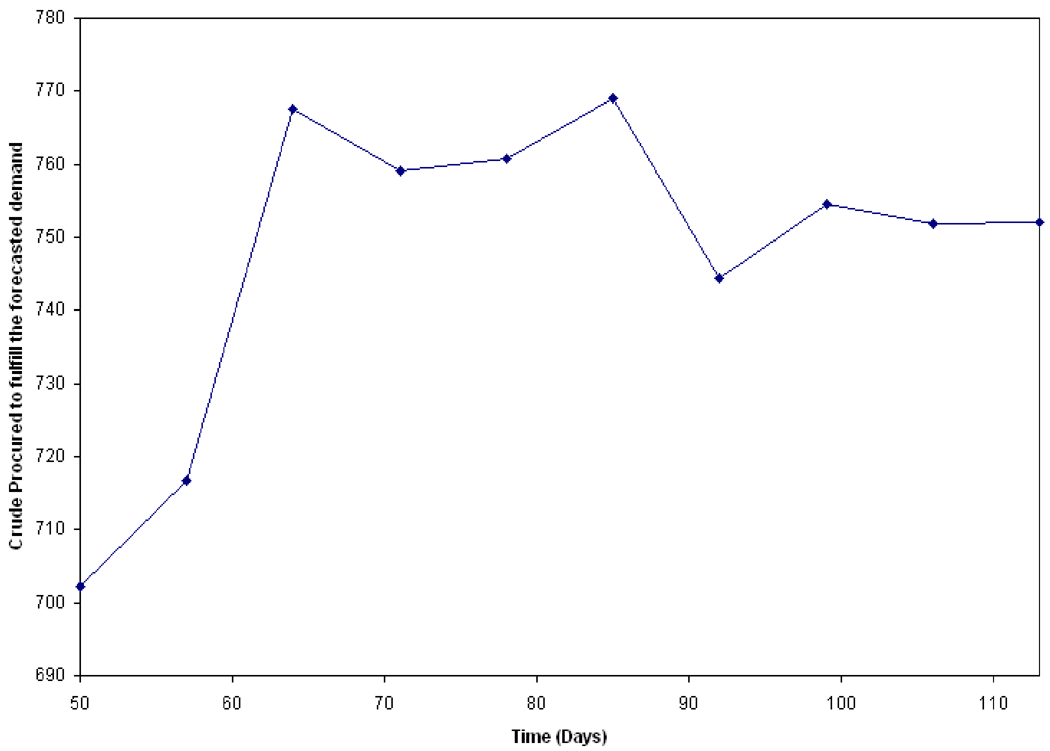

Figure 4.12: Crude procurement in each procurement cycle

4.3.2 Study 2: Transportation Disruption

One use of the supply chain model above is to understand the effect of disruptions on the supply chain. The effect can be studied in terms of impact on various performance indicators such as inventory, refinery operation, demand fulfilled, etc. In this case, transportation disruption – an important and frequent disruption in the supply chain – is considered. The disruption is introduced through a stochastic increase in the crude transportation time. For example, a ship scheduled to arrive on day 42nd is delayed at sea and arrives on the 48th day instead. Because of the ship delay, there is stock out in the refinery from the 44th to 48th day when even the safety stock is used up. Figure 4.13 plot the planned versus actual stock. Stock falls to 51.3 kbbl at the end of day 43, which is inadequate to operate the refinery even at minimum throughput. As seen in Figure 4.14, the throughput over this period goes to zero and the refinery unit has to be shutdown. This would result in the inability to meet demands and customer dissatisfaction. When the delay ship arrives on the 48th day, the inventory level goes up. The crude for the third procurement cycle also arrives on the 49th day and the stock becomes much higher than planned. Throughput is increased to maximum (120kbbl/ day) to meet demands.

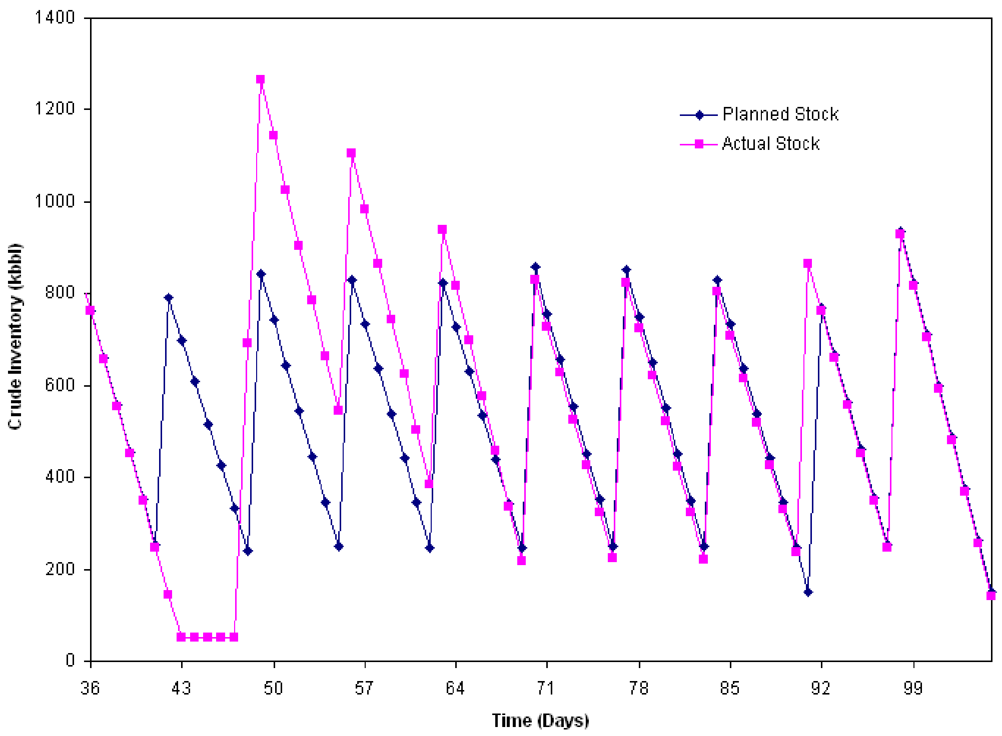

Figure 4.13: Crude inventory in case of transport disruption

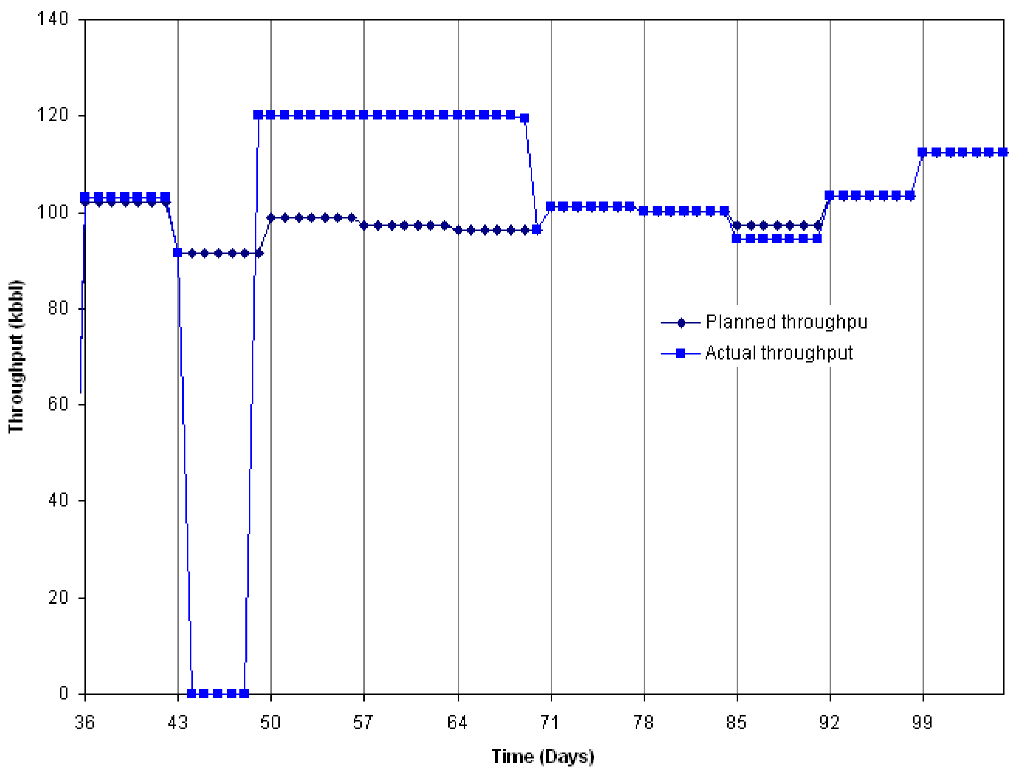

Figure 4.14: Actual versus Planned throughput in case of transport disruption

4.3.3 Study 3: Demand High

The normal operations of the refinery are designed to handle a 5% difference between projected and actual demand. Order fulfillment can be expected to be 100% in these cases since the refinery keeps a safety stock of 150 kbbl to handle small demand increases. In this study, we evaluate the effect of larger demand increases. Figure 4.15 shows the order fulfillment (%) along with uncertain demand. The small demand variations during cycles 1-6 are absorbed completely and order fulfillment remains at 100%. A large increase in demand during cycles 7–9 however leads to a drop in fulfillment to 64% – 69% since adequate crude inventories are not available. These lead to missed market opportunities, which could have been exploited if the supply chain can be made more nimble.

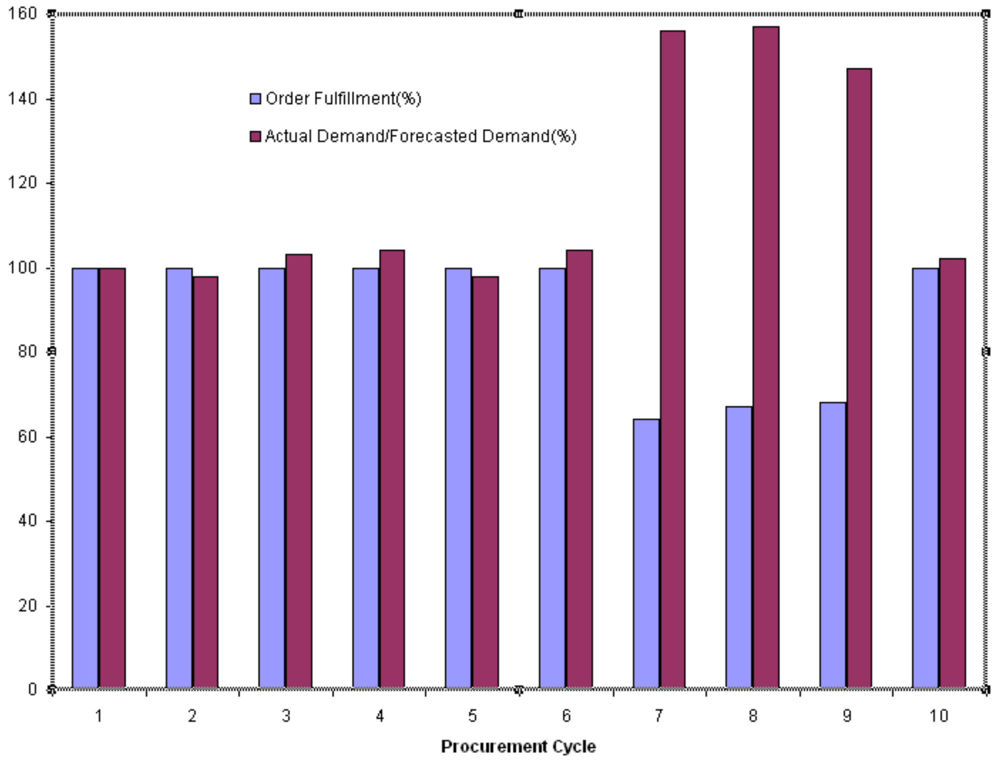

Figure 4.15: Order Fulfillment in case of increase in demand

4.4 Conclusion

The above results establish two important facts. First, we can conclude that the refinery model is able to simulate disruptions with the correct consequences. Second, this also corroborates that the developed framework MADE is capable of developing Supply Chain applications. The MADE illustrates one easy to use framework to model the functions and activities within a supply chain. A model and simulation developed using the agent-based approach, such as PRISMS-MADE, is use to study the dynamics of the supply chain in its normal as well as disrupted states. Our work on simulating an entire supply chain on MADE focus our attention on important issues in chemical supply chain those are discuss in subsequent chapters.

CHAPTER 5. GLOBAL SUPPLY AND DISTRIBUTION OF RAW MATERIALS

A multinational company's purchases go well beyond basic raw materials; they include catalysts, indirect materials, additives, etc. Strategic sourcing contracts offer several advantages and are common practice in many industries, especially the chemical industry. However, contracts come in various shades of price, commitments, duration, terms, flexibility, lead-time, quality, discounts, product bundling, etc. Selecting the best contracts and suppliers for a company's globally distributed sites in an integrated and global business environment can be nontrivial. In this chapter, we propose a relatively comprehensive classification of material supply contracts and propose a multi-period mathematical programming model that selects optimal contracts for the minimum total procurement cost in the face of several practical considerations such as different contract types, multi-tier prices and discounts, logistics and inventory costs, quantity/dollar purchase commitments, spot market, product bundling, etc. The model also identifies the optimal distribution of materials from various suppliers to plant sites. Our examples demonstrate substantial savings over ad hoc or heuristic methods.

Here, we address the contract selection problem from the perspective of a multinational company with globally distributed manufacturing facilities. Our objective is to develop a model that helps a company (buyer) analyze different types of contracts and select one or more best contracts, their starts, and purchase quantities in an integrated manner that addresses various aspects such as contract lengths, demands, prices, discounts, logistics costs, product bundling, contract commitments, etc. We consider total purchase cost as the sole decision criterion. Our model is especially useful, when the company must consider several suppliers offering different types of contracts and some acting as spot market suppliers.

We begin with a problem description and a classification of various contract types. We then develop a MILP formulation for selecting the best contracts and purchase plan. Finally, we illustrate our model using a realistic problem based on industrial data.

5.1 Problem Description

Figure 5.1 shows the schematic of a multi-national company (MNC) with S plant sites (s = 1, 2, …, S) located all around the world. Each site needs some raw materials, maintains inventory for them, which incurs holding costs. Let M be the total number of raw materials (m = 1, 2, …, M) needed by the S plant sites. The MNC has a global sourcing department to plan the purchase and distribution of raw materials to all plants over some planning horizon. This department is considering several potential suppliers globally to source all the raw materials using two sourcing strategies. One is to sign mutually agreed contracts with select suppliers. The other is to purchase materials from the spot market, which includes all the suppliers with which the MNC has no contracts. Let C denote the total number of contracts (c = 1, 2, …, C) offered by various potential suppliers that the MNC is evaluating.

A contract specifies the terms, conditions, prices, contract length, discounts, commitments, currency, etc. for the purchase of one or more materials. It may entice simultaneous purchase of multiple products using the idea of product bundling. Later, we classify various types of contracts in more detail. A potential supplier may offer one or more contracts with differing features and materials. For instance, supplier 1 offers four contracts and supplier 4 offers three contracts in Figure 5.1. A contract may involve providing materials to one or more plant sites. For instance, contract C6 procures materials for sites S5 and S2. A contract may also have capacity constraints, so it may be unable to fulfill the demands of a given plant site. In such a case, the plant may use two contracts. For instance, S5 uses C5 and C6 in Figure 5.1. Some contracts may already be continuing at time zero, while some may begin any time during the planning horizon. A contract may even extend beyond the planning horizon. Because of the variety of contracts and their features, selecting the best contracts over time is a non-trivial combinatorial problem whose optimal solution can reduce the MNC's material costs.

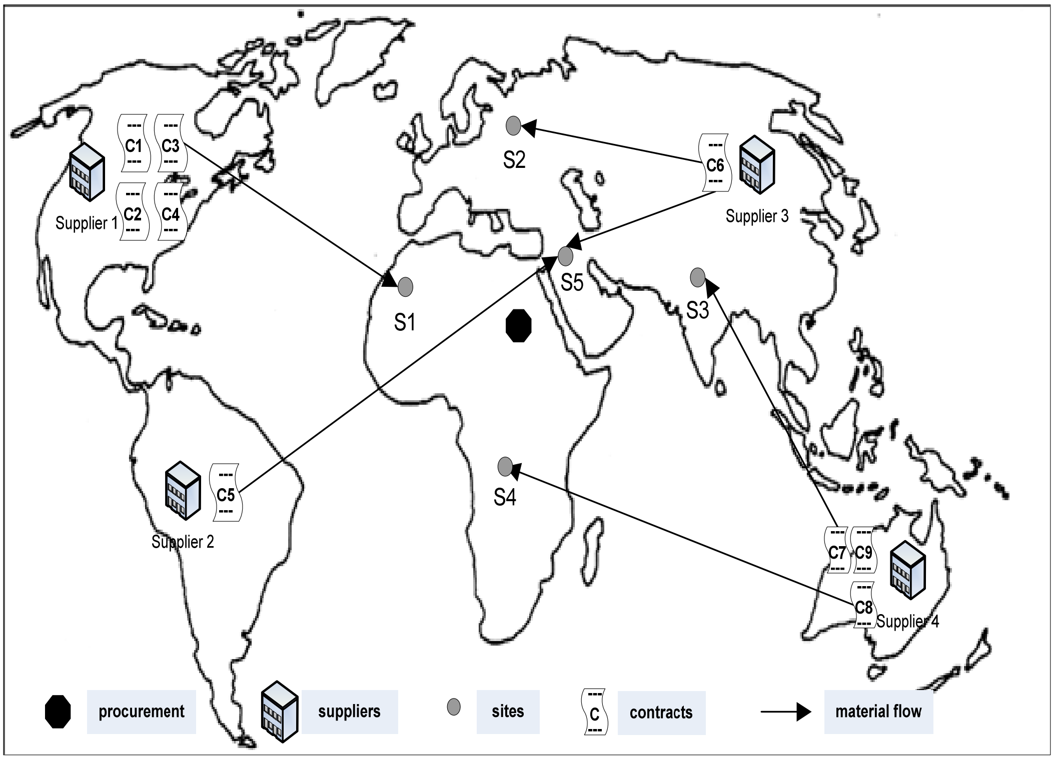

Figure 5.1: Material procurement and distribution in a global supply chain

The goal of the central sourcing department is to select the best suppliers and the best contracts from their one or more offerings. It also specifies the materials and amounts that each supplier should deliver to each plant site. Straight lines in Figure 5.1 show these distributions. In practice, an alternate strategy may exist, in which all suppliers deliver the materials to a central facility first and the central sourcing department distributes them to various plant sites. In this work, we do not consider such a scenario.

By replacing each supplier by the contracts that it offers, we view the supplier selection problem as a contract selection problem and state it as follows.

Given

1) contracts and their full details and features such as terms, conditions, prices, discounts, flexibility, materials, durations, etc. except start times,

2) planning horizon that comprises multiple periods of some pre-fixed length (week, month, quarter, etc.),

3) demands of raw materials at each plant site for each period,

4) inventory holding costs of materials at plant sites,

5) transportation costs of materials from suppliers to sites,

determine

1) the contracts that the MNC should sign and when they should begin,

2) the quantities of materials that it should purchase under various contracts in each period,

3) the quantities of materials that it should buy from the spot market in each period,

4) the amounts of materials distributed from each supplier to each plant site in each period,

5) the inventory profiles of materials at plant sites,

assuming

1) unit transportation cost of material is quantity-independent,

2) all plant sites use the same procurement cycle of one period,

3) a contract cannot be selected more than once during the planning horizon, but multiple copies of the same contract with different durations are possible,

4) contracts are selected at time zero, may begin at any time,

5) to minimize the total cost of purchasing, distributing, and storing the raw materials over the planning horizon.

5.2 Classification of Contracts

We define two types of supply contracts, namely quantity-commitment (QC) and dollar-commitment (DC). In a QC contract, the buyer agrees to purchase a minimum quantity of each material under the contract. In a DC contract, the buyer agrees to a minimum dollar amount of total purchases under the contract. The commitments in both these contracts must be met during each period (e.g. month, quarter, or entire contract duration) agreed to in the contract. Thus, we have two types of commitments; total and periodic. While the commitment period in the former is the entire contract duration, the latter involves sets of periods, which repeat during the contract length. Based on the two types and two periods of commitment, we define four classes of contracts: total quantity commitment (TQC), periodic quantity commitment (PQC), total dollar commitment (TDC), and periodic dollar commitment (PDC).

We can further subdivide these four classes into several types as shown in Figure 5.2 based on price discounts and flexibility on purchase commitments. Instead of describing the various types now, we describe them later, while modeling them. For now, we describe what price discounts and flexibility on purchase commitments mean. We define two types of price discounts: bulk and unit. A bulk discount applies to the total quantity of a purchase, and a unit discount applies to each unit of purchase beyond a certain qualifying purchase level. The unit discount does not apply to the first units of a purchase, which enable the buyer to reach the minimum qualifying purchase level. A contract may allow some flexibility on the purchase commitment at the cost of a penalty. If the buyer fails to make the minimum purchase, then he must pay some penalty for the shortfall.

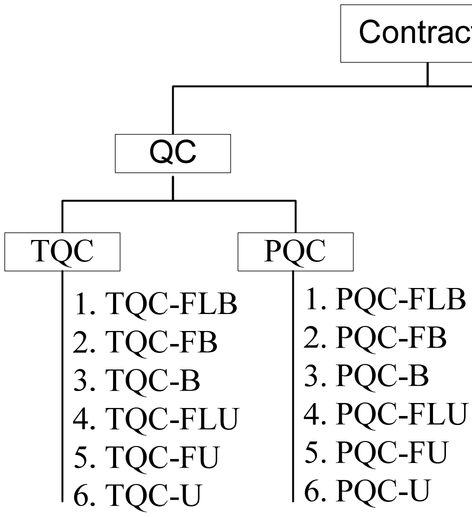

Figure 5.2: Classification of material supply contracts (T = total, P = periodic, Q = quantity, D = dollar, C = commitment, F = flexibility, L = limited, U = unit discount, B = bulk discount)

As discussed earlier, some previous work (Martínez-de-Albéniz et al., 2005) has addressed option contracts. We can view an option contract as a contract with flexibility, where the penalty acts as a premium or reservation price, and the remaining cost acts as the execution or exercise price. Thus, we see no need to define option contracts as a separate class, and our work addresses option contracts as well.

Furthermore, product bundling is another important contract feature. In addition to offering a separate contract for each material, a supplier may offer a contract that covers all materials and offers lower prices. This is to entice the buyer to commit to purchase multiple materials simultaneously. Such contracts may impose various types of minimum purchase commitments, and can be modeled one of the types described later, so there is no need for us to define a special contract type to handle product bundling.

5.3 MILP Formulation

As mentioned earlier, we replace each potential supplier by all its offered contracts and select contracts instead of suppliers. Because contracts are generally long-term, we assume that the length of each contract is a given multiple of week, month, or quarter, as a finer time resolution is needless. This enables us to use a uniform discrete-time representation and define the planning horizon to comprise T periods (t = 1, 2, …, T) of known equal lengths. A period could be a day, week, month, quarter, year, etc. Period 1 begins at time zero. We also assume that the commitment period for each PQC contract is a multiple of this period.

Please note that all constraints or equations in this chapter, unless otherwise specified, are to be written for all valid values of indices defining them and their constituent variables.

Now, the primary decision for the MNC is to select the best contracts from the pool of several contracts of different types, prices, durations, and suppliers, and determine their start times. We model these decisions by means of the following binary variables.

$$ys_{ct} = \begin{cases} 1 & \text{if contract } c \text{ begins at the start of period } t \\ 0 & \text{otherwise} \end{cases} \qquad 1 \le t \le T$$

$$z_c = \begin{cases} 1 & \text{if contract } c \text{ is selected} \\ 0 & \text{otherwise} \end{cases}$$

Because a contract cannot begin more than once during the planning horizon, and if selected, it must begin some time, we can relate the above two variables by,

$$z_c = \sum_{t=1}^{T} ys_{ct} \tag{5.1}$$

With an upper bound of 1.0 on z_c, eq. 1 allows us to treat z_c as a 0-1 continuous variable.

To detect if a contract c is in effect during a period, we define the following 0-1 continuous variable.

$$y_{ct} = \begin{cases} 1 & \text{if contract } c \text{ is in effect during period } t \\ 0 & \text{otherwise} \end{cases} = \sum_{t-CL_c+1}^{t} ys_{ct} \quad 1 \le t \le T \tag{5.2}$$

where, CL_c denotes the given length of contract c.

Note that a contract c may continue (we set $z_c = 1$) from the previous planning horizon.

A contract c may cover several raw materials. Let $\boldsymbol{M}_c = \{m \mid \text{material } m \text{ is covered under contract } c\}$. The model must decide the amount of each material to purchase at various times under each contract. Therefore, we define q_{mct} ($m \in \boldsymbol{M}_c$, $1 \le t \le T$) as the quantity of material m that the MNC buys under contract c during period t, and Q_{mc} ($m \in \boldsymbol{M}_c$) as the total quantity purchased over the planning horizon. Obviously,

$$Q_{mc} = \sum_{t=1}^{T} q_{mct} \tag{5.3}$$

If a contract is not in effect during a period t, then $q_{mct} = 0$ for each material m under that contract. Similarly, if it is in effect, then q_{mct} cannot exceed an upper limit (q_{mct}^U) imposed by the supplier. Therefore,

$$q_{mct} \le y_{ct} q_{mct}^U \tag{5.4}$$

If the supplier also has an upper limit ($Q_{mc}^U \ge \sum_t q_{mct}^U$) on the total purchase amount of m during the entire contract length, then we write,

$$Q_{mc} \le Q_{mc}^U z_c \tag{5.5}$$

Otherwise, we set $Q_{mc}^U = \sum_t q_{mct}^U$, and do not write the above constraint.

5.3.1 TQC Contracts

All TQC contracts have multiple prices (normal, discounted, high, etc.) that depend on Q_{mc}. To model these prices, we divide the total purchase range [0, Q_{mc}^U] for material m under contract c into R_{mc} price-tiers (r = 1, 2, …, R_{mc}) and define p_{mcr} as the unit price in price-tier r of m under c. Price-tier r is defined by the purchase range [$QL_{mc(r-1)}$, QL_{mcr}] , where QL_{mc0} = 0, QL_{mc1} is the minimum purchase commitment, and $QL_{mcR_{mc}} = Q_{mc}^U$. In other words, if $QL_{mc(r-1)} \le Q_{mc} < QL_{mcr}$, then the unit price for material m under contract c is p_{mcr}. While R_{mc}, p_{mcr}, QL_{mcr}, etc. will vary from contract to contract, we define the following binary variable to identify which unit price applies to each purchase.

$$\beta_{mcr} = \begin{cases} 1 & \text{if } QL_{mc(r-1)} \le Q_{mc} \le QL_{mcr} \\ 0 & \text{otherwise} \end{cases} \qquad m \in \boldsymbol{M}_c,\ r = 1, 2, \ldots, R_{mc}$$

If a contract c is selected, then each Q_{mc} under that contract must fall in one of its R_{mc} purchase ranges. Therefore,

$$\sum_{r=1}^{R_{mc}} \beta_{mcr} = z_c \tag{5.6}$$

Furthermore, we define the differential amount (ΔQ_{mcr}) in a purchase range r by writing,

$$Q_{mc} = \sum_{r=1}^{R_{mc}} (QL_{mc(r-1)}\beta_{mcr} + \Delta Q_{mcr}) \tag{5.7}$$

For a price p_{mcr} to apply, $QL_{mc(r-1)} \le Q_{mc} \le QL_{mcr}$ must hold, i.e.,

$$\Delta Q_{mcr} \le \beta_{mcr}[QL_{mcr} - QL_{mc(r-1)}] \tag{5.8}$$

We now develop the constraints for each specific contract type. For each of the following subsections, c will refer to a contract of the type being discussed in that subsection. Note that QL_{mc1} denotes the total quantity commitment for m under each TQC contract c.

<u>TQC-FLB: TQC contracts with flexibility and limited bulk discount</u>

These contracts offer flexibility on committed purchases and limited bulk discounts. The MNC need not purchase the minimum committed amount (QL_{mc1}), but must pay a stipulated penalty on each unit of unfulfilled commitment and a normal (undiscounted) price on each purchased unit. Once the MNC makes the minimum committed purchase (QL_{mc1}), then it qualifies for a bulk discount on its total purchases. However, this bulk discount is limited in that it does not apply to the quantity beyond a certain maximum purchase (say QL_{mc2}). If $Q_{mc} > QL_{mc2}$, then the MNC must pay the bulk-discount price on all units up to QL_{mc2} and a higher unit-price for each unit beyond QL_{mc2}. The rationale for the higher price could be the supplier facing a capacity constraint or the extra costs for supplying more units. The discounted price will usually depend upon the minimum commitment. Some suppliers may quote larger discounts but with larger commitments, and vice versa.

Let c be a contract of type TQC-FLB (Figure 5.3). As an example, Figure 5-5 shows contract C1 for m = 1 in Example 1 discussed in section 5.4. We view a TQC-FLB contract as having three price-tiers (R_{mc} = 3).

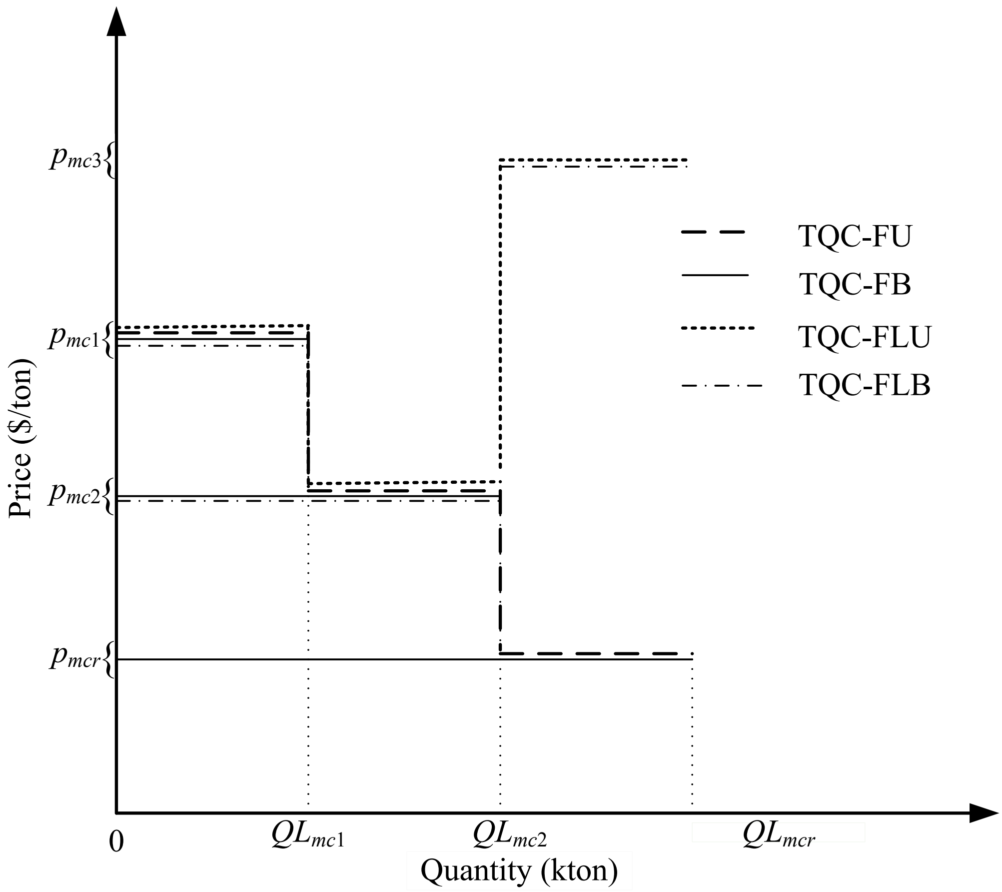

Figure 5.3: Price versus quantity for TQC-FLB, TQC-FB, TQC-FLU, and TQC-FU contracts. Note that although the lines representing different contract types are separate, they refer to the same price indicated for the bracket. For instance, all top four lines between 0 and QL_{mc1} have the same price, namely p_{mc1}.

The first purchase range is [0, QL_{mc1}] with the purchase cost of $p_{mc1}\Delta Q_{mc1} + \pi_{mc}(QL_{mc1}\beta_{mc1} - \Delta Q_{mc1})$, where p_{mc1} is the normal price for m, and π_{mc} is the unit penalty for the unfulfilled purchase commitment.

The second purchase range is [QL_{mc1}, QL_{mc2}] with $p_{mc2} < p_{mc1}$. The bulk price p_{mc2} applies to the entire purchase, so the purchase cost for this range is $p_{mc2}[QL_{mc1}\beta_{mc2}+\Delta Q_{mc2}]$.

The third range is $[QL_{mc2}, QL_{mc3} = Q_{mc}^{U}]$. p_{mc2} applies to the purchase up to QL_{mc2} and $p_{mc3} > p_{mc2}$ to the remainder. Thus, the purchase cost for this range is $p_{mc2}QL_{mc2}\beta_{mc3} + p_{mc3}\Delta Q_{mc3}$.

Summing the above three costs and using eq. 5.7, we get the total purchase cost for material *m* under contract *c* as,

$$PC_{mc} = Q_{mc}p_{mc2} + \Delta Q_{mc1}(p_{mc1} - p_{mc2}) + \pi_{mc}(QL_{mc1}\beta_{mc1} - \Delta Q_{mc1}) + \Delta Q_{mc3}(p_{mc3} - p_{mc2}) \quad (5.9)$$

Note that the purchase cost has a single binary variable (β_{mc1}) instead of β_{mc1}, β_{mc2}, and β_{mc3}. Therefore, it should be possible for us to eliminate ΔQ_{mc2}, β_{mc2}, and β_{mc3} from our formulation. For this, we modify eqs. 5.6 and 5.8 as follows.

$$\beta_{mc1} \le z_c \quad (5.6a)$$

$$\Delta Q_{mc1} \le \beta_{mc1}QL_{mc1} \quad (5.8a)$$

$$\Delta Q_{mc3} \le [QL_{mc3} - QL_{mc2}](z_c - \beta_{mc1}) \quad (5.8b)$$

We now need two constraints to ensure that if a contract *c* is selected, then Q_{mc} must fall in the right purchase range dictated by β_{mc1}. First, if $\beta_{mc1} = 0$, then $Q_{mc} \ge QL_{mc1}$, so we write,

$$Q_{mc} \ge \Delta Q_{mc1} + \Delta Q_{mc3} + QL_{mc1}(z_c - \beta_{mc1}) \quad (5.10a)$$

Second, if $\beta_{mc1} = 1$, then $Q_{mc} \le QL_{mc1}$. We achieve this by substituting ΔQ_{mc2} from eq. 5.7 into eq. 5.8 ($\Delta Q_{mc2} \le \beta_{mc2}[QL_{mc2} - QL_{mc1}]$), and then use eq. 5.6 to obtain,

$$Q_{mc} \le \Delta Q_{mc1} + QL_{mc2}(z_c - \beta_{mc1}) + \Delta Q_{mc3} \quad (5.10b)$$

Thus, the model for TQC-FLB contracts using single binary variable consists of eqs. 5.6a, 5.8a, 5.8b, 5.9, 5.10a, and 5.10b. An alternative formulation using all three binary variables (β_{mc1}, β_{mc2}, β_{mc3}) would be slightly tighter, but larger in terms of variables and constraints.

<u>TQC-FB: TQC contracts with flexibility and multi-tier bulk discounts</u>

These (Figure 5.3) are similar to TQC-FLB contracts, but without any upper limit on the purchase quantity that qualifies for a bulk discount. Furthermore, they offer multi-tier bulk discounts at multiple purchase levels. As the purchase amount increases, the bulk discount increases. The bulk-discount price at a certain tier applies only after the company purchases the minimum amount for that tier. Thus, if $Q_{mc} \geq QL_{mcr}$, then price $p_{mc(r+1)}$ applies to the entire purchase

For these contracts, we can still use the price-tier ranges and the total purchase cost under contract c of type TQC-FB is given by,

$$PC_{mc} = \pi_{mc}(QL_{mc1}\beta_{mc1} - \Delta Q_{mc1}) + \sum_{r=1}^{R_{mc}} Q_{mc}\beta_{mcr}p_{mcr}$$

Using eq. 5.7, this simplifies as,

$$PC_{mc} = \pi_{mc}(QL_{mc1}\beta_{mc1} - \Delta Q_{mc1}) + \sum_{r=1}^{R_{mc}} p_{mcr}(QL_{mc(r-1)}\beta_{mcr} + \Delta Q_{mcr}) \quad (5.11)$$

Note that eqs. 5.6, 5.7, and 5.8 apply in this case.

TQC-B: TQC contracts with multi-tier bulk discounts but no flexibility

These contracts are similar to the TQC-FB contracts, but allow no flexibility. The MNC must pay for the minimum committed purchase, even if its purchase does not exceed the minimum commitment. However, once the purchase exceeds the commitment, the multi-tier bulk discounts kick in at various levels, and apply to the entire purchase.

Clearly, the MNC must pay for QL_{mc1} at price p_{mc1}, if $Q_{mc} < QL_{mc1}$. However, if $Q_{mc} \geq QL_{mc1}$, then the multi-tier prices apply as in TQC-FB contracts. We model these scenarios exactly as in TQC-FB contracts, and get the total purchase cost as,

$$PC_{mc} = QL_{mc1}p_{mc1}\beta_{mc1} + \sum_{r\geq 2}^{R_{mc}} p_{mcr}(QL_{mc(r-1)}\beta_{mcr} + \Delta Q_{mcr}) \quad (5.12)$$

TQC-FLU: TQC contracts with flexibility and limited unit discount

These are similar to TQC-FLB, but offer limited unit discounts instead of limited bulk discounts. Recall that a unit discount price applies to the portion of purchase beyond the minimum committed amount. The company pays the normal (undiscounted) price for the commitment. However, in these contracts, the unit discount price applies up to a certain maximum purchase amount only. If the total purchase exceeds this maximum, then a higher price applies to the portion of purchase beyond that maximum.

Let *c* be a contract of type TQC-FLU. As for TQC-FLB contracts, we view this contract as having three price-tiers (R_{mc} = 3). The purchase cost for the first tier is $p_{mc1}Q_{mc} + \pi_{mc}(QL_{mc1}\beta_{mc1} - \Delta Q_{mc1})$. For the second tier, the normal price applies for the minimum purchase and a discounted price for each unit beyond the minimum, so the purchase cost is $p_{mc1}Q_{mc} + \Delta Q_{mc2}(p_{mc2} - p_{mc1})$. Note that the second term in the purchase cost expression is negative, so the higher price p_{mc1} applies to the entire Q_{mc}, while the lower price p_{mc2} applies to the purchase (ΔQ_{mc2}) above QL_{mc1}. This differs from TQC-FLB, where the discount applies to the entire purchase. The third range is $[QL_{mc2}, QL_{mc3} = Q^U_{mc}]$. p_{mc1} applies to the minimum commitment, p_{mc2} applies to the purchase beyond the minimum and up to QL_{mc2} and a higher price (p_{mc3}) to the remainder. Thus, the purchase cost for this range is $p_{mc1}Q_{mc} + \beta_{mc3}(QL_{mc2} - QL_{mc1})(p_{mc2} - p_{mc1}) + \Delta Q_{mc3}(p_{mc3} - p_{mc1})$.

Summing the above three costs and using eqs. 5.6 and 5.7, we get the purchase cost as,

$$\begin{aligned} PC_{mc} = {} & Q_{mc}p_{mc2} + \Delta Q_{mc1}(p_{mc1} - p_{mc2}) + \pi_{mc}(QL_{mc1}\beta_{mc1} - \Delta Q_{mc1}) + \Delta Q_{mc3}(p_{mc3} - p_{mc2}) \\ & + QL_{mc1}(z_c - \beta_{mc1})(p_{mc1} - p_{mc2}) \end{aligned} \tag{5.13}$$

As for TQC-FLB contracts, the total purchase cost has a single binary variable. Therefore, we can eliminate ΔQ_{mc2}, β_{mc2}, and β_{mc3} as done earlier. Thus, eqs. 5.6a, 5.8a, 5.8b, 5.10a, 5.10b, and 5.13 will hold.

<u>TQC-FU: TQC contracts with flexibility and multi-tier unit discounts</u>

These are similar to TQC-FLU contracts except that there is no upper limit for the discounted purchase and unit discounts are in several tiers. The discounted price at a certain tier applies only after the total purchase exceeds the minimum amount for that tier. Furthermore, they are the same as TQC-FB contracts, but with unit rather than bulk discounts. Unit discounts apply to purchases exceeding certain levels.

Figure 5.3 shows a generic TQC-FU contract and Figure 5.5 shows an example, namely a TQC-FU contract C4 for m = 1 in Example 1. Eqs. 5.6, 5.7, and 5.8 hold, and the total purchase cost is given by,

$$PC_{mc} = \left\{ \begin{array}{l} \pi_{mc}(QL_{mc1}\beta_{mc1} - \Delta Q_{mc1}) + \\ \sum_{r=1}^{R_{mc}} \left(\Delta Q_{mcr} p_{mcr} + \beta_{mcr} \sum_{\rho=1}^{\rho \le (r-1)} p_{mc\rho}[QL_{mc\rho} - QL_{mc(\rho-1)}] \right) \end{array} \right\} \quad (5.14)$$

<u>TQC-U: TQC contracts with multi-tier unit discounts but no flexibility</u>

They are similar to TQC-B contracts, but offer unit discounts instead of bulk discounts. The MNC must pay for the minimum amount, even if it does not purchase the minimum amount. Thus, similar to TQC-B contracts, they offer no flexibility. We model these contracts exactly as TQC-FU contracts I but with no flexibility. Thus, the purchase cost is:

$$PC_{mc} = QL_{mc1} p_{mc1} z_c + \sum_{r \ge 2}^{R_{mc}} \left(\Delta Q_{mcr} p_{mcr} + \beta_{mcr} \sum_{\rho \ge 2}^{\rho \le (r-1)} p_{mc\rho}(QL_{mc\rho} - QL_{mc(\rho-1)}) \right) \quad (5.15)$$

5.3.2 PQC Contracts

As in TQC, we have six subtypes of PQC contracts. In these contracts, the minimum commitment condition is to be honored during successive pre-fixed sets of periods within the contract duration. These contracts allow the prices of materials to vary from period to period and the price will depend on the quantity (q_{mct}) bought in period t instead of Q_{mc}. In this work, we assume that the pre-fixed commitment duration is one single period for all contracts. Let C1 be a PQC contract of two years duration with a minimum commitment of 50 kton, a planning horizon of H = 5 years, and a commitment period of 1 year. If C1 begins at the start of year 3, then the MNC's purchase of m must exceed 50 kton in both third and fourth years. Let R_{mct} denote the number of price-tiers in period t, and p_{mcrt} be the unit price in price-tier r. Binary variables and equations analogous to those for TQC contracts are follows.

$$\beta_{mcrt} = \begin{cases} 1 & \text{if } QL_{mc(r-1)t} \le q_{mct} \le QL_{mcrt} \\ 0 & \text{otherwise} \end{cases} \qquad m \in \boldsymbol{M}_c,\ r = 1, 2, \ldots, R_{mc}$$

$$\sum_{r=1}^{R_{mc}} \beta_{mcrt} = y_{ct} \tag{5.16}$$

$$q_{mct} = \sum_{r=1}^{R_{mc}} (QL_{mc(r-1)t}\beta_{mcrt} + \Delta q_{mcrt}) \tag{5.17}$$

$$\Delta q_{mcrt} \le \beta_{mcrt}[QL_{mcrt} - QL_{mc(r-1)t}] \tag{5.18}$$

Using the above, we derive the equations for the various PQC contracts as follows.

PQC-FLB Contracts:

The model for PQC-FLB contracts consists of eqs. 5.19-5.24.

$$PC_{mct} = q_{mct}p_{mc2t} + \Delta q_{mc1t}(p_{mc1t} - p_{mc2t}) + \pi_{mct}(QL_{mc1t}\beta_{mc1t} - \Delta q_{mc1t}) + \Delta q_{mc3t}(p_{mc3t} - p_{mc2t}) \tag{5.19}$$

$$\beta_{mc1t} \le y_{ct} \tag{5.20}$$

$$\Delta q_{mc1t} \le \beta_{mc1t} QL_{mc1t} \tag{5.21}$$

$$\Delta q_{mc3t} \le [Q^U_{mct} - QL_{mc2t}](y_{ct} - \beta_{mc1t}) \tag{5.22}$$

$$q_{mct} \ge \Delta q_{mc1t} + \Delta q_{mc3t} + QL_{mc1t}(y_{ct} - \beta_{mc1t}) \tag{5.23}$$

$$q_{mct} \le \Delta q_{mc1t} + QL_{mc2t}(y_{ct} - \beta_{mc1t}) + \Delta q_{mc3t} \tag{5.24}$$

PQC-FB Contracts:

$$PC_{mct} = \pi_{mct}(QL_{mc1t}\beta_{mc1t} - \Delta q_{mc1t}) + \sum_{r=1}^{R_{mc}} p_{mcrt}(QL_{mc(r-1)t}\beta_{mcrt} + \Delta q_{mcrt}) \tag{5.25}$$

PQC-B Contracts:

$$PC_{mct} = QL_{mc1t}p_{mc1t}\beta_{mc1t} + \sum_{r\geq 2}^{R_{mc}} p_{mcrt}(QL_{mc(r-1)t}\beta_{mcrt} + \Delta q_{mcrt}) \tag{5.26}$$

<u>PQC-FLU Contracts</u>**:**

Eqs. 5.20, 5.21, 5.22, 5.23, 5.24, and the following holds for PQC-FLU contracts.

$$PC_{mct} = \left\{ \begin{matrix} q_{mct}p_{mc2t} + \Delta q_{mc1t}(p_{mc1t} - p_{mc2t}) + \pi_{mct}(QL_{mc1t}\beta_{mc1t} - \Delta q_{mc1t}) + \\ \Delta q_{mc3t}(p_{mc3t} - p_{mc2t}) + QL_{mc1t}(y_{ct} - \beta_{mc1t})(p_{mc1t} - p_{mc2t}) \end{matrix} \right\} \tag{5.27}$$

<u>PQC-FU Contracts:</u>

$$PC_{mct} = \left\{ \begin{matrix} \pi_{mct}(QL_{mc1t}\beta_{mc1t} - \Delta q_{mc1t}) + \\ \sum_{r=1}^{R_{mc}} \left(\Delta q_{mcrt}p_{mcrt} + \beta_{mcrt} \sum_{\rho=1}^{\rho\leq(r-1)} p_{mc\rho t}(QL_{mc\rho t} - QL_{mc(\rho-1)t}) \right) \end{matrix} \right\} \tag{5.28}$$

<u>PQC-U Contracts:</u>

$$PC_{mct} = QL_{mc1t}p_{mc1t}y_{ct} + \sum_{r\geq 2}^{R_{mc}} \left(\Delta q_{mcrt}p_{mcrt} + \beta_{mcrt} \sum_{\rho\geq 2}^{\rho\leq(r-1)} p_{mc\rho t}(QL_{mc\rho t} - QL_{mc(\rho-1)t}) \right) \tag{5.29}$$

5.3.3 TDC Contracts

While TQC contracts had discounted unit prices, TDC contracts have multi-tier discounts on total purchase value. Let D_c denote the total purchase value for a TDC contract c. Using the same approach as for TQC contracts, we divide the purchase value range $[0, D_c^U]$ into R_c discount-tiers (r = 1, 2, …, R_c) and define d_{cr} as the fractional discount in discount-tier r. We define dollar range [$DL_{c(r-1)}$, DL_{cr}] for each discount-tier r, and define the following binary variable.

$$\alpha_{cr} = \begin{cases} 1 & \text{if } DL_{c(r-1)} \leq D_c \leq DL_{cr} \\ 0 & \text{otherwise} \end{cases} \qquad r = 1, 2, \ldots, R_c$$

Note that DL_{c1} denotes the purchase commitment irrespective of the materials and quantities. We can compute the total purchase value for a contract c by,

$$D_c = \sum_{m\in \boldsymbol{M}_c} \sum_t q_{mct}p_{mct} \tag{5.30}$$

Then, analogous to eqs. 5.6, 5.7, and 5.8 for TQC contracts, we obtain,

$$\sum_{r=1}^{R_c} \alpha_{cr} = z_c \tag{5.31}$$

$$D_c = \sum_{r=1}^{R_c} (DL_{c(r-1)} \alpha_{cr} + \Delta D_{cr}) \tag{5.32}$$

$$\Delta D_{cr} \le \alpha_{cr} [DL_{cr} - DL_{c(r-1)}] \tag{5.33}$$

TDC-FB: TDC contracts with flexibility and bulk discount

These dollar-commitment contracts (Figure 5.4) offer both flexibility and multi-tier bulk discounts. The MNC becomes eligible for multi-tier bulk discounts, when the purchase value exceeds the minimum commitment (DL_{c1}). Total purchase cost is computed by subtracting the discount valid for the applicable tier from the total purchase value. However, if the purchase value is less than DL_{c1}, then the buyer must pay the penalty for the unfulfilled commitment. For instance, consider a contract c1 for materials m1 and m2, which stipulates a minimum commitment of $5000K. The prices are $55 per ton for m1 and $45 per ton for m2. The contract offers only one tier for bulk discounts, which is 5%. The penalty for not fulfilling the commitment is 1% of the unfulfilled purchase commitment. If the MNC buys 60 kton of m1 and 60 kton of m2, then the total purchase value ($6,000K) exceeds $5000K and the MNC gets a discount of 5% on $6,000K. On the other hand, if it buys 10 kton of m1 and 10 kton of m2, then it gets no discount, but pays a penalty of 1% on $4000K in addition to the material cost of $1000K.

Let π_c denote the fractional penalty for the unfulfilled commitment. Then, the purchase cost for contract c is,

$$PC_c = \sum_{r=1}^{R_c} [(1 - d_{cr})(DL_{c(r-1)} \alpha_{cr} + \Delta D_{cr})] + \pi_c (DL_{c1} \alpha_{c1} - \Delta D_{c1}) \tag{5.34}$$

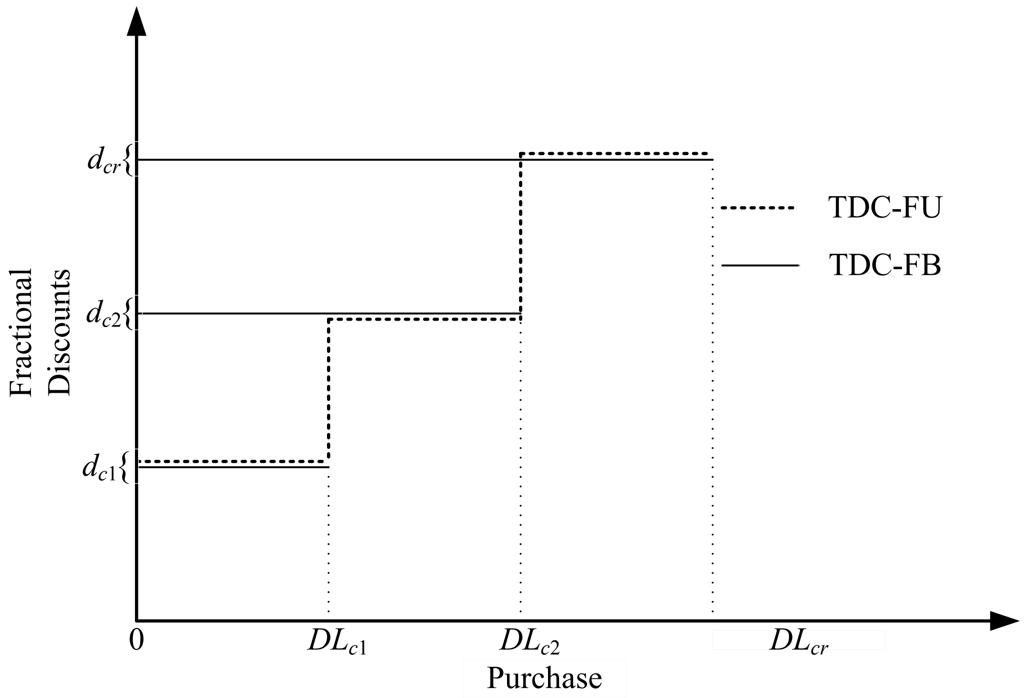

Figure 5.4: Fractional discount versus purchase value for TDC-FB and TDC-FU contracts. Note that although the lines representing different contract types are separate, they refer to the same discount indicated for the bracket. For instance, all top lines between 0 and DL_{c1} have the same discount, namely d_{c1}.

TDC-B: TDC contracts with bulk discounts but no flexibility

These are similar to TDC-FB contracts except with no flexibility. The buyer must pay the minimum dollar commitment, even if the purchase bill falls short of it. Once the purchase bill exceeds the commitment, then multi-tier bulk discounts kick in at various dollar levels.

In other words, if a contract c is selected, then the MNC must pay DL_{c1}, if its purchase bill falls short of DL_{c1}. Thus, the total purchase cost is computed as,

$$PC_c = DL_{c1}\alpha_{c1} + \sum_{r\geq 2}^{R_c}[(1-d_{cr})(DL_{c(r-1)}\alpha_{cr} + \Delta D_{cr})] \quad (5.35)$$

TDC-FU: TDC contracts with flexibility and multi-tier unit discounts

These are similar to TDC-FB contracts (Figure 5.4) but with unit discounts instead of bulk discounts. The discount at a tier applies to the purchase bill beyond the minimum level for that tier.

The total purchase cost is computed as follows:

$$PC_c = \left\{ \begin{array}{l} \sum_{r=1}^{R_c} [\Delta D_{cr}(1-d_{cr}) + \alpha_{cr} \sum_{\rho=1}^{\rho \le (r-1)} \{(DL_{c\rho} - DL_{c(\rho-1)})(1-d_{c\rho})\}] \\ +\pi_c (DL_{c1}\alpha_{c1} - \Delta D_{c1}) \end{array} \right\} \tag{5.36}$$

TDC-U: TDC contracts with no flexibility but unit discounts

These contracts are similar to TDC-FU but with no flexibility on the commitment. The MNC must pay the minimum commitment, even if the purchase bill falls short.

The total purchase cost is,

$$PC_c = DL_{c1}z_c + \sum_{r \ge 2}^{R_c} [\Delta D_{cr}(1-d_{cr}) + \alpha_{cr} \sum_{\rho=2}^{\rho \le (r-1)} \{(DL_{c\rho} - DL_{c(\rho-1)})(1-d_{c\rho})\}] \tag{5.37}$$

5.3.4 PDC Contracts

There are four subtypes of PDC contracts. Similar to PQC contracts, the commitment period is now a pre-fixed set of periods instead of the entire contract length. Analogous to the PQC contracts, the variables and equations for PDC are as follows.

$$\alpha_{crt} = \begin{cases} 1 & \text{if } DL_{c(r-1)t} \le D_{ct} \le DL_{crt} \\ 0 & \text{otherwise} \end{cases} \quad r = 1, 2, \ldots, R_c$$

$$D_{ct} = \sum_{m \in \boldsymbol{M}_c} q_{mct} p_{mct} \tag{5.38}$$

$$\sum_{r=1}^{R_c} \alpha_{crt} = y_{ct} \tag{5.39}$$

$$D_{ct} = \sum_{r=1}^{R_c} (DL_{c(r-1)t}\alpha_{crt} + \Delta D_{crt}) \tag{5.40}$$

$$\Delta D_{crt} \le \alpha_{crt}[DL_{crt} - DL_{c(r-1)t}] \tag{5.41}$$

$$PC_{ct} = \left\{ \begin{array}{c} \sum_{r=1}^{R_c} [(1-d_{crt})(DL_{c(r-1)t}\alpha_{crt} + \Delta D_{crt})] + \\ \pi_{ct}(DL_{c1t}\alpha_{c1t} - \Delta D_{c1t}) \end{array} \right\} \text{(PDC-FB contracts)} \tag{5.42}$$

$$PC_{ct} = DL_{c1t}\alpha_{c1t} + \sum_{r\geq 2}^{R_c}[(1-d_{crt})(DL_{c(r-1)t}\alpha_{crt} + \Delta D_{crt})] \text{(PDC-B contracts)} \quad (5.43)$$

$$PC_{ct} = \left\{ \begin{array}{l} \sum_{r=1}^{R_c}[\Delta D_{crt}(1-d_{crt}) + \pi_{ct}(DL_{c1t}\alpha_{c1t} - \Delta D_{c1t}) \\ +\alpha_{crt}\sum_{\rho=1}^{\rho\leq(r-1)}\{(DL_{c\rho t} - DL_{c(\rho-1)t})(1-d_{c\rho t})\}] \end{array} \right\} \text{(PDC-FU contracts)} \quad (5.44)$$

$$PC_{ct} = \left\{ \begin{array}{l} DL_{c1t}y_{ct} + \sum_{r\geq 2}^{R_c}[\Delta D_{crt}(1-d_{crt}) + \\ \alpha_{crt}\sum_{\rho=2}^{\rho\leq(r-1)}\{(DL_{c\rho t} - DL_{c(\rho-1)t})(1-d_{c\rho t})\}] \end{array} \right\} \text{(PDC-U contracts)} \quad (5.45)$$

5.3.5 Spot Market

Besides mutually agreed contracts, the MNC may allow the option to procure materials from the spot market. Spot market purchases normally come without any restrictions and prices vary with time. However, this flexibility may come at a cost, as the spot prices can be higher than contract prices. While this is often the case, the reverse is also possible. We model the spot market as contract $c = 0$ with a contract length of one period, but with no purchase commitments or discounts or limits on materials or quantities. Since the MNC can procure from the spot market as often as desired during the planning horizon, no ys_{0t} is needed and eqs. 5.1, 5.2 , 5.4 and 5.5 do not apply. However, we need two bounds to ensure that the total purchase amount of m does not exceed the open market capacity, namely $q_{m0t} \leq q^U_{m0t}$ and $Q_{m0} \leq Q^U_{m0}$. Then, the cost of purchases from the spot market is given by,

$$PC_{m0t} = q_{m0t}p_{m0t} \quad (5.46)$$

5.3.6 Distribution and Inventory of Materials

The MNC's central sourcing department manages the procurement and distribution of materials to all plant sites. It must ensure that demands for all sites are met in time. Therefore,

$$\sum_{c,t} S_{mcst} \geq \sum_{t} D_{mst} \tag{5.47}$$

where, D_{mst} is the demand of material *m* at site *s* during period *t* and S_{mcst} is the supply of *m* under contract *c* to plant site *s* in period *t*.

The total supply of a material under a contract must equal the amount procured, hence,

$$q_{mct} = \sum_{s} S_{mcst} \tag{5.48}$$

Finally, the inventory at plant site *s* at the end of period *t* is given by,

$$I_{mst} = I_{ms(t-1)} + \sum_{c} S_{mcst} - D_{mst} \tag{5.49}$$

5.3.7 Total Procurement Cost

The total procurement cost for the MNC includes the purchase costs of all materials, their distribution costs, and inventory costs. Let LC_{mcst} be the unit logistics cost of supplying material *m* to site *s* under contract *c* during *t*, and HC_{mst} be the holding cost of material *m* at plant site *s* during *t*. Then, the total procurement costs for the MNC is,

$$Cost = \sum_{m \in \boldsymbol{M}_c} \sum_{c} \sum_{t} PC_{mct} + \sum_{m \in \boldsymbol{M}_c} \sum_{c} \sum_{s} \sum_{t} S_{mcst} LC_{mcst} + \sum_{m \in \boldsymbol{M}_c} \sum_{s} \sum_{t} I_{mst} HC_{mst} \tag{5.50}$$

This completes our formulation for supply contract selection. The objective is to minimize the total procurement cost (eq. 5.50) subject to eqs. 5.1, 5.2, 5.4-5.9, 5.6a, 5.8a, 5.8b, 5.10a, 5.10b, 5.11-5.49. Table 5.1 lists the constraints applicable for each contract type.

5.4 Example 1

A MNC has three plant sites (s = 1, 2, 3) that require two materials (m = 1, 2). The planning horizon involves five periods (t = 1, 2, 3, 4, 5 years; T = 5). The central procurement department is evaluating nineteen supply contracts: three TQC-FLB (C1, C2, C3), three TQC-FB (C4, C5, C6), three TQC-U (C7, C8, C9), three PQC-FU (C10, C11, C12), three PQC-B (C13, C14, C15), two TDC-FB (C16, C17), and two PDC-U (C18, C19). Tables 5.2-5.4 list the data for this example. We solve our model using CPLEX v10.0.1 in GAMS 22.2 (Brooke et al., 2005) on a 3.00 GHz Pentium® PC with 2 GB of RAM.

We consider nine cases for this small example. The model solution time was negligible (< 1 CPU s) for all cases. Case 1, which serves as the basis, allows only spot purchases and no supply contracts. In contrast, Case 9 allows all contracts and spot purchases, so it gives the optimal procurement policy for this example. Cases 2-8 consider only the contracts of one specific type along with the spot market. Table 5.6 gives the model and solution statistics for all nine cases. Case 1 has the highest cost of 75,593 k$ in comparison to the minimum cost (Case 9) of 58,523.90 k$. The optimal plan includes three contracts, namely C1 (TQC-FLB), C16 (TDC-FB), and C19 (PDC-U), and spot purchases at various times. By using this plan, the MNC can reduce its purchase costs by 29.2% in this example.

Table 5.7 and 5.8 shows the profiles of material purchases under different contracts for various cases. In Case 2, only two (C1 and C2) of the three TQC-FLB contracts are selected. However, spot purchases are made for m = 1 in all years except the second. During these years, the plan honors its minimum purchase commitments on C1 and C2 to avoid penalties. In contrast, m = 2 is purchased entirely under contracts, as spot prices are always higher. While C2 supplies m = 2 to two plant sites

(s = 1 and 2) for the first two years, C1 supplies m = 2 to all plant sites for the last three years and to s = 3 for the first two years. In Case 3 also, m = 1 is purchased from the spot market in all years except the second. However, the plan utilizes the discount under C6 by making purchases at tier 3. In all the cases, m = 1 is purchased partially from the spot market in years 3, 4, and 5. In Case 5, the plan selects C10, a PQC-FU contract with a length of 3 years, but still pays the penalty for not fulfilling the minimum commitment for m = 1 during the third and fourth years and buys from the spot market. In Case 7, both contracts (C16 and C17) are selected and the purchase falls in the third tier. In Case 8, only C19 is selected and all purchases for m = 1 are spot. In Case 9, C1 supplies m = 1 to sites (s = 1 and 2) in the first year, but supplies to s = 2 only in the second year. C1 also supplies m = 2 to all sites for first four years. Interestingly, C16 also supplies m = 2 to s = 3 in the second year.

Thus, the optimal solution shows a variety of interesting features such as one contract supplying multiple materials to multiple sites and multiple contracts/suppliers supplying material to a single site, combinations of spot and contract purchases, etc. It is clear that such a solution is difficult to obtain manually. While it may be possible to do so for this small example, it will be impossible for a larger one. Just to see what a manual approach can achieve for this example, let us examine the prices of various contracts. First, note that the spot market offers the lowest price for m = 1 in the first, third, fourth, and fifth years. Then, C1 offers the next best prices for both m = 1 (20$) and m = 2 (12$). However, the limit on the purchase of m = 2 under the discounted price of C1 restricts the MNC’s purchase of m = 2 to under 1,150 kton from C1. The next tier price under C1 is higher than the next best price, so MNC should use another contract. To fulfill the remaining demand, C19 offers the next best price after C1, namely 18$ and 15$ for the fourth and fifth years. Using this intuitive purchase strategy, we get 59,937.30 k$ as the total purchase cost, which is 2.42% higher than the minimum cost from our model. Clearly, such an approach is not possible, when the problem size and complexity increase. Moreover, even if we were to propose a solution, it may be significantly worse than the optimal. We now consider the following larger example based on simulated data for a large MNC.

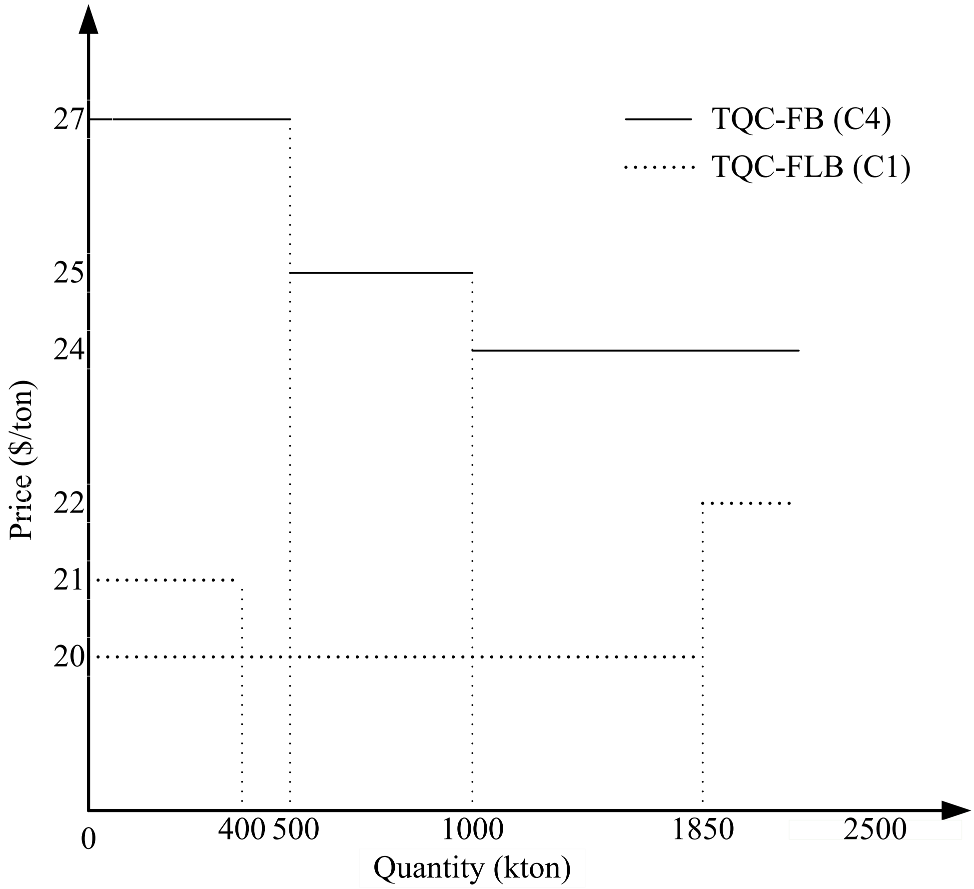

Figure 5.5: Price versus quantity for TQC-FLB and TQC-FU contracts based on the data of Example 1 of m = 1

5.5 Example 2

A MNC has ten plants (s = 1-10) that produce two final products (spandex and Nylon-6) using ten raw materials (m = 1-10). The raw materials are Glycol (m = 1), DMAc (N, N Dimethyl Acetamide, m = 2), MDI (Methyl Di-isocyanate, m = 3), Titanium dioxide (m = 4), EDA (Ethylene DiAmine, m = 5), DEA (Diethyl Amine, m = 6), Adipic Acid (m = 7), Caprolactum (m = 8), additive-1 (m = 9), and additive-2 (m = 10).

The company is considering 46 contracts (*c* = 1-46, C1-C46) of eight types: five TQC-B, six TQC-FLU, seven TQC-FU, seven PQC-FLB, five PQC-U, five TDC-FU, five TDC-B, and six PDC-FB. The planning horizon is five years with five identical periods. Tables 5.9 – 5.20 list the data for this example. Again, we use CPLEX v10.0.1 in GAMS 22.2 on a 3.00 GHz Pentium® PC with 2 GB of RAM.

When no contracts are used and all purchases are spot (case 1), the model reduces to an LP and gives a total procurement cost of 1,864,881.5 k$. In contrast, the minimum possible procurement cost (case 2, which considers all contracts) for this example is 1,580,695.14 k$, which represents a savings of 18%. The solution time for case 2 is 36 CPU s. Table 5.21 shows the purchases from various contracts for each site. Of the 46 possible contracts, eight (C31, C32, C33, C34, C36, C38, C42, and C45) are selected in the optimal solution together with spot purchases at appropriate times. It is interesting to note that all these eight contracts are of DC type. For Glycol, C31 (TDC-FU) and C36 (TDC-B) supply to all plant sites and no spot purchase is used. C36 is used for the first two years, and C31 for the last three years. For DMAc, a combination of C32 (TDC-FU), C38 (TDC-B), and spot purchases is the best. For EDA, C31 is the only contract supplying all plant sites during the third and fifth years. In contrast, two contracts (C34 and C36) are optimal for the first year. Interestingly, the best policy is to purchase additive-1 entirely from the spot market for the first year, but use C42 and C45 for the remaining years. The strategy for additive-2 is somewhat similar, as spot purchases are the preferred option for the first and fifth years, and purchases under C42 and C45 for the remaining years. It is also interesting that one contract satisfies the demands of each material of all plant sites for one or more years except for EDA, where a combination of C34 and C36 is optimal for the first year. For DEA, C36 supplies to all plant sites for the first and third years, C34 for the second year, and C33 for the last two years. This is similar to adipic acid and caprolactum. For adipic acid, C36 supplies for the first year, C34 for the second year, and C31 for the last three years. For caprolactum, a combination of C34 and C32 is optimal.

5.6 Example 3

We mentioned earlier that our model allows contracts to continue from previous years and is suitable for revising procurement plan as and when updated data or new supply options become available. To illustrate this, we revise the plan obtained for Example 1 after two years of execution due to changes in demand that prompt the procurement department to reassess its plan. In addition to the new demands, we update the potential unsigned contracts with updated prices at the end of the first two years in Example 1. Thus, all data of Example 1, except the demand (Table 5.2) and price data (Table 5.5), apply for this example. Note that the zero time for this Example is the start of the third year in Example 1 and the horizon length is three years. The optimal plan for Example 1 (case 9) had three contracts, namely C1 (TQC-FLB), C16 (TDC-FB), and C19 (PDC-U) along with spot purchases. C1 was signed for five years; so it must be honored for the first three years in this example. Similarly, C16 was signed for three years starting from the first year in Example 1, so it must be honored for the first year in this example. Thus, we change the contract length of C16 to 1 year in this example and set z_{16} = 1. Note that purchases have been made under C1 and C16 in the first two years, hence the minimum commitments for C1 and C16 are adjusted by subtracting the quantity/amount of actual purchases. For instance, the minimum qualifying purchases for m = 1 in the three tiers are 400, 1850, and 2500 kton respectively in C1 and the quantity bought during the first and second years in Example 1 are 300 and 100 kton respectively. This makes all the purchases under C1 to fall in the second tier and beyond. This makes $QL_{m11} = 0$, $QL_{m12} = 1450$, and $QL_{m13} = 2100$ kton. C19 was set to be in effect from the last year in Example 1, so it will exist during the third year in Example 3.

The optimal revised procurement plan selects two more contracts C2 (TQC-FLB) and C17 (TDC-FB) in addition to the three existing contracts (C1, C16, and C19). Table 5.8 (case 10) shows the purchase profiles under the five contracts (C1, C19, C16, C2, and C17). The demand for $m = 1$ at $s = 1$ has increased from 80 kton to 480 kton in the first year. In Example 1, all purchases for this year were from the spot market, but now they are equally distributed between C2 and the spot market. The reason behind this is the capacity constraint for the spot market. However, for the next two years, all purchases for $m = 1$ at $s = 1$ are from the spot market as in Example 1. For $m = 2$ at $s = 1$, the demand has increased from 100 to 900 kton in the first year. Now, C17 is used instead of C1 for $m = 2$. If C1 is used, then the total quantity falls in the third tier for which the price is 19 \$/kton, but by using C17, the purchase falls in the third tier of C17 with a fractional discount of 15% and a unit price of 18 \$/kton.

Let us now examine what the consequences of following the optimal procurement strategy obtained from Example 1 would be in the face of increased demands. In the first year, the total demand for $m = 1$ has increased from 460 kton to 1260 kton. As per the original procurement plan, the demand would have to be satisfied by procuring 420 kton from spot market (14 \$/kton) and 840 kton from C16 (21 \$/kton). This would have incurred a cost of 420*14+840*21*0.84 = 20,976.60 k\$ for $m = 1$ in the first year. In contrast, the revised plan procures 420 kton from spot market (14 \$/kton) and 840 kton from C2 (15 \$/kton), thus reduces the cost by 2,217.60 k\$. Similarly, consider the procurement of $m = 2$ for the second year. The original plan would have purchased 650 kton under C1 (19 \$/kton) and 245 kton from the spot market (21 $/kton). In contrast, the revised plan obtains 495 kton from C1 (12 $/kton) and 400 kton from C17 (18 $/kton with a fractional discount of 0.15). Although both plans purchase *m* = 2 under C1, the difference in the price arises because the third-tier (higher) price applies in the original plan as opposed to the second-tier (lower) price in the revised plan. Thus, the revised plan reduces costs for *m* = 2 during the second year by (650*19+245*21) – (495*12+400*18*0.85) = 5435 k$. In brief, it is clear that if the procurement department had not revised the plan, the optimal strategy from Example 1 would have been suboptimal and would have resulted in higher costs.

5.7 Conclusion

We addressed the strategic and integrated sourcing and distribution of materials in a global business environment for a MNC, which are key planning decisions in many supply chains including the chemical. The contract classification presented in this chapter is relatively comprehensive and is applicable to the chemical and a variety of other supply chains. It is based on several key real-life contract features such as purchase commitments, commitment durations, purchase flexibility, variable contract lengths, product-bundling, and multi-tier bulk/unit prices and discounts, which have not been addressed in an integrated manner by previous work. Our proposed multi-period mixed-integer linear programming model not only selects the best contracts and suppliers that minimize the total procurement cost including the logistics and inventory costs, but also assigns the suppliers and decides the supply distribution to various globally distributed sites of a MNC. Relative to previous work, our model is suitable for reviewing the supply strategy and contracts periodically. It not only accommodates existing contracts, but also allows new contracts to extend beyond the horizon.

Our proposed deterministic model is fast even for an industrial-scale example. This is a desirable feature, because it will need to be solved repeatedly for a real-life stochastic scenario, in which several cost/price parameters will be uncertain. Thus, this MILP model provides a basis for future work involving business uncertainties. Furthermore, a company usually has other non-quantifiable criteria for contract selection such as reliability, service quality, etc. Addressing these together in a quantitative model is a challenge that warrants further attention.

Table 5.1: Constraints for various contracts with eqs. 47-49 being common for all contracts and eqs. 1, 2, 4, and 5 being common for all except spot market

Contract Type	Constraints	Contract Type	Constraints	Contract Type	Constraints
TQC-FLB	6a, 8a, 8b, 10a, 10b, 9	PQC-FB	16, 17, 18, 25	TDC-FU	30 - 33, 36
TQC-FB	6, 7, 8, 11	PQC-B	16, 17, 18, 26	TDC-U	30 - 33, 37
TQC-B	6, 7, 8, 12	PQC-FLU	20 - 24, 27	PDC-FB	38 - 42
TQC-FLU	6a, 8a, 8b,10a, 10b, 13	PQC-FU	16, 17, 18, 28	PDC-B	38 - 41, 43
TQC-FU	6, 7, 8, 14	PQC-U	16, 17, 18, 29	PDC-FU	38 - 41, 44
TQC-U	6, 7, 8, 15	TDC-FB	30 - 33, 34	PDC-U	38 - 41, 45
PQC-FLB	19 - 24	TDC-B	30 - 33, 35	Spot Market	46

Table 5.2: Demands (D_{mst}) and inventory holding costs (HC_{mst}) for raw materials for Example 1 and Example 3

			Example 1					Example 3		
s	*m*	HC_{mst} ($/ton)	D_{ms1} to D_{ms5} (kton)					D_{ms1} to D_{ms3} (kton)		
1	1	10	200	400	80	140	150	480	40	350
	2	10	100	100	100	130	100	900	530	600
2	1	17	100	100	300	100	100	600	0	900
	2	19	90	90	190	90	90	590	290	0
3	1	10	200	100	80	90	100	180	290	500
	2	10	100	90	80	75	105	0	75	105

Table 5.3: Contracts (c), contract lengths (CL_c), contract capacities (q^U_{mct}) for period t, total capacities (Q^U_{mc}), and quantity or dollar commitments (QL_{mcr} or DL_{cr}) for Example 1

c		CL_c (yr)	q^U_{1ct} (10^5 ton)	Q^U_{1c} (10^5 ton)	QL_{1cr} or DL_{cr} (10^5 ton or 10^3 \$) $r=1$	$r=2$	$r=3$	q^U_{2ct} (10^5 ton)	Q^U_{2c} (10^5 ton)	QL_{2cr} or DL_{cr} (10^5 ton or 10^3 S) $r=1$	$r=2$	$r=3$
C1	TQC-FLB	5	25	25	4.0	18.5	25	18	18	3.5	11.5	18
C2		3	20	20	4.9	12.0	20	20	20	3.6	12	20
C3		2	20	20	3.0	10.0	20			NA		
C4	TQC-FB	5	24	24	5.0	10	24			NA		
C5		3			NA			18	18	4.0	10	18
C6		2	22	22	4.5	10	22	18	18	2.1	10	18
C7	TQC-U	2	23	23	5.0	10	23	16	16	4.0	10	16
C8		3	22	22	4.5	10	22			NA		
C9		1			NA			16	16	5.0	10	16
C10	PQC-FU	3	22	22	0.6	2.4	22	18	18	0.5	5.9	18
C11		2	20	20	0.4	5.0	20			NA		
C12		1			NA			17	17	2.0	4.8	17
C13	PQC-B	3			NA			18	18	1.0	2.0	18
C14		2	23	23	0.8	2.5	23			NA		
C15		1			NA			19	19	1.0	4.0	19
C16	TDC-FB	3	18	18	1.0	8.0	1500	13	13	1.0	8	1500
C17		2	12	12	5.0	9.0	200	12	12	5.0	9	200
C18	PDC	3	12	12	0.1	3	100			NA		
C19		2			NA			12	12	0.2	4	100
C20	spot	1	25	25		NA				NA		
		1			NA			25	25		NA	

Table 5.4: Price (p_{mcrt} for QC contracts & p_{mct} for DC contracts \$/ton), logistics cost (LC_{mcst}), penalty (π_{mct} for QC contracts & π_{ct} for DC contracts), and percent discounts (d_{crt} for DC contracts %) for Example 1

c	m	p_{mc11} to p_{mc15} or p_{mc1} to p_{mc5}	p_{mc21} to p_{mc25} or d_{c21} to d_{c25}	p_{mc31} to p_{mc35} or d_{c31} to d_{c35}	LC_{mc1t} to LC_{mc3t} (\$/ton)			π_{mc1} to π_{mc5} or π_{c1} to π_{c5} (\$/ton or %)
C1	1	21.0 (t=1-5)	20.0 (t=1-5)	22.0 (t=1-5)	1.95	1.85	1.9	5.0 (t=1-5)
	2	17.0 (t=1-5)	12.0 (t=1-5)	19.0 (t=1-5)	0.80	0.80	1.4	3.0 (t=1-5)
C2	1	23.0 (t=1-5)	22.0 (t=1-5)	26.0 (t=1-5)	0.80	0.80	1.8	4.0 (t=1-5)
	2	21.0 (t=1-5)	16.0 (t=1-5)	22.0 (t=1-5)	0.77	0.77	1.4	3.0 (t=1-5)
C3	1	24.0 (t=1-5)	23.0 (t=1-5)	24.0 (t=1-5)	1.10	1.10	1.3	4.0 (t=1-5)
C4	1	27.0 (t=1-5)	25.0 (t=1-5)	24.0 (t=1-5)	0.75	0.75	1.3	4.0 (t=1-5)
C5	2	20.0 (t=1-5)	19.0 (t=1-5)	18.0 (t=1-5)	0.87	0.87	1.7	2.0 (t=1-5)
C6	1	24.5 (t=1-5)	24.0 (t=1-5)	22.0 (t=1-5)	1.00	1.00	1.5	2.0 (t=1-5)
	2	21.0 (t=1-5)	20.0 (t=1-5)	18.0 (t=1-5)	1.10	1.10	1.6	1.0 (t=1-5)
C7	1	26.0 (t=1-5)	25.0 (t=1-5)	24.0 (t=1-5)	0.90	0.90	2.0	5.0 (t=1-5)
	2	19.0 (t=1-5)	18.0 (t=1-5)	16.0 (t=1-5)	1.15	0.99	2.0	2.0 (t=1-5)
C8	1	25.0 (t=1-5)	24.0 (t=1-5)	22.0 (t=1-5)	1.00	1.50	1.6	4.0 (t=1-5)
C9	2	20.0 (t=1-5)	18.0 (t=1-5)	16.0 (t=1-5)	0.80	0.90	1.0	1.0 (t=1-5)
C10	1	21.0 (t=1-5)	20.0 (t=1-5)	19.0 (t=1-5)	1.80	1.00	0.9	6.0 5.0 4.5 4.0 5.0
	2	20 20 20 20 21	19 19 20 18 19	18 18 19 17 18	0.90	0.80	0.9	2.0 3.0 2.0 3.0 2.0
C11	1	24 25 26 24 24	23 23 25 24 23	22 21 24 23 22	0.90	0.90	1.9	5.0 6.0 5.0 4.0 5.0
C12	2	20 21 20 20 20	18 20 19 19 19	16 19 19 18 18	0.50	0.50	0.3	2.0 3.0 4.0 4.0 5.0
C13	2	21 22 22 21 22	20 21 21 20 20	19 20 20 19 19	1.00	1.00	1.2	2.0 3.0 2.0 1.5 2.0
C14	1	26 27 26 27 26	25 25 25 26 25	24 23 24 25 24	0.80	0.80	1.8	5.0 4.0 4.0 3.0 4.0
C15	2	21 22 22 22 20	20 21 21 21 19	19 20 20 20 18	1.20	1.20	1.2	2.0 3.0 1.5 1.0 1.0
C16	1	21 (t=1-5)	13 (t=1-5)	16 (t=1-5)	1.1	1.1	1.0	1.0 (t=1-5)
	2	22 21 22 20 18			0.9	0.9	0.5	
C17	1	25 24 25 26 25	14 (t=1-5)	15 (t=1-5)	0.8	0.8	1.8	4.0 (t=1-5)
	2	20 19 21 19 18			1.0	1.0	1.1	
C18	1	27 26 24 25 22	2 1 3 2 4	3 4 5 6 5	1.2	1.2	1.0	4.0 1.0 2.0 1.0 2.0
C19	2	21 22 19 18 15	4 7 1 4 1	7 8 5 4 2	1.0	1.0	1.2	3.0 3.0 0.1 0.2 0.2
C20	1	19 25 14 12 11	NA		1.2	1.2	1.0	NA
C21	2	20 22 21 21 22			1.3	1.3	1.0	

Table 5.5: Price (p_{mcrt} for QC contracts & p_{mct} for DC contracts \$/ton) for Example 3

c	m	p_{mc11} to p_{mc15} or p_{mc1} to p_{mc5}					p_{mc21} to p_{mc25}					p_{mc31} to p_{mc35}				
C1	1	21.0 (t=1-5)					20.0 (t=1-5)					22.0 (t=1-5)				
	2	17.0 (t=1-5)					12.0 (t=1-5)					19.0 (t=1-5)				
C2	1	18.0 (t=1-5)					15.0 (t=1-5)					20.0 (t=1-5)				
	2	21.0 (t=1-5)					16.0 (t=1-5)					22.0 (t=1-5)				
C3	1	22.0 (t=1-5)					21.0 (t=1-5)					24.0 (t=1-5)				
C4	1	20.0 (t=1-5)					19.0 (t=1-5)					18.0 (t=1-5)				
C5	2	20.0 (t=1-5)					19.0 (t=1-5)					18.0 (t=1-5)				
C6	1	22.0 (t=1-5)					20.0 (t=1-5)					18.0 (t=1-5)				
	2	18.0 (t=1-5)					17.0 (t=1-5)					16.0 (t=1-5)				
C7	1	22.0 (t=1-5)					21.0 (t=1-5)					20.0 (t=1-5)				
	2	19.0 (t=1-5)					18.0 (t=1-5)					16.0 (t=1-5)				
C8	1	25.0 (t=1-5)					24.0 (t=1-5)					22.0 (t=1-5)				
C9	2	20.0 (t=1-5)					18.0 (t=1-5)					16.0 (t=1-5)				
C10	1	21.0 (t=1-5)					20.0 (t=1-5)					19.0 (t=1-5)				
	2	20	20	20	20	21	19	19	20	18	19	18	18	19	17	18
C11	1	24	25	26	24	24	23	23	25	24	23	22	21	24	23	22
C12	2	20	21	20	20	20	18	20	19	19	19	16	19	19	18	18
C13	2	21	22	22	21	22	20	21	21	20	20	19	20	20	19	19
C14	1	26	27	26	27	26	25	25	25	26	25	24	23	24	25	24
C15	2	21	22	22	22	20	20	21	21	21	19	19	20	20	20	18
C16	1	21 (t=1-5)					NA									
	2	22	21	22	20	18										
C17	1	20 (t=1-5)														
	2	18 (t=1-5)														
C18	1	22 (t=1-5)														
C19	2	21	22	19	18	15										
C20	1	19	25	14	12	11										
C21	2	20	22	21	21	22										

Table 5.6: Model and solution statistics for Examples 1 and 2

Example	Case	Binary Variables	Continuous Variables	Constraints	Cost [10^3\$]
1	1	0	81	69	75593.00
	2	20	234	172	61055.60
	3	27	222	155	71968.85
	4	27	222	155	74166.20
	5	75	334	251	69656.00
	6	60	279	210	72157.00
	7	16	199	139	63907.75
	8	40	223	173	72302.60
	9	265	1227	841	58523.90
2	1	0	1,101	761	1,864,881.50
	2	860	12,797	4,757	1,580,695.14

Table 5.7: Quantities (kton) of materials bought under different contracts in Example 1 (case 2 to 7)

			m =1			m =2		
case	c	t	s = 1 to 3			s =1 to 3		
2	C1	1	100	100	0	0	0	100
		2	0	100	100	0	0	90
		3		-		100	190	80
		4		-		130	90	75
		5		-		100	90	105
	C2	1	90	0	0	100	90	0
		2	400	0	0	100	90	0
	spot	1	10	0	200		-	
		3	80	300	80		-	
		4	140	100	90		-	
		5	150	100	100		-	
3	C5	2		0		100	90	90
		3		0		100	190	80
		4		0		185	90	75
	C6	1	200	100	100	100	90	20
		2	400	100	100		0	
	spot	1	0	0	100	0	0	80
		3	80	300	80		0	
		4	140	100	90		0	
		5	150	100	100	45	90	105
4	C7	2	400	100	0	100	90	90
		3		-		100	190	80
	spot	1	200	100	200	100	90	100
		2	0	0	100		-	
		3	80	300	80		-	
		4	140	100	90	130	90	75
		5	150	100	100	100	90	105
5	C10	2	400	100	100	100	90	90
		3		0		100	190	80
		4		0		130	90	75
	C12	5		0		100	90	105
	spot	1	200	100	200	100	90	100
		3	80	300	80		0	
		4	140	100	90		0	
		5	150	100	100		0	
6	C13	2		-		100	90	90
		3		-		100	190	80
		4		-		130	90	75
	C14	1	0	80	0		0	
		2	400	100	100		0	
	C15	5		0		100	90	105
	spot	1	200	20	200	100	90	100
		3	80	300	80		0	
		4	140	100	90		0	
		5	150	100	100		0	
7	C16	1	200	100	200	100	90	100
		2	400	100	100	100	90	90
		3		0		100	190	80
	C17	4		0		130	90	75
		5		0		100	90	105
	spot	3	80	300	80		0	
		4	140	100	90		0	
		5	150	100	100		0	

Table 5.8: Quantities (kton) of materials bought under different contracts in Example 1 (case 8 and case 9) and Example 3 (case 10)

case	c	t	m =1 s = 1 to 3			m =2 s =1 to 3		
8	C19	4	0			130	90	75
		5	0			100	90	105
	spot	1	200	100	200	100	90	100
		2	400	100	100	100	90	90
		3	80	300	80	100	190	80
		4	140	100	90		0	
		5	150	100	100		0	

case	c	t	m =1 s = 1 to 3			m =2 s =1 to 3		
9	C1	1	200	100	0	100	90	100
		2	0	100	0	100	90	5
		3		0		100	190	80
		4		0		130	90	75
		5		0			0	
	C16	1	0	0	200		0	
		2	400	0	100	0	0	85
	C19	5		0		100	90	105
	spot	3	80	300	80		0	
		4	140	100	90		0	
		5	150	100	100		0	

case	c	t	m =1 s = 1 to 3			m =2 s =1 to 3		
10	C1	1		0		0	170	0
		2		0		205	290	0
	C2	1	240	600	0	0	420	0
	C17	1		0		900		0
		2		0		325	0	75
	C19	3		0		600	0	105
	spot	1	240	0	180		0	
		2	40	0	290		0	
		3	350	900	500		0	

Table 5.9: Demands (Demands (D_{mst} kton) and inventory holding costs (HC_{mst} \$/ton) for raw materials (m = 1 to 5) for Example 2

s	D_{1s1} to D_{1s5}					D_{2s1} to D_{2s5}					D_{3s1} to D_{3s5}					D_{4s1} to D_{4s5}					D_{5s1} to D_{5s5}				
1	200	400	80	140	150	100	100	100	130	100	100	0	0	100	100	9	9	8	10	10	0	100	100	200	100
2	100	100	300	100	100	90	90	190	90	90	110	100	95	50	50	11	10	11	0	0	100	100	95	55	100
3	200	100	80	90	100	100	90	80	75	105	0	100	100	200	100	0	0	30	0	10	85	100	85	300	400
4	100	200	0	0	100	0	0	100	100	75	0	100	100	0	100	20	6	10	20	10	10	10	100	60	100
5	90	0	0	90	100	0	0	75	100	110	0	0	0	300	200	10	0	10	20	20	100	95	75	75	95
6	100	100	0	0	0	0	100	200	100	200	100	200	95	0	0	0	0	10	20	0	85	85	100	0	0
7	0	0	100	100	75	100	110	95	0	0	0	100	200	100	0	20	10	0	0	0	100	0	0	0	400
8	100	110	210	200	100	0	100	110	200	0	100	200	0	50	50	29	29	19	20	0	90	95	95	100	100
9	80	95	110	100	100	0	0	100	0	0	85	80	75	100	100	20	0	0	20	20	100	100	0	0	0
10	85	0	75	110	85	100	110	100	85	100	100	0	0	100	0	19	19	20	0	0	0	0	200	200	95
	HC_{1s1} to HC_{1s5}					HC_{2s1} to HC_{2s5}					HC_{3s1} to HC_{3s5}					HC_{4s1} to HC_{4s5}					HC_{5s1} to HC_{5s5}				
1	10 (t=1-5)					10 (t=1-5)					8.0	8.0	9.0	8.0	8.0	24	20	20	20	20	20 (t=1-5)				
2	11	10	9	11	7	10	10	12	11	11	8.0	8.0	9.0	8.0	9.0	24	18	21	21	21	20	19	22	22	21
3	12	9	10	11	12	11	11	11	12	11	9.0	8.0	9.0	9.0	9.0	22	21	18	21	19	21	19	21	19	21
4	11	12	12	11	11	9	11	11	12	9	8.0	8.0	9.0	8.0	7.0	24	21	21	21	21	20	22	20	22	18
5	9 (t=1-5)					11 (t=1-5)					10.0	11.0	9.0	10.0	8.0	20	19	18	22	21	21	21	19	22	19
6	10 (t=1-5)					11 (t=1-5)					9.0 (t=1-5)					20	20	20	20	19	12 (t=1-5)				
7	8 (t=1-5)					11 (t=1-5)					8.0	8.0	9.0	8.0	8.0	24	20	20	20	20	20 (t=1-5)				
8	11 (t=1-5)					9 (t=1-5)					7.0 (t=1-5)					20 (t=1-5)					18 (t=1-5)				
9	9 (t=1-5)					10 (t=1-5)					8.0	8.0	9.0	8.5	9.0	22 (t=1-5)					20 (t=1-5)				
10	10 (t=1-5)					8 (t=1-5)					8.0	8.0	9.0	8.0	8.0	24	20	20	20	20	20 (t=1-5)				

Table 5.10: Demands (Demands (D_{mst} kton) and inventory holding costs (HC_{mst} \$/ton) for raw materials (m = 6 to 10) for Example 2

	$D_{6s\,1}$ to $D_{6s\,5}$					$D_{7s\,1}$ to $D_{7s\,5}$					$D_{8s\,1}$ to $D_{8s\,5}$					$D_{9s\,1}$ to $D_{9s\,5}$					$D_{10s\,1}$ to $D_{10s\,5}$				
1	0	0	100	100	200	100	200	200	0	0	200	100	120	100	0	0	15	25	0	0	10	5	15	0	0
2	200	100	195	0	200	200	200	0	100	0	120	250	0	100	0	10	25	10	0	0	0	15	0	10	10
3	0	195	100	100	195	100	100	100	0	0	100	100	0	0	120	20	10	20	10	0	10	0	10	10	0
4	195	100	100	195	100	200	100	100	200	0	100	150	120	120	0	15	20	0	10	10	5	10	5	5	10
5	95	110	0	0	0	100	200	100	0	0	100	200	100	0	0	0	10	10	5	10	6	10	15	5	10
6	100	110	0	110	100	95	95	100	110	100	95	95	190	90	0	19	19	0	10	10	25	19	10	10	20
7	195	0	100	110	110	110	110	200	0	200	100	100	100	0	200	10	10	25	10	10	9	20	15	15	10
8	100	110	100	110	100	200	200	100	110	195	200	200	0	100	295	12	12	20	10	5	20	15	15	10	10
9	0	110	0	100	110	200	100	200	195	100	100	150	100	295	100	10	15	12	29	0	20	5	20	19	0
10	110	100	110	100	0	0	80	45	55	100	0	0	245	155	100	0	18	15	5	10	10	8	15	25	10
	$HC_{6s\,1}$ to $HC_{6s\,5}$					$HC_{7s\,1}$ to $HC_{7s\,5}$					$HC_{8s\,1}$ to $HC_{8s\,5}$					$HC_{9s\,1}$ to $HC_{9s\,5}$					$HC_{10s\,1}$ to $HC_{10s\,5}$				
1	1.0 (t=1-5)					10 (t=1-5)					30	30	29	28	30	0.6	0.6	1.0	0.8	0.9	0.1	0.2	0.3	0.1	0.1
2	1.0	1.0	1.0	0.9	1.0	10	12	10	11	9	30	32	29	29	31	0.6	0.6	1.0	1.8	1.0	0.1	0.3	0.3	0.2	1.1
3	1.0	1.0	0.9	1.0	0.9	11	10	11	11	11	31	30	27	25	23	0.7	0.6	1.0	0.8	0.7	0.1	0.2	0.3	0.1	0.2
4	1.0 (t=1-5)					12	11	11	11	12	30	31	29	28	31	0.6	0.6	1.0	0.8	0.9	0.1	0.2	0.3	0.1	0.1
5	1.1	1.2	1.0	1.2	1.1	11	10	9	11	9	29	28	29	30	31	0.6	0.6	1.0	0.8	0.9	0.1	0.2	0.3	0.1	0.1
6	1.1 (t=1-5)					9	9	10	10	10	30	30	25	25	26	0.6	0.6	1.0	0.8	0.9	0.1	0.2	0.3	0.1	0.1
7	1.0 (t=1-5)					9 (t=1-5)					26 (t=1-5)					0.5	0.5	1.1	0.5	0.7	0.2	0.2	0.3	0.2	0.2
8	1.1 (t=1-5)					9 (t=1-5)					28	28	29	28	28	0.6	0.6	1.0	0.8	0.9	0.1	0.2	0.3	0.1	0.1
9	1.0 (t=1-5)					11 (t=1-5)					30	30	29	28	30	0.7	0.7	1.0	0.8	0.9	0.1	0.2	0.3	0.1	0.1
10	1.0 (t=1-5)					10 (t=1-5)					30	30	29	28	30	0.6	0.6	1.0	0.8	0.9	0.1	0.2	0.3	0.1	0.1

Table 5.11: Contracts (c), contract lengths (CL_c), materials (m), contract capacities (q^U_{mct}) for period t, total capacities (Q^U_{mc}), quantity commitment (QL_{mcr}), price (p_{mcr}), logistics cost (LC_{mcst}) and penalty (π_{mc}) for TQC-B (C1-C5) contracts for Example 2

c	CL_c (yr)	m	q^U_{mct} (10^5 ton)	Q^U_{mc} (10^5 ton)	QL_{mc1} to QL_{mc3} (10^5 ton)			p_{mc1} to p_{mc3} ($/ton)			LC_{mcst} ($/ton)	π_{mc} ($/ton)
C1	5	1	45.0	45.0	14.0	24.0	45.0	25.0	24.0	23.0	1.95	5.0
		2	40.0	40.0	13.5	23.5	40.0	20.0	18.0	17.0	0.80	3.0
		3	40.0	40.0	14.0	24.0	40.0	49.0	48.0	47.0	1.80	7.0
		4	4.00	4.0	1.4	2.40	4.0	78.0	77.0	74.0	0.01	8.0
		5	30.0	30.0	14.0	24.0	30.0	100.0	99.0	95.0	2.00	10.0
C2	3	1	30.0	30.0	14.9	24.9	30.0	25.0	24.0	20.0	0.80	4.0
		2	30.0	30.0	13.6	23.6	30.0	20.0	19.0	16.0	0.77	3.0
		6	35.0	35.0	13.0	23.0	35.0	9.0	8.0	5.0	0.80	1.0
		7	45.0	45.0	10.0	20.0	45.0	19.0	18.0	15.0	1.77	3.0
		8	30.0	30.0	10.0	25.0	30.0	150.0	145.0	140.0	2.80	15.0
C3	2	1	20.0	20.0	13.0	18.0	20.0	24.0	23.0	22.0	1.10	3.4
		9	4.0	4.0	1.0	2.0	4.0	5.0	3.0	2.0	0.10	1.0
		10	3.00	3.00	1.2	2.2	3.0	1.0	0.9	0.6	0.01	0.1
C4	4	6	35.0	35.0	9.0	19.0	35.0	11.0	10.0	8.0	0.80	1.1
		7	35.0	35.0	10.0	20.0	35.0	19.0	18.0	16.0	1.77	3.5
		8	45.0	45.0	10.0	19.0	45.0	150.0	140.0	135.0	2.80	16.0
C5	1	1	35.0	35.0	9.0	19.0	35.0	25.0	24.0	20.0	1.95	6.0
		2	40.0	40.0	9.0	20.0	40.0	20.0	19.0	16.0	0.80	4.0
		6	45.0	45.0	12.0	22.0	45.0	9.0	8.0	6.0	0.80	2.0
		9	4.5	4.5	0.9	1.9	4.5	5.0	4.5	3.0	0.10	1.0
		10	3.5	3.5	1.0	2.0	3.5	1.0	0.9	0.5	0.01	0.1

Table 5.12: Contracts (c), contract lengths (CL_c), materials (m), contract capacities (q^U_{mct}) for period t, total capacities (Q^U_{mc}), quantity commitment (QL_{mcr}), price (p_{mcr}), logistics cost (LC_{mcst}) and penalty (π_{mc}) for TQC-FLU (C6-C11) contracts for Example 2

	CL_c		q^U_{mct}	Q^U_{mc}	QL_{mcr} (10^5 ton)			p_{mcr} ($/ton)			LC_{mcst}	Π_{mc}
c	(yr)	m	(10^5 ton)	(10^5 ton)	r=1	r=2	r=3	r=1	r=2	r=3	($/ton)	($/ton)
C6	5	1	44.0	44.0	12.00	25.00	44.00	27.0	26.0	28.0	0.75	4.0
		3	40.0	40.0	10.00	20.00	40.00	50.0	52.0	54.0	1.75	7.0
		4	4.5	4.5	1.00	2.00	4.50	79.0	75.0	80.0	0.01	7.0
		7	35.0	35.0	10.00	20.00	35.00	20.0	18.0	22.0	1.75	3.0
		8	55.0	55.0	10.00	30.00	55.00	150.0	145.0	152.0	2.75	16.0
C7	3	2	38.0	38.0	10.00	20.00	38.00	20.0	18.0	22.0	0.87	2.0
		5	50.0	50.0	10.00	30.00	50.00	100.0	90.0	102.0	1.87	9.0
		8	55.0	55.0	9.00	29.00	55.00	150.0	148.0	151.0	2.87	13.0
		10	5.5	5.5	1.90	2.90	5.50	1.0	0.9	1.2	0.01	0.2
C8	2	1	32.0	32.0	9.50	29.50	32.00	25.0	24.0	27.0	1.00	2.0
		2	40.0	40.0	8.00	28.00	40.00	21.0	20.0	23.0	1.10	1.0
		9	5.0	5.0	1.85	3.85	5.00	5.0	4.5	6.0	0.01	1.0
		10	5.0	5.0	1.90	2.90	5.00	1.1	1.0	1.5	0.01	0.1
C9	2	4	5.0	5.0	1.85	2.85	5.00	75.0	70.0	80.0	0.01	6.0
		5	50.0	50.0	9.00	29.00	50.00	101.0	96.0	104.0	2.00	11.0
		6	50.0	50.0	18.00	28.00	50.00	9.0	8.0	9.5	0.80	1.0
		7	55.0	55.0	18.00	28.00	55.00	19.0	15.0	20.0	1.77	3.0
C10	2	8	50.0	50.0	18.00	28.00	50.00	153.0	150.0	154.0	2.87	15.0
		9	5.5	5.5	1.90	3.90	5.50	6.0	5.0	7.0	0.10	1.0
		10	5.5	5.5	1.90	3.90	5.50	1.1	0.8	1.3	0.01	0.1
C11	3	9	5.5	5.5	1.00	3.00	5.50	5.5	5.0	6.0	0.10	1.0
		10	5.5	5.5	2.00	4.00	5.50	0.9	0.8	1.0	0.01	0.2

Table 5.13: Contracts (c), contract lengths (CL_c), materials (m), contract capacities (q^U_{mct}) for period t, total capacities (Q^U_{mc}), quantity commitment (QL_{mcr}), price (p_{mcr}), logistics cost (LC_{mcst}) and penalty (π_{mc}) for TQC-FU (C12-C18) contracts for Example 2

c	CL_c (yr)	m	q^U_{mct} (10^5 ton)	Q^U_{mc} (10^5 ton)	QL_{mc1} to QL_{mc3} (10^5 ton)			p_{mc1} to p_{mc3} (\$/ton)			LC_{mcst} (\$/ton)	π_{mc} (\$/ton)
C12	2	1	43.0	43.0	15.0	35.0	43.0	26.0	25.0	23.0	0.90	5.00
		2	16.0	16.0	4.0	8.0	16.0	22.0	20.0	17.0	1.15	2.00
		9	4.0	4.0	1.0	2.0	4.0	6.0	5.0	3.0	0.10	2.00
		10	4.6	4.6	0.9	2.9	4.6	1.1	1.0	0.8	0.15	0.05
C13	3	6	50.0	50.0	14.5	34.5	50.0	11.0	10.0	9.0	0.80	1.00
		7	55.0	55.0	18.0	38.0	55.0	19.0	17.0	16.0	1.77	2.00
		8	55.0	55.0	20.0	40.0	55.0	153.0	150.0	148.0	2.87	14.00
C14	1	2	40.0	40.0	15.0	35.0	40.0	21.0	19.0	18.0	1.15	4.00
		8	50.0	50.0	9.0	29.0	50.0	153.0	150.0	148.0	2.87	14.00
		9	5.0	5.0	1.0	3.0	5.0	6.0	4.0	3.0	0.10	1.10
		10	5.0	5.0	1.0	3.0	5.0	1.1	0.9	0.8	0.15	0.20
C15	1	4	5.0	5.0	1.5	2.5	5.0	80.0	75.0	72.0	0.01	8.00
		5	50.0	50.0	10.0	30.0	50.0	101.0	98.0	97.0	2.00	10.00
		6	50.0	50.0	12.0	22.0	50.0	9.0	8.0	7.8	0.80	1.00
		7	50.0	50.0	12.0	32.0	50.0	19.0	17.0	16.0	1.77	4.00
C16	4	8	53.0	53.0	10.0	30.0	53.0	153.0	150.0	146.0	2.87	16.00
		9	5.0	5.0	1.0	3.0	5.0	6.0	5.5	5.0	0.10	1.50
		10	5.0	5.0	1.0	2.0	5.0	1.1	0.9	0.7	0.01	0.20
C17	2	6	50.0	50.0	12.0	32.0	50.0	9.0	8.0	7.0	0.80	2.00
		7	50.0	50.0	12.0	22.0	50.0	21.0	20.0	18.0	1.77	4.00
		8	50.0	50.0	12.0	32.0	50.0	154.0	152.0	150.0	2.87	16.00
C18	4	1	50.0	50.0	20.0	30.0	50.0	26.0	24.0	23.0	0.90	6.00
		2	40.0	40.0	12.0	22.0	40.0	19.0	18.0	17.0	1.15	3.00
		8	45.0	45.0	9.0	29.0	45.0	150.0	145.0	140.0	2.87	17.00
		9	5.0	5.0	1.0	3.0	5.0	6.0	5.0	4.0	0.10	2.00

Table 5.14: Contracts (c), contract lengths (CL_c yr), materials (m), contract capacities (q^U_{mct} 10^5 ton) for period t, total capacities (Q^U_{mc} 10^5 ton), quantity commitment (QL_{mcrt} 10^5 ton), price (p_{mcrt} \$/ton), logistics cost (LC_{mcst} \$/ton) and penalty (π_{mct} \$/ton) for PQC-FLB (C19-C25) contracts for Example 2

c	CL_c	m	q^U_{mct}	Q^U_{mc}	QL_{mc1t} to QL_{mc3t}			p_{mc11} to p_{mc15}					p_{mc21} to p_{mc25}					p_{mc31} to p_{mc35}					LC_{mcst}	π_{mc1} to π_{mc5}				
C19	3	1	50	50	4.0	8.0	50.0	26.0	26.0	26.0	27.0	25.0	24.0	24.0	25.0	25.0	24.5	27.0	27.0	27.0	28.0	26.0	1.80	6.0	5.0	4.5	4.0	5.0
		2	40	40	3.0	18.0	40.0	20.0	20.0	20.0	20.0	21.0	19.0	19.0	19.5	18.0	19.0	21.0	21.0	21.0	21.0	22.0	0.90	2.0	3.0	2.0	3.0	2.0
		6	50	50	4.0	10.0	50.0	10.0	10.0	10.0	10.0	11.0	9.0	9.0	9.0	8.0	10.0	11.0	11.0	11.0	11.0	12.0	1.00	1.0	1.5	2.0	1.0	1.0
		7	50	50	4.0	14.0	50.0	20.0	20.0	20.0	20.0	21.0	19.0	19.0	19.5	18.0	19.0	21.0	21.0	21.0	21.0	22.0	1.90	3.0 (t=1-5)				
C20	2	1	50	50	3.0	10.0	50.0	24.0	25.0	26.0	24.0	24.0	23.0	23.0	25.0	23.0	23.0	25.0	26.0	27.0	25.0	25.0	0.90	5.0	6.0	5.0	4.0	5.0
		4	5	5	0.5	1.5	5.0	75.0	75.0	76.0	75.0	75.0	72.0	72.0	72.0	72.0	72.0	80.0	78.0	78.0	77.0	76.0	0.01	8.0 (t=1-5)				
		5	50	50	5.0	15.0	50.0	100.0	99.0	96.0	97.0	97.0	99.0	98.0	92.0	95.0	95.0	102.0	100.0	100.0	100.0	100.0	1.90	10.0	10.0	9.0	10.0	10.0
C21	1	2	40	40	5.0	18.0	40.0	20.0	21.0	20.0	20.0	20.0	18.0	20.0	19.0	19.0	19.0	21.0	22.0	22.0	22.0	22.0	0.50	2.0	3.0	4.0	4.0	5.0
		5	50	50	7.0	15.0	50.0	98.0	98.0	95.0	98.0	96.0	96.0	96.0	92.0	96.0	94.0	100.0	100.0	100.0	100.0	98.0	1.50	10.0 (t=1-5)				
		10	5	5	0.4	1.5	5.0	1.0	1.0	1.1	1.1	1.0	0.8	0.9	1.0	1.0	0.9	1.1	1.1	1.2	1.3	1.1	0.01	0.1 (t=1-5)				
C22	3	5	50	50	3.0	12.0	50.0	98.0	98.0	96.0	98.0	96.0	97.0	96.0	92.0	96.0	94.0	99.0	100.0	100.0	100.0	98.0	2.00	10.0	10.0	9.0	10.0	10.0
		6	50	50	4.0	14.0	50.0	10.0	11.0	10.0	10.0	12.0	9.0	10.0	9.0	9.0	11.0	11.0	12.0	11.0	11.0	12.0	0.80	1.0 (t=1-5)				
		8	50	50	8.0	12.0	50.0	150.0	148.0	150.0	148.0	146.0	145.0	146.0	148.0	145.0	140.0	152.0	150.0	152.0	150.0	150.0	2.87	14.0 (t=1-5)				
		9	5	5	0.4	1.4	5.0	5.0	5.0	5.0	5.0	5.0	4.5	4.0	4.5	4.5	4.0	5.5	6.0	5.5	5.5	5.5	0.10	1.0 (t=1-5)				
C23	5	5	50	50	8.0	12.0	50.0	98.0	98.0	96.0	98.0	96.0	97.0	97.0	95.0	96.0	94.0	100.0	99.0	99.0	100.0	97.0	2.00	10.0	10.0	9.0	10.0	10.0
		6	50	50	4.0	14.0	50.0	11.0	10.5	10.0	10.0	12.0	8.0	10.0	9.0	9.0	11.0	11.0	11.0	11.0	11.0	12.0	0.80	1.0 (t=1-5)				
		7	50	50	4.0	14.0	50.0	21.0	21.0	20.0	20.0	21.0	20.0	19.0	19.5	18.0	19.0	21.5	22.0	21.0	21.0	22.0	1.90	3.0 (t=1-5)				
C24	3	7	50	50	4.0	14.0	50.0	22.0	21.0	21.0	21.0	20.0	20.0	19.0	18.0	20.0	19.0	21.0	22.0	21.5	21.0	21.0	1.90	4.0 (t=1-5)				
		8	50	50	4.0	12.0	50.0	152.0	148.0	155.0	148.0	148.0	147.0	145.0	150.0	145.0	140.0	153.0	150.0	157.0	150.0	150.0	2.90	14.0 (t=1-5)				
		9	5	5	0.4	1.4	5.0	5.0	5.5	5.0	5.0	5.5	4.0	4.5	5.0	4.5	4.5	5.5	6.0	5.5	5.5	6.0	0.02	1.0 (t=1-5)				
C25	3	4	5	5	0.5	1.5	5.0	76.0	74.0	75.0	75.0	76.0	72.0	72.0	72.0	72.0	72.0	78.0	78.0	78.0	77.0	77.0	0.01	8.0 (t=1-5)				
		5	50	50	8.0	15.0	50.0	100.0	100.0	96.0	97.0	97.0	95.0	98.0	92.0	95.0	96.0	105.0	102.0	100.0	100.0	100.0	1.90	10.0	10.0	9.0	10.0	10.0

Table 5.15: Contracts (c), contract lengths (CL_c yr), materials (m), contract capacities (q^U_{mct} 10^5 ton) for period t, total capacities (Q^U_{mc} 10^5 ton), quantity commitment (QL_{mcrt} 10^5 ton), price (p_{mcrt} \$/ton), logistics cost (LC_{mcst} \$/ton) and penalty (π_{mct} \$/ton) for PQC-U (C26-C30) contracts for Example 2

c	CL_c	m	q^U_{mct}	Q^U_{mc}	QL_{mc1} to QL_{mc3}			p_{mc11} to p_{mc15}					p_{mc21} to p_{mc25}					p_{mc31} to p_{mc35}					LC_{mcst}	π_{mc1} to π_{mc5} (\$/ton)				
C26	3	2	38	38	3.0	10.0	38.0	21.0	21.5	22.0	21.0	22.0	20.0	21.0	21.0	20.0	20.0	19.0	20.0	20.0	19.0	19.0	1.00	2.0	3.0	2.0	1.5	2.0
		5	40	40	4.0	20.0	40.0	102.0	100.0	100.0	102.0	101.0	98.0	98.0	98.0	100.0	97.0	96.0	96.0	96.0	96.0	95.0	2.00	12.0	11.0	10.0	10.0	10.0
		10	5	5	1.0	2.0	5.0	1.0	1.1	1.2	1.3	1.2	0.9	0.9	1.0	1.0	1.0	0.8	0.7	0.8	0.8	0.8	0.03	0.1 (t=1-5)				
C27	2	1	23	23	5.0	20.0	23.0	26.0	27.0	26.0	27.0	26.0	25.0	25.0	25.0	26.0	25.0	24.0	23.0	24.0	25.0	24.0	0.80	5.0	4.0	4.0	3.0	4.0
		2	19	19	5.0	10.0	19.0	21.0	21.5	22.0	21.0	22.0	20.0	21.0	21.0	20.0	20.0	19.0	20.0	20.0	19.0	19.0	0.80	3.0	3.0	3.0	3.0	2.0
		3	40	40	5.0	10.0	40.0	51.0	51.5	52.0	50.0	50.0	50.0	50.0	48.0	46.0	47.0	49.0	48.0	45.0	44.0	45.0	1.80	7.0 (t=1-5)				
		4	5	5	0.5	2.0	5.0	76.0	74.0	75.0	78.0	78.0	74.0	72.0	72.0	75.0	76.0	72.0	71.0	70.0	72.0	74.0	0.02	8.0 (t=1-5)				
C28	1	5	50	50	4.0	20.0	50.0	102.0	100.0	100.0	102.0	103.0	100.0	99.0	98.0	100.0	100.0	98.0	96.0	95.0	96.0	95.0	1.20	10.0 (t=1-5)				
		6	50	50	4.0	20.0	50.0	11.0	10.0	10.0	10.0	12.0	10.0	9.0	9.0	9.0	11.0	9.0	8.0	8.0	8.0	10.0	1.00	1.0 (t=1-5)				
		7	55	55	4.0	10.0	55.0	22.0	21.0	21.0	21.0	20.0	20.0	19.0	19.0	20.0	19.0	18.0	18.0	18.0	19.0	18.0	1.40	3.0 (t=1-5)				
		8	50	50	4.0	10.0	50.0	152.0	150.0	153.0	150.0	151.0	150.0	148.0	150.0	148.0	148.0	147.0	145.0	147.0	145.0	145.0	2.20	14.0 (t=1-5)				
C29	4	9	5	5	0.4	1.0	5.0	5.0	5.5	5.0	5.5	5.5	4.0	5.0	4.5	5.0	5.0	3.5	4.5	4.0	4.5	4.0	0.10	1.0 (t=1-5)				
		10	5	5	0.4	1.0	5.0	1.1	1.2	1.2	1.3	1.2	0.9	0.9	1.0	1.1	1.0	0.9	0.8	0.9	0.9	0.8	0.01	0.1 (t=1-5)				
C30	3	1	50	50	4.0	10.0	50.0	25.0	26.0	26.0	27.0	26.0	24.0	25.0	25.0	26.0	25.0	23.0	24.0	24.0	25.0	24.0	0.80	5.0	4.0	4.0	3.0	4.0
		8	55	55	4.0	10.0	55.0	151.0	150.0	152.0	150.0	151.0	150.0	148.0	150.0	148.0	148.0	148.0	145.0	147.0	145.0	145.0	2.20	14.0 (t=1-5)				
		9	5	5	0.4	1.0	5.0	5.0	5.5	5.0	5.5	5.5	4.0	5.0	4.5	5.0	5.0	3.5	4.5	4.0	4.5	4.0	0.10	1.0 (t=1-5)				

Table 5.16: Contracts (c), contract lengths (CL_c yr), materials (m), contract capacities (q^U_{mct} 10^5 ton) for period t, total capacities (Q^U_{mc} 10^5 ton), dollar commitment (DL_{cr} k\$), price (p_{mct} \$/ton), logistics cost (LC_{mcst} \$/ton), penalty (π_c %) and discounts (d_{cr} %) for TDC-B (C36-C40) contracts for Example 2

c	CL_c	m	q^U_{mct}	Q^U_{mc}	DL_{c1} to DL_{c3}			p_{mc1} to p_{mc5}					LC_{mcst}	π_c	d_{c2} to d_{c3}	
C31	3	1	48	48	10.0	28.0	150000	21.0 (t=1-5)					1.10	1.0	13.0	16.0
		5	43	43				100.0	101.0	100.0	99.0	100.0	1.90			
		6	50	50				10.0	9.0	9.0	10.0	10.0	1.10			
		7	45	45				20.0	21.0	20.0	19.0	20.0	1.20			
C32	2	2	40	40	13.0	29.0	20000	20.0	19.0	21.0	19.0	18.0	0.80	1.0	14.0	15.0
		8	53	53				152.0	150.0	148.0	152.0	150.0	2.00			
		9	5	5				5.0	4.0	5.5	5.0	5.0	0.10			
		10	5	5				1.0	1.1	0.9	1.1	1.2	0.01			
C33	2	3	40	40	14.5	20.0	30000	50.0	49.0	51.0	49.0	48.0	1.80	2.0	10.0	15.0
		4	5	5				78.0	80.0	81.0	76.0	76.0	0.02			
		5	50	50				100.0	101.0	102.0	98.0	102.0	1.20			
		6	50	50				10.5	9.5	10.0	9.0	9.0	1.00			
C34	3	5	50	50	15.0	30.0	1000000	100.0	99.0	101.0	98.0	102.0	1.20	3.0	12.0	15.0
		6	50	50				11.0	8.0	10.0	10.0	10.0	1.00			
		7	50	50				21.0	20.0	21.0	18.0	19.0	1.20			
		8	50	50				150.0	145.0	148.0	150.0	150.0	2.00			
C35	2	7	50	50	16.0	45.0	1000	21.0	22.0	20.0	19.0	20.0	1.20	1.0	10.0	12.0
		8	40	40				151.0	150.0	148.0	153.0	150.0	2.00			
		9	4	4				5.5	4.5	5.0	5.0	4.0	0.10			
		10	4	4				1.1	1.0	0.9	1.2	1.0	0.01			

Table 5.17: Contracts (c), contract lengths (CL_c yr), materials (m), contract capacities (q^U_{mct} 10^5 ton) for period t, total capacities (Q^U_{mc} 10^5 ton), dollar commitment (DL_{cr} k\$), price (p_{mct} \$/ton), logistics cost (LC_{mcst} \$/ton), penalty (π_c %) and discounts (d_{cr} %) for TDC-B (C36-C40) contracts for Example 2

c	CL_c (yr)	m	q^U_{mct} (10^5 ton)	Q^U_{mc} (10^5 ton)	DL_{cr} (10^3\$) $r=1$	$r=2$	$r=3$	p_{mct} (\$/ton) $t=1$-5					LC_{mcst}	Π_c (%)	d_{cr} (%) $r=2$	$r=3$
C36	3	1	42	42	15	34	300000			21.0			1.20	0.010	0.10	0.15
		5	42	42				100.0	101.0	100.0	99.0	100.0	1.20			
		6	50	50				10.0	9.0	9.0	10.0	10.0	1.00			
		7	50	50				20.0	21.0	20.0	19.0	20.0	1.20			
C37	2	2	40	40	19	33	2000	20.0	19.0	21.0	19.0	18.0	1.00	0.020	0.06	0.10
		8	50	50				152.0	150.0	148.0	152.0	150.0	2.00			
		9	5	5				5.0	4.0	5.5	5.0	5.0	0.10			
		10	5	5				1.0	1.1	0.9	1.1	1.2	0.01			
C38	3	1	40	40	20	29	3000			21.0			0.80	0.030	0.08	0.12
		2	40	40				20.0	19.0	21.0	19.0	18.0	0.80			
		3	45	45				50.0	49.0	51.0	49.0	48.0	1.80			
		4	4	4				78.0	80.0	81.0	76.0	76.0	0.02			
		5	50	50				100.0	101.0	100.0	99.0	100.0	1.20			
C39	4	6	50	50	21	39	1000	10.0	9.0	9.0	10.0	10.0	1.00	0.025	0.09	0.13
		7	50	50				20.0	21.0	20.0	19.0	20.0	1.20			
		8	50	50				151.0	150.0	148.0	152.0	150.0	2.00			
		9	5	5				5.5	4.5	5.0	5.0	4.0	0.10			
		10	5	5				1.0	1.1	0.9	1.1	1.2	0.01			
C40	4	1	50	50	20	30	5000			21.0			0.80	0.005	0.02	0.04
		2	40	40				20.0	19.0	21.0	19.0	18.0	0.80			
		6	50	50				10.0	9.0	9.0	10.0	10.0	1.00			
		7	50	50				20.0	21.0	20.0	19.0	20.0	1.20			

Table 5.18: Contracts (c), contract lengths (CL_c yr), materials (m), contract capacities (q^U_{mct} 10^5 ton) for period t, total capacities (Q^U_{mc} 10^5 ton), price (p_{mct} \$/ton) and logistics cost (LC_{mcst} \$/ton)) for PDC-FB (C41-C46) contracts for Example 2

c	CL_c	m	q^U_{mct}	Q^U_{mc}	p_{mc1} to p_{mc5}					LC_{mcst}
C41	2	1	45.0	45.0	24.0	23.0	21.0	22.0	22.0	1.20
		2	45.0	45.0	19.0	19.0	21.0	19.0	18.0	1.30
		3	40.0	40.0	50.0	49.0	51.0	49.0	48.0	1.20
		4	5.0	5.0	78.0	80.0	81.0	79.0	76.0	0.03
		5	50.0	50.0	100.0	101.0	100.0	99.0	100.0	1.20
C42	3	6	50.0	50.0	11.0	9.0	10.0	10.0	10.0	1.00
		7	55.0	55.0	20.0	21.0	21.0	19.0	20.0	1.20
		8	55.0	55.0	151.0	150.0	145.0	152.0	150.0	2.00
		9	5.0	5.0	5.5	4.5	4.5	5.0	4.0	0.10
		10	5.0	5.0	1.0	1.1	0.9	1.1	1.2	0.01
C43	5	1	50.0	50.0	25.0	23.0	25.0	22.0	22.0	1.20
		2	40.0	40.0	18.0	19.0	20.0	19.0	18.0	1.30
		3	40.0	40.0	51.0	49.0	48.0	49.0	48.0	1.20
		4	5.0	5.0	80.0	80.0	81.0	79.0	76.0	0.03
C44	4	5	50.0	50.0	99.0	100.0	100.0	99.0	100.0	1.20
		6	50.0	50.0	11.0	9.0	11.0	11.0	10.0	1.00
		7	50.0	50.0	20.0	21.0	21.0	21.0	20.0	1.20
		8	50.0	50.0	151.0	150.0	145.0	152.0	150.0	2.00
C45	3	9	5.0	5.0	5.5	4.5	5.5	4.0	3.5	0.10
		10	5.0	5.0	1.0	1.1	0.8	0.9	1.5	0.01
C46	2	4	5.0	5.0	81.0	78.0	78.0	79.0	76.0	0.03
		5	50.0	50.0	99.0	100.0	101.0	98.0	98.0	1.20
		6	50.0	50.0	11.0	9.0	9.0	10.0	11.0	1.00
		7	50.0	50.0	20.0	21.0	21.0	21.0	20.0	1.20

Table 5.19: Contracts (c), contract lengths (CL_c yr), materials (m), contract capacities (q^U_{mct} 10^5 ton) for period t, total capacities (Q^U_{mc} 10^5 ton), price (p_{mct} \$/ton) and logistics cost (LC_{mcst} \$/ton)) for spot market (C47) for Example 2

c	CL_c	m	q^U_{mct}	Q^U_{mc}	p_{mc1} to p_{mc5}					LC_{mcst}
C47	1	1	55.0	55.0	25.0	26.0	24.0	20.0	23.0	1.10
	2	1	45.0	45.0	20.0	19.0	18.0	17.0	20.0	0.98
	3	1	40.0	40.0	50.0	51.0	50.0	48.0	50.0	1.10
	4	1	5.5	5.5	78.0	75.0	100.0	101.0	78.0	0.01
	5	1	50.0	50.0	100.0	98.0	98.0	99.0	100.0	1.90
	6	1	50.0	50.0	10.0	9.0	10.0	9.5	10.0	0.98
	7	1	55.0	55.0	20.0	21.0	19.0	18.0	20.0	1.50
	8	1	55.0	55.0	150.0	151.0	145.0	150.0	150.0	2.98
	9	1	5.5	5.5	5.0	5.0	6.0	5.5	5.0	0.10
	10	1	5.5	5.5	1.0	1.1	1.0	1.0	1.0	0.01

Table 5.20: Dollar commitment (DL_{crt}), penalty (π_{ct}) and fractional discounts (d_{crt}) for PDC-FB contracts for Example 2

c	DL_{c11} to DL_{c15} (k$)					DL_{c21} to DL_{c25} (k$)					DL_{c31} to DL_{c35} (k$)				
C41	0.50	0.60	0.70	0.80	0.90	2.00	2.60	3.00	3.50	3.90	7.0	4.5	7.0	5.0	7.0
C42	0.55	0.65	0.45	0.55	0.55	4.00 (t=1-5)					100.0 (t=1-5)				
C43	0.40 (t=1-5)					1.20	4.20	3.20	3.20	2.20	1200.0	2200.0	2200.0	5200.0	4200.0
C44	0.40	0.40	0.45	0.50	0.50	1.50	1.30	1.20	1.20	1.10	120.0	120.0	120.0	1200.0	1200.0
C45	0.20	0.20	0.25	0.25	0.3	1.50 (t=1-5)					1200.0	1000.0	1000.0	1200.0	1200.0
C46	0.40	0.45	0.40	0.45	0.5	1.50 (t=1-5)					100.0	100.0	1000.0	100.0	100.0
	π_{c1} to π_{c5} (%)					d_{c21} to d_{c25} (%)					d_{c31} to d_{c35} (%)				
C41	4.00	1.00	2.00	1.00	2.00	2.00	1.00	3.00	2.00	4.00	3.00	4.00	5.00	6.00	5.00
C42	3.00	3.00	0.10	0.20	0.20	4.00	7.00	1.00	4.00	1.00	7.00	8.00	5.00	4.00	2.00
C43	0.10 (t=1-5)					0.10 (t=1-5)					1.00 (t=1-5)				
C44	4.00 (t=1-5)					1.00 (t=1-5)					7.00 (t=1-5)				
C45	0.10 (t=1-5)					0.10 (t=1-5)					0.20 (t=1-5)				
C46	2.00 (t=1-5)					1.00 (t=1-5)					2.00 (t=1-5)				

Table 5.21: Quantity (kton) of materials bought from different contracts in Example 2

	$m=1$					$m=3$					$m=5$						$m=7$					$m=9$				
	$t=1$	$t=2$	$t=3$	$t=4$	$t=5$	$t=1$	$t=2$	$t=3$	$t=4$	$t=5$	$t=1$	$t=1$	$t=2$	$t=3$	$t=4$	$t=5$	$t=1$	$t=2$	$t=3$	$t=4$	$t=5$	$t=1$	$t=2$	$t=3$	$t=4$	$t=5$
s	C36	C36	C31	C31	C31	C38	C38	C38	C33	C33	C34	C36	C34	C31	C33	C31	C36	C34	C31	C31	C31	spot	C42	C42	C45	C45
1	200	400	80	140	150	100	0	0	100	100	0	0	100	100	200	100	100	200	200	0	0	0	15	25	0	0
2	100	100	300	100	100	110	100	95	50	50	0	100	100	95	55	100	200	200	0	100	0	10	25	10	0	0
3	200	100	80	90	100	0	100	100	200	100	0	85	100	85	300	400	100	100	100	0	0	20	10	20	10	0
4	100	200	0	0	100	0	100	100	0	100	0	10	10	100	60	100	200	100	100	200	0	15	20	0	10	10
5	90	0	0	90	100	0	0	0	300	200	100	0	95	75	75	95	100	200	100	0	0	0	10	10	5	10
6	100	100	0	0	0	100	200	95	0	0	0	85	85	100	0	0	95	95	100	110	100	19	19	0	10	10
7	0	0	100	100	75	0	100	200	100	0	0	100	0	0	0	400	110	110	200	0	200	10	10	25	10	10
8	100	110	210	200	100	100	200	0	50	50	0	90	95	95	100	100	200	200	100	110	195	12	12	20	10	5
9	80	95	110	100	100	85	80	75	100	100	100	0	100	0	0	0	200	100	200	195	100	10	15	12	29	0
10	85	0	75	110	85	100	0	0	100	0	0	0	0	200	200	95	0	80	45	55	100	0	18	15	5	10
	$m=2$					$m=4$					$m=6$						$m=8$					$m=10$				
	C38	C38	spot	C32	C32	C38	C38	C38	C33	C33		C36	C34	C36	C33	C33	C34	C34	C34	C32	C32	spot	C42	C45	C45	spot
1	100	100	100	130	100	9	9	8	10	10		0	0	100	100	200	200	100	120	100	0	10	5	15	0	0
2	90	90	190	90	90	11	10	11	0	0		200	100	195	0	200	120	250	0	100	0	0	15	0	10	10
3	100	90	80	75	105	0	0	30	0	10		0	195	100	100	195	100	100	0	0	120	10	0	10	10	0
4	0	0	100	100	75	20	6	10	20	10		195	100	100	195	100	100	150	120	120	0	5	10	5	15	0
5	0	0	75	100	110	10	0	10	20	20		95	110	0	0	0	100	200	100	0	0	6	10	15	15	0
6	0	100	200	100	200	0	0	10	20	0		100	110	0	110	100	95	95	190	90	0	25	19	10	30	0
7	100	110	95	0	0	20	10	0	0	0		195	0	100	110	110	100	100	100	0	200	9	20	15	15	10
8	0	100	110	200	0	29	29	19	20	0		100	110	100	110	100	200	200	0	100	295	20	15	15	20	0
9	0	0	100	0	0	20	0	0	20	20		0	110	0	100	110	100	150	100	295	100	20	5	20	19	0
10	100	110	100	85	100	19	19	20	0	0		110	100	110	100	0	0	0	245	155	100	10	8	15	35	0

CHAPTER 6. MODEL EXTENSIONS FOR THE GLOBAL SUPPLY

We made two major assumptions in our models of chapter 5. For TQC contracts, we assumed that prices did not vary with time, which is not realistic. For instance, the price of crude oil is very volatile even on a daily basis and it strongly influences the price of petrochemical feed stocks. Hence, the fluctuation in the prices of materials necessitates that we relax this assumption. For PQC/PDC contracts, we assumed the commitment to be for every single period. Again, this assumption is not realistic, as contracts may have different commitment periods. For instance, a supplier offers two PQC contracts, C1 and C2. C1 is a 3-year contract with a minimum commitment of 100 kton and C2 is a 4-year contract with a minimum commitment of 150 kton. It is not necessary that the commitment duration is a single period or 1 year for both C1 and C2. It is possible that C1 has a commitment period of 6 months and C2 has 1 year. We now describe how our basic model can be modified to relax these two assumptions.

6.1 Time-Varying Prices

In our basic model for TQC contracts, prices vary with price-tier, but not with time. For each price-tier r, we defined a purchase range [$QL_{mc(r-1)}$, QL_{mcr}]. To compute the cost, we found the tier r in which the total purchase quantity for that contract falls. We multiplied that total quantity by the price in that tier to get the purchase cost for bulk discounts. For unit discounts, we computed the quantity purchased in each tier range and multiplied that by the price in that tier. Now, we consider the price to vary with tier as well as time. This poses a challenge, because we must now keep track of the period in which a quantity is purchased and the price-tier in which that purchase falls.

For bulk discounts, we can find the tier r in which the total purchase falls. This will determine the price tier that we should use for computing cost in all periods. Thus, the tier would remain constant, but the corresponding price will vary with period. This makes the purchase cost a non-linear function.

For unit discounts, we can find the quantity purchased in each tier r during t. However, this is not straightforward, as no direct relation exists between price tier r and period t. For instance, consider a contract C1 for a material m1, which stipulates three price-tiers (R = 3) having tier ranges [0, 100], [100, 250], and [250, 350] kton. If the MNC buys 120 kton during the first period and 180 kton during the second, then the quantities purchased in the first and second tiers during the first year are 100 kton, and 20 kton respectively, and those in the second and third tiers during the second year are 130 kon and 50 kton. Thus, the quantities purchased in the first tier for the second and subsequent years and those in the second tier for the third and subsequent years are all zero. Thus, in contrast to bulk discounts, the tier changes with time. This makes it imperative for us to keep track of the cumulative purchase along time and as the purchase quantity crosses over from one tier to the next, we must change the price accordingly. This is not all; however, as we must also find the tier in which the total purchase falls. This is to account for the situation, where the company fails to meet the minimum purchase commitment and may face a penalty due to unfulfilled commitment.

We now describe how the constraints for each contract type can be modified for time-varying prices. We consider the TQC contracts with unit discounts first.

<u>TQC-FU: TQC contracts with flexibility and multi-tier unit discounts</u>

We define p_{mcrt} as the unit price of material m under contract c in price-tier r during period t. As mentioned earlier, we must keep track of the cumulative purchase along time. Thus, we define q'_{mct} as the cumulative quantity of material *m* that the MNC buys under contract *c* up to and including period *t*. In other words,

$$q'_{mct} = \sum_{t'=1}^{t' \le t} q_{mct'} \tag{6.1}$$

To compute the purchase cost over time, we need one more binary variable that identifies the tier *r* in which q'_{mct} falls. Hence,

$$\alpha_{mcrt} = \begin{cases} 1 & \text{if } QL_{mc(r-1)} \le q'_{mct} \le QL_{mcr} \\ 0 & \text{otherwise} \end{cases}$$

$$q'_{mct} = \sum_{r=1}^{R_{mc}} (QL_{mc(r-1)}\alpha_{mcrt} + \Delta Q'_{mct}) \tag{6.2a}$$

$$\Delta Q'_{mct} \le \sum_{r} \alpha_{mcrt}[QL_{mcr} - QL_{mc(r-1)}] \tag{6.2b}$$

Note that α_{mcrT} (where planning horizon comprises of *T* periods) identifies the tier in which Q_{mc} falls. If the contract is selected, then the cumulative purchase up to period *t* must fall in one of the price-tiers. Hence,

$$\sum_{r} \alpha_{mcrt} = z_c \tag{6.3}$$

If q'_{mct} is in tier *r*, then the quantity purchased in tiers *r*' > *r* during period *t* must be zero. Also, the quantities purchased in tiers *r*″ < *r* during a period *t*' > *t* must also be zero.

$$\Delta QQ_{mcr't} \le (z_c - \alpha_{mcrt}) * (QL_{mcr'} - QL_{mc(r'-1)}) \qquad r' \ge (r+1) \tag{6.4a}$$

$$\Delta QQ_{mcr''t'} \le (z_c - \alpha_{mcrt}) * (QL_{mcr''} - QL_{mc(r''-1)}) \; r'' \le (r+1),\ t' \ge (t+1) \tag{6.4b}$$

Where, ΔQQ_{mcrt} is the quantity of material *m* that the MNC buys under contract *c* in tier *r* during period *t*. If q'_{mct} for the planning horizon is in tier *r* (*t* = T), then the purchase in tiers *r*' < *r* must be equal to purchase range of tier *r*'. Hence,

$$\sum_{t} \Delta QQ_{mcr't} \ge \alpha_{mcrT}(QL_{mcr'} - QL_{mc(r'-1)}) \qquad r' \le (r-1) \tag{6.5a}$$

$$\sum_t \Delta QQ_{mcrt} \le (QL_{mcr} - QL_{mc(r-1)}) \tag{6.5b}$$

Also, quantity purchased during *t* must be equal to sum of quantity purchased under all tiers during *t*.

$$q_{mct} = \sum_r \Delta QQ_{mcrt} \tag{6.6a}$$

Now, we define another positive variable LQ_{mc} as the amount by which q'_{mcT} (where planning horizon comprises of *T* periods) falls short of QL_{mc1}.

$$LQ_{mc} \ge QL_{mc1}\alpha_{mc1T} - q'_{mcT} \tag{6.6b}$$

With this, the purchase cost under contract *c* is given by,

$$PC_{mc} = \pi_{mc} LQ_{mc} + \sum_{r,t} \Delta QQ_{mcrt} p_{mcrt} \tag{6.7}$$

<u>TQC-U: TQC contracts with multi-tier unit discounts but no flexibility</u>

As in TQC-B contracts, the purchase cost can be computed as,

$$PC_{mc} = p_{mc11} QL_{mc1} z_c + \sum_{r\ge 2, t=1}^{R_{mc}, T} p_{mcrt} \Delta QQ_{mcrt} \tag{6.8}$$

<u>TQC-FB: TQC contracts with flexibility and multi-tier bulk discounts</u>

They offer multi-tier bulk discount at various level of purchase. Eqs. 5.6, 5.7, and 5.8 will hold.

$$\sum_{r=1}^{R_{mc}} \beta_{mcr} = z_c \tag{6.9}$$

$$Q_{mc} = \sum_{r=1}^{R_{mc}} (QL_{mc(r-1)}\beta_{mcr} + \Delta Q_{mcr}) \tag{6.10}$$

$$\Delta Q_{mcr} \le \beta_{mcr}[QL_{mcr} - QL_{mc(r-1)}] \tag{6.11}$$

Total purchase cost under contract *c* of type TQC-FB is given by,

$$PC_{mc} = \pi_{mc}(QL_{mc1}\beta_{mc1} - \Delta Q_{mc1}) + \sum_{r=1, t=1}^{R_{mc}, T} q_{mct}\beta_{mcr} p_{mcrt}$$

The above equation is non-linear due to the second term, which involves one continuous and one binary variable. We linearize this exactly by introducing a variable as follows,

$$\gamma_{mcrt} = q_{mct}\beta_{mcr}$$

Summing the above over price-tier *r* and period *t*, we get these two equations,

$$\sum_{r=1}^{R_c}\gamma_{mcrt} \le q_{mct} \tag{6.12a}$$

$$\sum_{t}\gamma_{mcrt} \le Q_{mc}^{U}\beta_{mcr} \tag{6.12b}$$

We need one additional equation, which is as follows,

$$\gamma_{mcrt} \ge q_{mct} - Q_{mc}^{U}(1-\beta_{mcr}) \tag{6.13}$$

Hence, the total purchase cost is,

$$PC_{mc} = \pi_{mc}(QL_{mc1}\beta_{mc1} - \Delta Q_{mc1}) + \sum_{r=1,t=1}^{R_{mc},T}\gamma_{mcrt}\,p_{mcrt} \tag{6.14}$$

<u>TQC-B: TQC contracts with multi-tier bulk discounts but no flexibility</u>

Unlike TQC-FB contracts, these contracts allow no flexibility. The MNC pays for the minimum committed purchase, even if the purchase is less than the minimum commitment. These contracts allow multi-tier discounts. The total purchase cost is given by,

$$PC_{mc} = p_{mc11}QL_{mc1}\beta_{mc1} + \sum_{r\ge 2,t=1}^{R_{mc},T} p_{mcrt}\beta_{mcr}q_{mct}$$

$$PC_{mc} = p_{mc11}QL_{mc1}\beta_{mc1} + \sum_{r\ge 2,t=1}^{R_{mc},T} p_{mcrt}\gamma_{mcrt} \tag{6.15}$$

6.2 Commitment over Multiple Periods

The difference from TQC/TDC contracts is that the commitment period (τ) acts like a period (t) of TQC/TDC. We find the number of commitment periods (n_c) by dividing the contract length (CL_c) with the duration of commitment periods (CP_c)

$$n_c = CL_c / CP_c \tag{6.16}$$

Now, we define three binary variables

$$XP_{c\tau t} = \begin{cases} 1 & \text{if commitment } \tau \text{ of contract } c \text{ is in effect during period } t \\ 0 & \text{otherwise} \end{cases}$$

$$XF_{c\tau t} = \begin{cases} 1 & \text{if commitment } \tau \text{ of contract } c \text{ begins at the start of period } t \\ 0 & \text{otherwise} \end{cases}$$

$$XL_{c\tau t} = \begin{cases} 1 & \text{if commitment } \tau \text{ of contract } c \text{ ends at the end of period } t \\ 0 & \text{otherwise} \end{cases}$$

Based on n_c, we can identify the commitment period (τ) that can be possible for a contract c. Thus, we define $XP_{c\tau t}$, $XF_{c\tau t}$, and $XL_{c\tau t}$ only for (c, τ) $\in CK$ = {(c, τ) | contract c may have τ commitment period}.

$$XP_{c\tau t} = XP_{c\tau(t-1)} + XF_{c\tau t} - XL_{c\tau(t-1)} \qquad (c,\ \tau) \in CK \tag{6.17}$$

$$XP_{c\tau t} \geq XL_{c\tau t} \qquad (c,\ \tau) \in CK \tag{6.18}$$

If the contract c is selected then each commitment period in c begins and ends only once, so

$$\sum_t XF_{c\tau t} = \sum_t XL_{c\tau t} = z_c \qquad (c,\ \tau) \in CK \tag{6.19a, b}$$

Whereas, there can be multiple periods for the commitment τ to be in effect.

$$\sum_t XP_{c\tau t} = z_c * CP_c \qquad (c,\ \tau) \in CK \tag{6.20}$$

Equations 6.17, 6.18, 6.19a, 6.19b, and 6.20 together ensure that $XF_{c\tau t}$, and $XL_{c\tau t}$ will be binary automatically, when $XP_{c\tau t}$ are so. Therefore, $XF_{c\tau t}$, and $XL_{c\tau t}$ are 0-1 continuous variables. Using these variables, the time $TF_{c\tau}$ at which τ begins and the time $TL_{c\tau}$ at which it ends are

$$TF_{c\tau} = TL_{c\tau} - CP_c + 1 \qquad (c,\ \tau) \in CK \tag{6.21}$$

$$TL_{c\tau} = \sum_t tXL_{c\tau t} \qquad (c,\ \tau) \in CK \tag{6.22}$$

To ensure that commitment $\tau + 1$ begins only after the commitment τ ends, we have

$$TF_{c(\tau+1)} = TL_{c\tau} + 1 \qquad (c,\ \tau) \in CK \tag{6.23}$$

We define $qq_{mc\tau}$ ($m \in \boldsymbol{M}_c$, $1 \le \tau \le N_c$) as the quantity of material m that the MNC buys under contract c during a commitment period τ

$$qq_{mc\tau} = \sum_t q_{mct} XP_{c\tau t}$$

Note that the above equation is non-linear. It involves one continuous and one binary variable. We linearize this exactly by introducing a variable as follows,

$$\theta_{mc\tau t} = q_{mct} XP_{c\tau t}$$

Summing the above over period t, material m, and commitment τ, we get these equations,

$$\sum_t \theta_{mc\tau t} \le \sum_t q_{mct} \qquad (c,\ \tau) \in CK \tag{6.24a}$$

$$\sum_m \theta_{mc\tau t} \le XP_{c\tau t} \sum_m Q^U_{mc} \qquad (c,\ \tau) \in CK \tag{6.24b}$$

$$\sum_\tau \theta_{mc\tau t} \le q_{mct} \qquad (c,\ \tau) \in CK \tag{6.24c}$$

Hence,

$$qq_{mc\tau} = \sum_t \theta_{mc\tau t} \qquad (c,\ \tau) \in CK \tag{6.25}$$

We need one additional equation, which is as follows,

$$\theta_{mc\tau t} \ge q_{mct} - Q^U_{mc}(1 - XP_{c\tau t}) \qquad (c,\ \tau) \in CK \tag{6.26}$$

Also, quantity purchase via contract c is equal to quantity purchase through all possible commitment period in contract c. Hence,

$$\sum_t q_{mct} = \sum_\tau qq_{mc\tau} \qquad (c,\ \tau) \in CK \qquad (6.27)$$

Binary variables and equations analogous to those for TQC contracts are as follows.

$$\sigma_{mcr\tau} = \begin{cases} 1 & \text{if } QL'_{mc(r-1)\tau} \le qq_{mc\tau} \le QL'_{mcr\tau} \\ 0 & \text{otherwise} \end{cases} \qquad m \in \boldsymbol{M}_c,\ r = 1, 2, \ldots, R_{mc}$$

$$\sum_{r=1}^{R_{mc}} \sigma_{mcr\tau} = z_c \qquad (c,\ \tau) \in CK \qquad (6.28)$$

$$qq_{mc\tau} = \sum_{r=1}^{R_{mc}} (QL'_{mc(r-1)\tau}\sigma_{mcr\tau} + \Delta qq'_{mcr\tau}) \qquad (c,\ \tau) \in CK \qquad (6.29)$$

$$\Delta qq'_{mcr\tau} \le \sigma_{mcr\tau}[QL'_{mcr\tau} - QL'_{mc(r-1)\tau}] \qquad (c,\ \tau) \in CK \qquad (6.30)$$

Now, we derive the equations for the various PQC contracts as follows. We assume the following

1. Prices vary with commitment period τ

PQC-FB Contracts:

$$PC_{mc\tau} = \pi_{mc\tau}(QL'_{mc1\tau}\sigma_{mc1\tau} - \Delta qq'_{mc1\tau}) + \sum_{r=1}^{R_{mc}} p_{mcr\tau}(QL'_{mc(r-1)\tau}\sigma_{mcr\tau} + \Delta qq'_{mcr\tau}) \qquad (6.31)$$

PQC-B Contracts

$$PC_{mc\tau} = QL'_{mc1\tau}p_{mc1\tau}\sigma_{mc1\tau} + \sum_{r\ge 2}^{R_{mc}} p_{mcr\tau}(QL'_{mc(r-1)\tau}\sigma_{mcr\tau} + \Delta qq'_{mcr\tau}) \qquad (6.32)$$

PQC-FU Contracts:

$$PC_{mc\tau} = \left\{ \begin{aligned} &\pi_{mc\tau}(QL'_{mc1\tau}\sigma_{mc1\tau} - \Delta qq'_{mc1\tau}) + \\ &\sum_{r=1}^{R_{mc}} \left(\Delta qq'_{mcr\tau}p_{mcr\tau} + \sigma_{mcr\tau} \sum_{\rho=1}^{\rho\le(r-1)} p_{mc\rho\tau}(QL'_{mc\rho\tau} - QL'_{mc(\rho-1)\tau}) \right) \end{aligned} \right\} \qquad (6.33)$$

PQC-U Contracts:

$$PC_{mc\tau} = QL'_{mc1\tau} p_{mc1\tau} z_c + \sum_{r \geq 2}^{R_{mc}} \left(\Delta qq'_{mcr\tau} p_{mcr\tau} + \sigma_{mcr\tau} \sum_{\rho \geq 2}^{\rho \leq (r-1)} p_{mc\rho\tau} (QL'_{mc\rho\tau} - QL'_{mc(\rho-1)\tau}) \right) \quad (6.34)$$

6.3 Example

We consider Example 1 of chapter 5. In this example, the MNC has three plant sites (s = 1, 2, 3) that require two materials (m = 1, 2). The planning horizon involves five periods (t = 1, 2, 3, 4, 5 years; T = 5). The central procurement department is evaluating nineteen supply contracts: three TQC-FLB (C1, C2, C3), three TQC-FB (C4, C5, C6), three TQC-U (C7, C8, C9), three PQC-FU (C10, C11, C12), three PQC-B (C13, C14, C15), two TDC-FB (C16, C17), and two PDC-U (C18, C19). We consider three cases. We consider two cases. In Case 1, price changes with tier as well as time for TQC contracts and in Case 2, commitment is over multiple periods for PQC contracts. We solve our model using CPLEX v10.0.1 in GAMS 22.2 (Brooke et al., 2005) on a 3.00 GHz Pentium® PC with 2 GB of RAM.

6.3.1 Case 1

We consider two scenarios for this case. Scenario 1 considers only TQC-FB contracts along with the spot market while scenario 2 considers only TQC-U contracts along with the spot market. Note that these two scenarios are Case 3, and Case 4 of Example 1 of Chapter 5. The difference from Chapter 5 is that here price changes with tier as well as time in contrast to Chapter 5 where price changes with tier only. Data of Tables 5.2 to 5.4 are applicable for this example except the price data. The price for this Example is listed in Table 6.1. Note that the average p_{mcrt} (price for material m under contract c in tier r during period t) is same as p_{mcr} (price for material m under contract c in tier r). For instance, consider a contract of TQC-FB having three price tier for a material and price in first tier (p_{mc1}) is 27 \$/ton. Now, price is changing with tier as well as time so for the planning horizon of five years there are five prices (p_{mcrt}) for tier 1. The prices for each time are 27, 25, 27, 29, and 27 $/ton. The average of these prices are 27 $/ton which is the price in tier 1.

<u>*Scenario 1*</u>

Table 6.2 gives the model and solution statistics for all the scenarios. For scenario 1, the optimal cost is 72,157 k$ in contrast to the 71,968 k$ (Case 3 of Example 1 of Chapter 5). This is due to the price variation with time. The (new) optimal plan includes C5, C6, and spot purchases at various times which are same as that of the original optimal plan (Case 3 of Example 1 of Chapter 5). Table 6.3 shows the profiles of material purchases under different contracts. Material m = 1 is purchased same as that of original optimal plan. However, material m = 2 is purchased entirely under contracts, in contrast to the original optimal plan where m = 2 is purchased from the spot market in the first and last year. This is due to the higher spot prices in year 1 (20$/ton) and year 5 (22$/ton) in comparison to the price offered by C6 in tier 2 (19$/ton) in the first year and C5 in tier 2 (18$/ton) during the fifth year. The average price offered by C5 in tier 2 is 19$/ton and the average price offered by C6 in tier 2 is 20$/ton. The average price offered by C5 and C6 during the second tier is lower than the spot prices in year 1 and year 5, hence in the original optimal plan, (where average price is used) m = 2 is purchased from spot market in year 1 and year 5. Now, when price vary with time spot prices are higher hence C5 and C6 are used.

Just to compare the cost if the purchases are made according to the original optimal plan. The cost for m = 1 is same in the original and new optimal plan. However, for m = 2, purchase is made from C5, C6, and spot market. The purchase cost in the first year is 210*19+80*20 = 5,590 k$, in the second year is 280*18 = 5,040 k$, in the third year is 370*19 = 7,030 k$, in the fourth year is 350*19 = 6,650 k$, and in the fifth year is (105+90+45)*22= 5,280 k$. Inventory holding cost is 550 k$/ton. Total purchase cost plus inventory holding cost for *m* = 2, if purchases are made according to the original plan, is 30,140 k$. However, from the new optimal plan the purchase cost in the first year is 290*19 = 5,510 k$, in the second year is 5,600 k$, in the third year is 370*20 = 7,400 k$, in the fourth year is 295*20 = 5900 k$, and in the fifth year is 295*18 = 5,310 k$. The inventory holding cost is zero. Total purchase cost plus inventory cost from the new optimal plan is 29,720 k$ which is 1.4% lesser than the original optimal plan. Clearly, following the original optimal plan is significantly worse than the optimal when price varies with time as well as tier.

Scenario 2

The optimal cost is 73,216.20 k$ as compared to the cost of 74,166.20 k$ from the original optimal plan (Case 4 of Example 1 of Chapter 5). The optimal (new) contracts are same as that of the original optimal plan. However, the quantities purchased from spot market and contracts are different from the original optimal plan (Refer Table 6.3). Material *m* = 1 during the second year (600 kton) is purchased entirely from the C7. Note that first 500 kton falls in the first tier and next 100 kton falls in the second tier as purchase range are [0, 500], [500, 1000], and [1000, 2300] kton. The price applicable for 500 kton is the first tier price during the second year (24 k$/kton) and for 100 kton is the second tier price during the second year (23 k$/kton). Hence, the cost is 500*24+100*23 = 14,300 k$. However, in the original optimal plan the purchase for *m* = 1 during the second year is partially from spot market (100 kton) and partially from C7 (500 k$). The average price for *m* = 1 in the first tier during all years is 26 k$/kton and spot price during the second year is 25 k$/ton. The cost (original optimal plan) during the second year for *m* = 1 is 500*26+100*25 = 15,500 k$ which is 1200 k$ more than the new optimal plan. This is due to the price varying with time as well as tier.

6.3.2 Case 2

Here we consider PQC-B contracts along with the spot market. Note that this is Case 6 of Example 1 of Chapter 5. The difference is that now commitment is for multiple of periods. To compare with Example 1 of Chapter 5, if the commitment duration is 2 years then the minimum commitment to be honored during this commitment period is twice that of the commitment during a single period. For instance, consider a contract C1 for material m1 of contract length 4 years, which stipulates a minimum commitment of 50 kton during each period. Now, commitment duration may not be a single period and hence, commitment duration for C1 is two years, which means that C1 has two commitment periods and the minimum commitment for these periods are 50*2 = 100 kton. Now, the price is changing with commitment period as well as tier. Data of Tables 5.2 to 5.4 are applicable for this example except the price and quantity commitment. The price, quantity commitment, and commitment period are listed in Table 6.4.

The optimal contracts are same as that of the original optimal plan (Case 6 of Example 1). However, the cost is 71,649 k$ in comparison to 72,157 k$ as compared to the original plan. Now, material $m = 1$ is purchased entirely from the spot market in the first year (Cost: 500*19 = 9500 k$) as compared to the combination of C14 and spot market (80*25+420*19 = 9980 k$) in the original plan. C14 is selected as it offers lower price in the second year (23 k$/kton) in the third price tier. However, contract length of C14 is two years so minimum commitment (80 kton) is purchased from C14 during the first year although the price offered by C14 is high (25 k$/kton) during the first year. Now, the price varies with the commitment period and commitment duration of C14 is two years. C14 is selected during the first year but all purchases are done during the second year as minimum commitment has to be honored for every commitment period instead of time period. Thus, the optimal purchase is different from the original optimal plan. It is clear that if the procurement department had not revised the plan, the optimal strategy obtained from Example 1 (Case 6) of Chapter 5 would have been suboptimal and would have resulted in higher costs.

6.4 Discussion

We relaxed two major assumptions of Chapter 5, price varies with time as well as price-tier and minimum commitment is honored during successive prefixed sets of periods within the contract duration, which are not realistic. We solved Example 1 of Chapter 5 in presence of the above mentioned extension and compared the optimal solution with the original solution. It is interesting to note that even if the average price during tier and the average commitment during time periods are same but still the original optimal plan is worse than the optimal and the optimal cost reduces significantly.

Our proposed extended deterministic model is fast. This is a desirable feature, because it will need to be solved repeatedly for a real-life stochastic scenario, in which several cost/price parameters will be uncertain. Thus, this MILP model provides a basis for future work involving business uncertainties.

Table 6.1: Prices (p_{mcrt}, \$/ton) for TQC-FB and TQC-U Contracts in Case 1

c	m	p_{mc11} to p_{mc15}					p_{mc21} to p_{mc25}					p_{mc31} to p_{mc35}				
C4	1	27	25	27	29	27	26	24	25	24	26	25	23	24	23	25
C5	2	19	20	21	22	18	18	19	20	20	18	17	18	19	19	17
C6	1	24	25	23	26	24.5	24	25	22	26	23	22	22	21	23	22
	2	21	22	20	20	22	19	20	19	20	22	18	17	17	17	21
C7	1	24	24	26	28	28	23	23	25	27	27	20	20	23	26	26
	2	20	19	18	18	20	19	17	17	17	20	16	15	15	15	19
C8	1	25	23	26	26	25	23	23	25	25	24	21	23	21	22	23
C9	2	22	21	20	19	18	21	18	18	17	16	18	16	16	15	15

Table 6.2: Model and Solution Statistics for Case 1 and 2

Case	Scenario	binary variables	continuous variables	constraints	Cost [× 103 \$]
1	1	27	282	247	72,157.00
	2	75	358	439	73,216.20
2	1	40	314	275	71,649.00

Table 6.3: Quantities (kton) of Materials Bought under Different Contracts in Case 1 and Case 2

case	Scenario	c	t	m=1, s = 1 to 3			m=2, s=1 to 3		
1	1	C5	3		0		100	190	80
			4		0		130	90	75
			5		0		100	90	105
		C6	1	200	100	100	100	90	100
			2	400	100	100	100	90	90
		spot	1	0	0	100		0	
			3	80	300	80		0	
			4	140	100	90		0	
			5	150	100	100		0	
2	1	C13	3		-		100	190	80
			4		-		130	90	75
			5		-		100	90	75
		C14	1	0	0	0		0	
			2	400	100	100		0	
		C15	2		0		100	90	90
		spot	1	200	100	200	100	90	100
			3	80	300	80		0	
			4	140	100	90		0	
			5	150	100	100		0	

case	Scenario	c	t	m=1, s = 1 to 3			m=2, s=1 to 3		
1	2	C7	2	400	100	100	100	90	90
			3		-		100	190	80
		spot	1	200	100	200	100	90	100
			2	0	0	0		-	
			3	80	300	80		-	
			4	140	100	90	130	90	75
			5	150	100	100	100	90	105

Table 6.4: Contracts (c), Contract Lengths (CL_c), Material (m), Commitment Duration (CP_c), Commitment period (τ), quantity commitments ($QL_{mcr\tau}$), and price ($p_{mcr\tau}$) for Case 2

	CL_c		CP_c		$QL_{mcr\tau}$ (10^5 ton)			$p_{mcr\tau}$		
c	(yr)	m	(yr)	τ	r=1	r=2	r=3	r=1	r=2	r=3
C13	3	2	1	1	1.0	2.0	18	21	20	19
				2	1.0	2.0	18	21.5	21	20
				3	1.0	2.0	18	22	21	20
C14	2	1	2	1	1.6	5.0	46	26	25	23
C15	1	2	1	1	1.0	4.0	19	20	19	18

CHAPTER 7. CHEMICAL LOGISTICS

Logistics costs in the chemical and related industries are among the highest in asset-intensive supply chains. This chapter presents a systematic framework for managing chemical logistics in an integrated manner. The objective of this paper is to model the outsourcing of various logistics services in terms of the contracts offered by various 3PLs. The contracts are designed to fulfill partial or full bundles of various logistics needs, tasks, and services, which can be performed at globally distributed sites. We account for product bundling and transport expenses between various sites in bulk or packaged or container forms and to various customers. Our goal is to identify the contracts (hence the providers) and the location of each service, which serve the total needs of a company in an integrated and most cost-effective manner.

We address this problem from the perspective of a chemical company who signs one/multiple contracts with logistics companies. We first develop a powerful framework for representing this complex problem in a comprehensive and general manner, and then use that to develop a multi-period mixed integer linear programming (MILP) formulation. We use several examples to highlight the advantages of the proposed approach.

7.1 Problem Description

The supply chain or network of a chemical MNC comprises S sites (s = 1, 2, 3, …, S) located around the world. We classify these sites (see Figure 7.1) into three categories, production (j), hub (k), and demand (i). Production sites convert raw materials into products in bulk form. Hub sites perform one or more logistics tasks such as packaging, marking, labeling, drumming, etc. on materials in various forms. Demand sites are the customers that require products in specified final forms. When the final form in which a demand site needs a material is different from the bulk form in which a production site produces it, one or more logistics tasks are required to achieve the desired transformation and deliver the final product to the customer. The desired transformation and delivery can be achieved in multiple ways and with the help of multiple logistics suppliers. For instance, consider polyethylene (PE), whose bulk form is a granular powder, but it is delivered to customers as bags of PE powder on pallets. To effect this delivery, one may first transport PE powder to a hub site in bulk form, where it is melted, extruded through a tubular/flat film extruder, and welded and/or cut into bags. The bags are then labeled, marked, and placed on pallets, which are transported to the demand sites in standard containers.

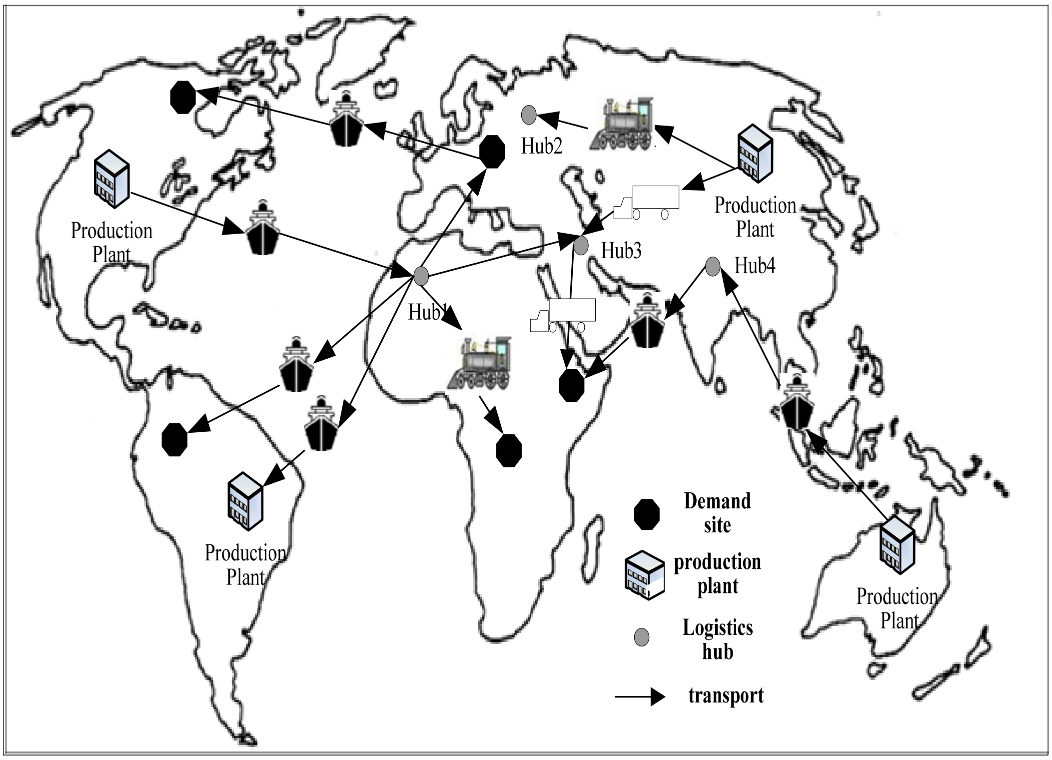

Figure 7.1: Schematic of a logistics network with demand, hub, and production sites

A hub site may perform a range of logistics activities such as warehousing, documentation, final assembly/packaging, inventory management, product and package labeling, track and trace, stock count, order planning and processing, reverse logistics, terminaling and storage (of chemicals), freight consolidation, break-bulk, blending and mixing, drumming, containerization, order management (documentation, customs clearance, etc.), marking, labeling, sampling, packaging, and transport. Note that all logistics tasks except transportation can be done at a single site, whereas transportation needs both an origin and a destination. Hence, we classify these activities/tasks into two categories, transport (u) and non-transport (v). All tasks except transport are one-site tasks belonging to the second category. These tasks process the material in one form to produce the same material in another form. For instance, such a task may take the material in bulk form and drum+label it. To illustrate the alternate ways in which the logistics tasks can be performed for a product, let us consider the following example.

7.1.1 Example 1

Chemical A is produced in Shanghai and is delivered to various demand sites in North America. Tasks such as transport, containerizing, drumming, labeling, and customs clearance are needed to effect this delivery. If it is possible to transport A in three forms, namely bulk, container, or drum, then there exist several options (Figure 7.2) for delivering A.

Option 1: Ship to San Francisco in bulk. Clear customs in San Francisco. Containerize+label at a logistics site in San Francisco. Transport tank containers from San Francisco to various demand sites.

Option 2: Ship to San Francisco in bulk. Clear customs in San Francisco. Drum+label at a logistics site in San Francisco. Transport drums from San Francisco to various demand sites.

Option 3: Ship to Philadelphia in bulk. Clear customs in Philadelphia. Containerize+label at a logistics site in Philadelphia. Transport containers from Philadelphia to various demand sites.

Option 4: Ship to Singapore in bulk. Clear customs in Singapore. Containerize+label at a logistics site in Singapore. Transport tank containers from Singapore to various demand sites, which includes multi-modal transport and customs clearance at appropriate sites.

Option 5: Ship to Bangkok in bulk. Clear customs in Bangkok. Drum+label at a logistics hub site in Bangkok. Transport drum from Bangkok to various demand sites, which includes multi-modal transport and customs clearance at appropriate sites.

Option 6: Ship to Kareemun (Indonesia) in bulk. Clear customs in Kareemun. Containerize+label at a logistics hub site in Kareemun. Transport tank containers from Kareemun to San Francisco. Clear customs in San Francisco. Transport tank containers from San Francisco to various demand sites.

Option 7: One could deliver partial amounts of A via one or more of the above options.

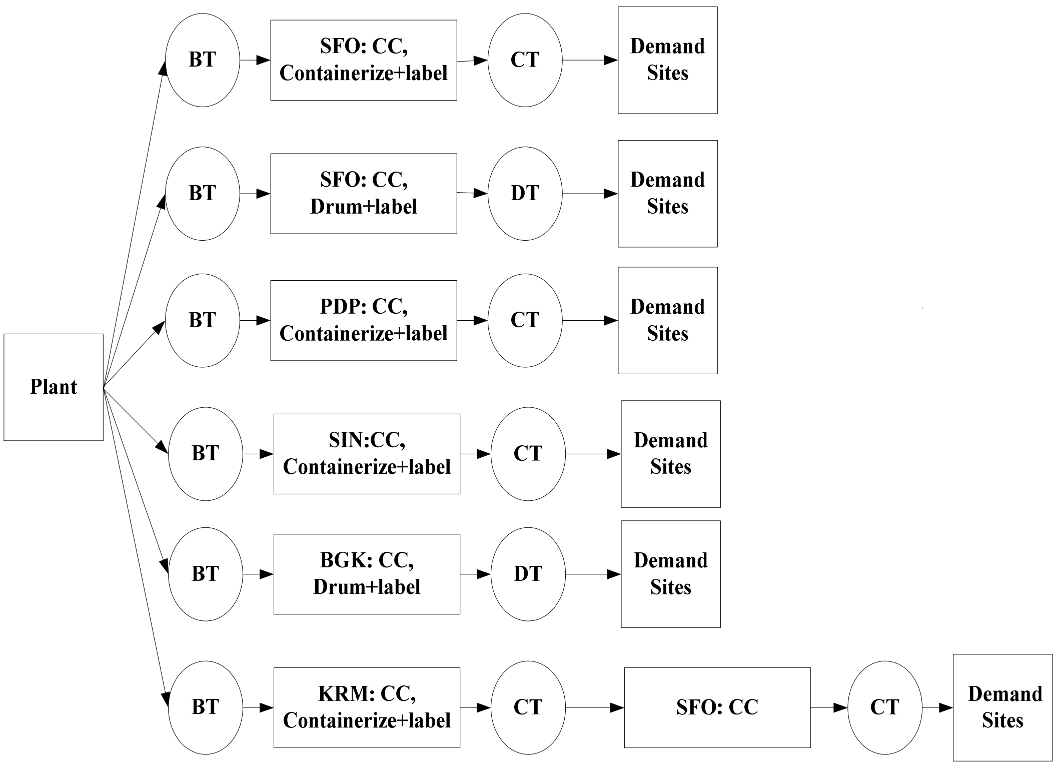

Figure 7.2: Various options for delivering A in Example 1 (BT = bulk transport, CT = container transport, DT = drum transport, CC = clear customs, SFO = San Francisco, PDP = Philadelphia, SIN = Singapore, BGK = Bangkok, KRM = Kareemun)

Obviously, the above are only some of the possible options and it is difficult to know what the optimal mix of options is, as this problem involves the selection of both hub sites and specific tasks that should be done at each hub site. In general, these options could be offered to the company by various third party logistics (3PL) firms in terms of contracts. These contracts may fulfill partial or full bundles of various logistics needs, tasks, and services, which can be performed at different places. Each contract *c* can have the following attributes.

1) Length (CL_c)and fixed cost (FC_c) of contract

2) Non-transport tasks that it offers to perform for various materials at different hub sites

3) Transport tasks for various materials, forms, origins, and destinations

4) Cost structures for all transport and non-transport tasks

5) A contract may offer a multi-tiered pricing structure based on volume discounts.

In Chapter 5, we defined two types of discounts: bulk and unit. A bulk discount applies to the total quantity of (service) purchase, and a unit discount applies to each unit beyond a certain qualifying level. For example, contract C1 offers multi-tier bulk pricing for transporting material A from Singapore to Bangkok. If the amount of material is less than 1000 kton, then the unit transport cost is 200 $/kton. However, if it is between 1001 and 5000 kton, then the unit cost is 170 $/kton for the total amount of material. If C1 offers unit discounts instead of bulk and total amount transported is 1500 kton, then the first 1000 kton are charged at 200 $/kton, and the remaining amount is charged at 170 $/kton. A contract may involve multiple materials and/or multiple tasks. It may provide transportation tasks only, non-transport tasks only, or combinations of transport and non-transport tasks. Some 3PLs may offer discounts for buying multiple services (service/task bundling) or the same service for multiple materials (product bundling). Such types of bundling may make it attractive to consolidate services in terms of fewer 3PLs.

A company may also have the option of carrying out some or all tasks in-house. An in-house task may require some fixed (investment) cost, and its operating cost may be different from that of an outsourced task. Here, the operating cost refers to the cost of performing a task, while the fixed cost refers to the investment required for the infrastructure needed to execute that task.

Let us illustrate the concept of logistics contracts using Example 1, which has 14 contracts (C1 - C14). Of these, C1 and C12 refer to the in-house options.

C1: In-house contract – Ship to Singapore in bulk. Clear customs in Singapore. Containerize+Label at a logistics hub site in Singapore. Transport tank containers from Singapore to various demand sites, which includes multi-modal transport and customs clearance at appropriate sites.

C2: Ship to Singapore in bulk.

C3: Containerize+Label at a logistics hub site in Singapore.

C4: Transport from Singapore to various demand sites.

C5: Ship to Bangkok (Thailand) in bulk. Clear customs in Bangkok. Drum+label at logistics hub site in Bangkok. Transport drums from Bangkok to various demand sites, which includes multi-modal transport and customs clearance at appropriate sites.

C6: Drum+label at a logistics hub site in Bangkok.

C7: Ship to Bangkok in bulk. Clear customs in Bangkok. Transport drums from Bangkok to San Francisco. Clear customs in San Francisco.

C8: Transport tank containers from Shanghai to San Francisco. Clear customs in San Francisco.

C9: Containerize+label at a logistics hub site in San Francisco.

C10: Ship to San Francisco in bulk. Clear customs in San Francisco. Containerize+label at a logistics hub site in San Francisco. Transport tank containers from San Francisco to various demand sites.

C11: Ship to Singapore in bulk. Transport tank containers from Singapore to San Francisco. Clear customs in San Francisco.

C12: In-house contract that ships to Singapore in bulk and transports tank containers from Singapore to San Francisco.

C13: Clear customs at various demand sites of North America.

C14: Containerize+label at a logistics hub site in Kareemun (Indonesia).

Now, the MNC must analyze all the above options and select a mix of contracts and 3PLs to fulfill all its logistics needs at the minimum cost. To this end, its logistics department may invite several 3PLs to offer a variety of contracts for its logistics needs. The above examples show that selecting the right 3PLs and assigning appropriate tasks to them is not straightforward. Hence, we need a systematic and integrated approach to solve this problem, which we state as follows.

Given

1) contracts and their full details and features such as terms, conditions, tasks, materials, prices, fixed costs, durations, task sites, etc. except start times,

2) planning horizon that comprises multiple periods of some pre-fixed length (week, month, quarter, etc.),

3) demand of materials at each demand site for each period,

4) inventory holding costs at production and demand sites,

5) production capacity of each production site during each period,

determine

1) the contracts that the MNC should select and when they should begin,

2) the quantities of materials shipped under various contracts from one site to another during each period,

3) the quantities of materials processed under various contracts at various sites during each period,

4) the hub sites at which tasks are to be performed over time,

5) the inventory profiles at production and demand sites,

assuming

1) a contract cannot be selected more than once during the planning horizon, but multiple copies of the same contract with different durations can be offered,

2) contracts have fixed durations, they are selected at time zero, and they can begin at any time,

3) no inventory at hub sites,

4) the demand is fully satisfied,

5) the system is deterministic with known demands and costs that may vary with period,

to minimize the total cost of integrated logistics and holding the materials over the planning horizon. The schematic representation of this problem is shown in Figure 6.3

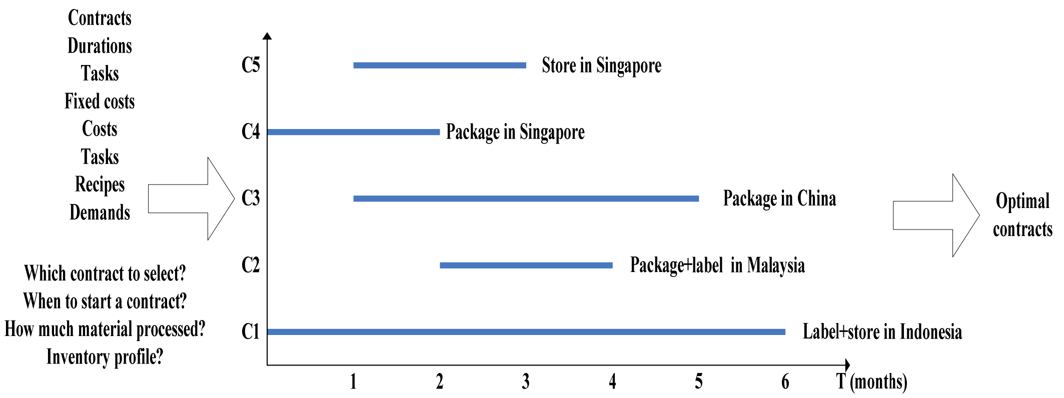

Figure 7.3: Schematic representation of the logistics contract selection problem

7.2 MILP Formulation

By replacing each 3PL by its contracts, we can view the entire problem as that of contract selection, which is clearly an optimization problem. However, to formulate it as such, we need a comprehensive representation of the logistics needs and options. We now present a framework for modeling the various logistics options in terms of logistics recipes, as used in the batch process scheduling literature (Sundaramoorthy & Karimi, 2005).

7.2.1 Logistics Recipe

We define a logistics task as the one that converts a given material via a given contract from one form to another at a specific site or transports it from one site to another in a specific form. We define a recipe as an ordered series of tasks that collectively transform a material from its bulk form to the final form desired by the customer, and deliver it to the customer in that final form. We assign a unique label to each task and material form. To visualize the possible options for transforming and delivering materials to customers, we borrow the idea of superstructure from heat exchanger network synthesis literature (Yee et al., 1990) to embed all possible recipes in one graphical view. To illustrate this recipe superstructure, consider a material B that needs to be delivered from Singapore to Bangkok, for which six contracts (C1 to C6) are available for selection. B is delivered to various customers in three forms, namely bulk, container, or drum. To differentiate among these, we define three forms, namely B1, B2, and B3. B1 is material B delivered in tank containers, B2 is in drums, and B3 is in bulk. There are several ways (recipes) of delivering B from Singapore to Bangkok. Note that B is produced in bulk form (B3).

Recipe 1: Transport B3 to Kareemun (Indonesia), clear customs, containerize and drum at Kareemun to get B1 and B2 via C1. Transport B1 and B2 to Bangkok and clear customs in Bangkok via C1.

Recipe 2: Ship B3 to Kareemun (Indonesia) via C1. Clear customs, and containerize at a logistics hub site in Kareemun via C2. Transport B1 from Kareemun to Bangkok via C2. Clear customs at a logistics hub site in Bangkok via C3.

Recipe 3: Drum and containerize at a logistics hub site in Singapore via C4. Transport B1 and B2 from Singapore to Bangkok via C4. Clear customs in Bangkok via C4.

Recipe 4: Ship B3 to Bangkok via C5. Clear customs, drum and/or containerize at a logistics hub site in Bangkok via C5.

Recipe 5: Ship B3 to Port Kallang (Malaysia) via C6. Clear customs, containerize and drum at Port Kallang. Transport B1 and B2 to Bangkok. Clear customs in Bangkok via C6.

Figure 7.4 shows the recipe superstructure for B.

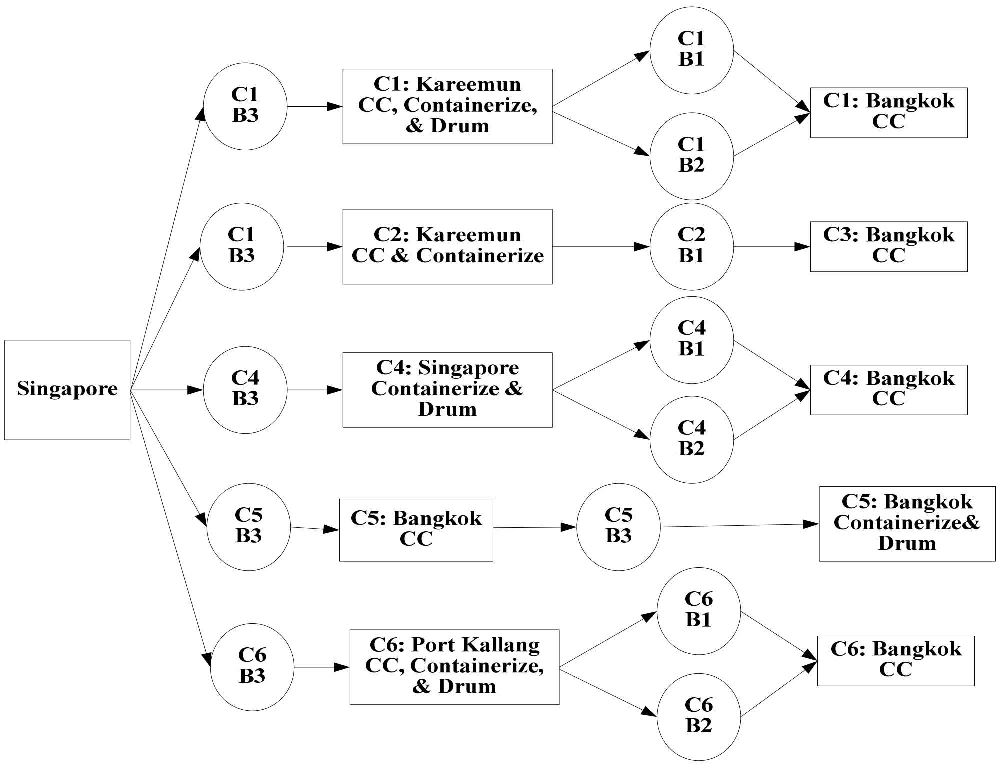

Figure 7.4: Logistics recipe superstructure for B (CC = clear customs)

7.2.2 Formulation

We assume that each contract has a fixed known length. Because logistics decisions are generally long-term, we assume that all contract lengths are multiples of one or more months or quarters, as a finer time resolution is unnecessary. This enables us to use a uniform discrete-time representation and define the planning horizon to comprise T periods (t = 1, 2, …, T) of equal lengths. Period 1 begins at time zero.

With the above simplifications, the primary decision for the MNC is to select the best contracts from the pool of all contracts and determine their start/end times. To model these decisions, we define the following binary variables.

$$z_c = \begin{cases} 1 & \text{if contract } c \text{ is selected} \\ 0 & \text{otherwise} \end{cases}$$

$$ys_{ct} = \begin{cases} 1 & \text{if contract } c \text{ begins at the start of period } t \\ 0 & \text{otherwise} \end{cases} \qquad 1 \le t \le T$$

Since a contract cannot begin more than once during the horizon, and, if selected, it must begin some time during the horizon, we write,

$$z_c = \sum_t ys_{ct} \tag{7.1}$$

Eq. 7.1 allows us to treat z_c as a continuous 0-1 variable. As mentioned earlier, every contract c has a fixed cost FC_c.

Knowing the length (CL_c) of contract c, ys_{ct} allows us to see if it is in effect during a period using the following 0-1 continuous variable.

$$y_{ct} = \begin{cases} 1 & \text{if contract } c \text{ is in effect during period } t \\ 0 & \text{otherwise} \end{cases} = \sum_{t-CL_c+1}^{t} ys_{ct} \tag{7.2}$$

Note that a contract c may continue (we set z_c = 1) from the previous planning horizon.

Recall that tasks (w) are of two types, transport and non-transport. A transport task (say u) will involve several specifications such as the material m to be transported, the contract c that will govern that transport, the origin site s, the destination site s', and the form n in which m is to be transported. A non-transport task (say v) will involve material m on which task is done, the contract c that will govern the task, the origin form n, the destination form n', and the site k where task is done. As mentioned earlier, a contract may cover only a transport task, or only non-transport tasks, or a combination of transport and non-transport tasks.

A contract will normally specify one or more unit costs for each task that it covers. For instance, for a transport task, it may specify one or more unit costs depending on the quantity of material that is transported. Thus, in general, a contract may have multi-tier pricing structure (Chapter 5) for each task. To model this structure and the resulting costs, we divide the total quantity transported for material m under contract c into R_u (or R_v) price-tiers and define p_{urt} (or p_{vrt}) as the unit logistics cost for price-tier r during period t. For each price-tier r, we define a quantity range [$QL_{w(r\text{-}1)}$, QL_{wr}], r = 0, 1, 2, ..., R_w, where QL_{w0} is the minimum quantity that must be processed if task w is selected. For example, suppose that a contract c offers a transport task u for material m = 1 from production site s = 1 to hub site k = 2 in the form n = 1. The minimum transport quantity QL_{w0} is zero. If the total quantity transported is below 500 kton, then it charges some base price. If the quantity goes above 500 kton, then it offers a discounted pricing. Thus, this task has two price tiers (R_u = 2). The quantity ranges for these two tiers are [0, 500] kton and [500, 10000] kton. To model such multi-tiered price structures that are common in practice, we define another binary variable.

$$\alpha_{wrt} = \begin{cases} 1 & \text{if price tier } r \text{ is in effect for task } w \text{ during } t \\ 0 & \text{otherwise} \end{cases}$$

Note that information such as material, contract, origin, destination, form, etc. are implicit in *u*. Clearly, if a contract is in effect during a period *t*, then the amount shipped must fall in one of the *r* price-tiers. Hence,

$$\sum_{r=1}^{R_w} \alpha_{wrt} = y_{ct} \qquad c = c(w) \tag{7.3}$$

where, $c(w)$ denotes the contract that governs task *w*. Now, let Q_{wt} denote the quantity on which task *w* is done during period *t.* Furthermore, we define the differential amount (ΔQ_{wrt}) in the price-tier range *r* by writing,

$$Q_{wt} = \sum_{r=1}^{R_w} (QL_{w(r-1)}\alpha_{wrt} + \Delta Q_{wrt}) \tag{7.4a}$$

For a price p_{wrt} to apply, $QL_{w(r-1)} \le Q_{wt} < QL_{wr}$ must hold, i.e.,

$$\Delta Q_{wrt} \le \alpha_{wrt}[QL_{wr} - QL_{w(r-1)}] \tag{7.4b}$$

<u>Mass Balances</u>

Let us first consider the overall mass balance for a material *m* at a hub site *k*. Since a hub site does not hold any inventory as per our assumption, the total amount of material *m* entering site *k* during period *t* must equal the total amount of *m* leaving *k* during *t*. In other words, we must sum the flows of a material in all forms on both sides (in and out) of site *k* and force both sums to be equal. Hence, for every material *m* and hub site *k*, we write,

$$\sum_{u \ni m(u)=m \,\&\, s'(u)=k} Q_{ut} = \sum_{u' \ni m(u')=m \,\&\, s(u')=k} Q_{u't} \tag{7.5}$$

Now, let us consider the mass balance for a form *n* of material *m* at hub site *k*.

The amount of *n* leaving site *k* must equal the amount entering site *k*, plus the amount produced at site *k*, minus the amount consumed at site *k*. In other words,

$$\sum_{u \ni m(u)=m \,\&\, s(u)=k \,\&\, n(u)=n} Q_{ut} = \sum_{u \ni m(u)=m \,\&\, s'(u)=k \,\&\, n(u)=n} Q_{ut} + \sum_{v \ni m(v)=m \,\&\, n'(v)=n \,\&\, k(v)=k} Q_{vt} - \sum_{v \ni m(v)=m \,\&\, n(v)=n \,\&\, k(v)=k} Q_{vt} \tag{7.6}$$

For an explanation of eq. 6, consider Figure 7.5.

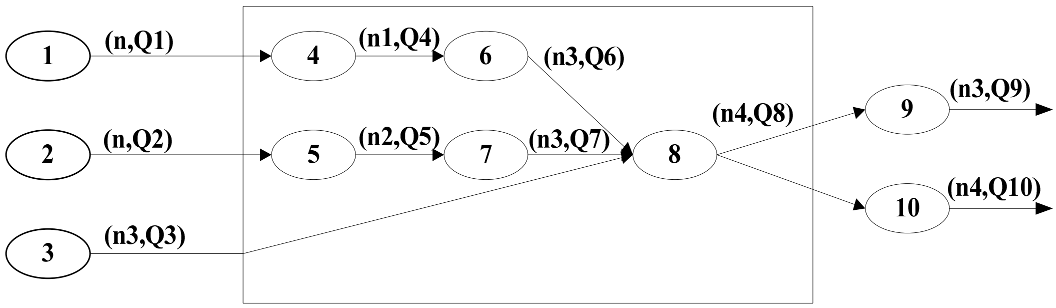

Figure 7.5: A logistics hub site *k* performing multiple non-transport tasks (tasks 4, 5, 6, 7, and 8)

Site *k* performs multiple tasks for material *m*. Tasks 1 and 2 (transport tasks) respectively bring *Q*1 and *Q*2 amounts of form *n* into site *k*. Transport task 3 brings *Q*3 amount of form *n*3 into site *k*. Non-transport tasks 4 and 5 process *Q*4 and *Q*5 amounts respectively of form *n* into forms *n*1 and *n*2. Task 6 processes *Q*6 amount of form *n*1 into *n*3 and task 7 processes *Q*7 amount of form *n*2 into *n*3. Task 8 transforms *Q*8 amount of *n*3 into *n*4. Transport tasks 9 and 10 ship *Q*9 and *Q*10 amounts of forms *n*3 and *n*4 respectively from site *k*. Then, the overall mass balance (eq 7.5) for this illustrative scenario is,

$$Q1 + Q2 + Q3 = Q9 + Q10 \quad (7.5a)$$

The mass balances for individual forms *n*, *n*1, *n*2, *n*3, and *n*4 are,

$$0 = (Q1 + Q2) + 0 - (Q4 + Q5) \quad (7.6a)$$

$$0 = 0 + Q4 - Q6 \quad (7.6b)$$

$$0 = 0 + Q5 - Q7 \quad (7.6c)$$

$$Q9 = Q3 + (Q6 + Q7) - Q8 \quad (7.6d)$$

$$Q10 = 0 + Q8 - 0 \quad (7.6e)$$

Note that eq. 7.6 makes eq. 7.5 redundant, therefore eq. 7.5 is not included in the formulation.

Lastly, we consider overall mass balances at the production and demand sites. For this, we let PQ_{mst} denote the quantity of material m produced at a site s during period t. We take $PQ_{mst} \geq 0$ for a production site, and $PQ_{mst} \leq 0$ for a demand site. Since both production and demand sites can hold inventory, the following mass balance must hold for any site s that is not a hub site.

$$I_{mst} = I_{ms(t-1)} + PQ_{mst} + \sum_{u \ni m(u)=m \,\&\, s'(u)=s} Q_{ut} - \sum_{u' \ni m(u')=m \,\&\, s(u')=s} Q_{u't} \tag{7.7}$$

Total Logistics Cost

The total logistics cost has three components. The first is the fixed costs associated with selecting various contracts. Let FX_c denote the fixed cost for selecting a contract c. Then, the total fixed cost is the first term in eq (7.9). The second is the holding costs at various sites. Since hub sites hold no inventories, their holding costs are zero. For other sites, we take the average of start and end inventories for each period and multiply the result by holding cost HC_{mst} for material m at site s during t. This is the second term in eq. (7.9).

The last is the total cost of performing all tasks. Let p_{wrt} be the unit cost in price-tier r for task w during period t. Recall that we have two types of multi-tier discounts (Chapter 5). For bulk discounts, the cost of a task w is,

$$PC_{wt} = \sum_{r=1}^{R_w} p_{wrt}(QL_{w(r-1)}\alpha_{wrt} + \Delta Q_{wrt}) \tag{7.8a}$$

The cost for unit discounts is,

$$PC_{wt} = \sum_{r \geq 1}^{R_w} \left(\Delta Q_{wrt} p_{wrt} + \alpha_{wrt} \sum_{\rho \geq 1}^{\rho \leq (r-1)} p_{w\rho t}(QL_{w\rho} - QL_{w(\rho-1)}) \right) \tag{7.8b}$$

Thus, the total logistic cost is,

$$TC = \sum_c Fx_c z_c + \frac{1}{2} \sum_{m,s,t} HC_{mjt}[I_{mjt} + I_{mj(t-1)}] + \sum_{w,t} PC_{wt} \tag{7.9}$$

This completes our MILP formulation for selecting logistics contracts with minimum cost. Eq. (7.9) gives the cost to be minimized and eqs. 7.1-7.8 excluding eq. 7.5 are the constraints. We now illustrate the application of this model with a small example.

7.3 Example 2

A MNC has two production sites (j = 1 and j = 10) that produce one material (A, m = 1). It has two demand sites (i = 7 and i = 9). The material is produced in the bulk form (n = 1), containerized (or drummed) and labeled (n = 2 or 3), and clears customs (n = 5). Table 7.1 gives the production capacities, customer demands, holding costs, and quantity ranges for price-tiers. Figures 7.6 and 7.7 show the logistics recipe. The planning horizon has five periods (t = 1, 2, 3, 4, 5 years; T = 5) and the MNC is evaluating ten logistics contracts (C1-C10, c = 1-10). C1 represents the in-house option and others (C2-C10) represent outsourcing to various 3PLs. All contracts offer bulk discounts. Table 7.2 lists the contracts, their durations, and fixed costs. Table 7.3 lists the tasks and their costs. We use CPLEX v10.0.1 in GAMS 22.2 (Brooke et al., 2005) on a 3.00 GHz Pentium® PC with 2 GB of RAM and Windows XP to solve our model.

As shown in Figure 7.6 and 7.7, many logistics recipes are possible for A. In one recipe involves transport in bulk form from j = 1 to s = 2, containerize+label at hub site k = 2, transport from k = 2 to k = 3, clear customs at site k = 3, and transport from k = 3 to i = 7, i = 9, etc. The MNC wishes to select the contracts that fulfill its total logistics needs at the minimum cost.

For this example, we compare the results of two scenarios. In scenario 1, we do not allow partial selection of contracts, but break a contract into distinct contracts that represent partial contracts. For instance, C1 offers ten transport tasks and eight non-transport tasks. If C1 is selected, then all the eighteen tasks must be selected. However, to include the possibility that the MNC may want to assign these tasks to different providers in different combinations, we also allow contracts that offer these services alone or in various combinations, i.e., subcontracts. Thus, we may allow a contract that offers only transportation from site 1 to site 2 (C11), another that offers only transport from site 10 to site 2 (C12), another that offers all the ten transport tasks as one package (C21), another that offers all non-transport tasks as one package (C22), etc.

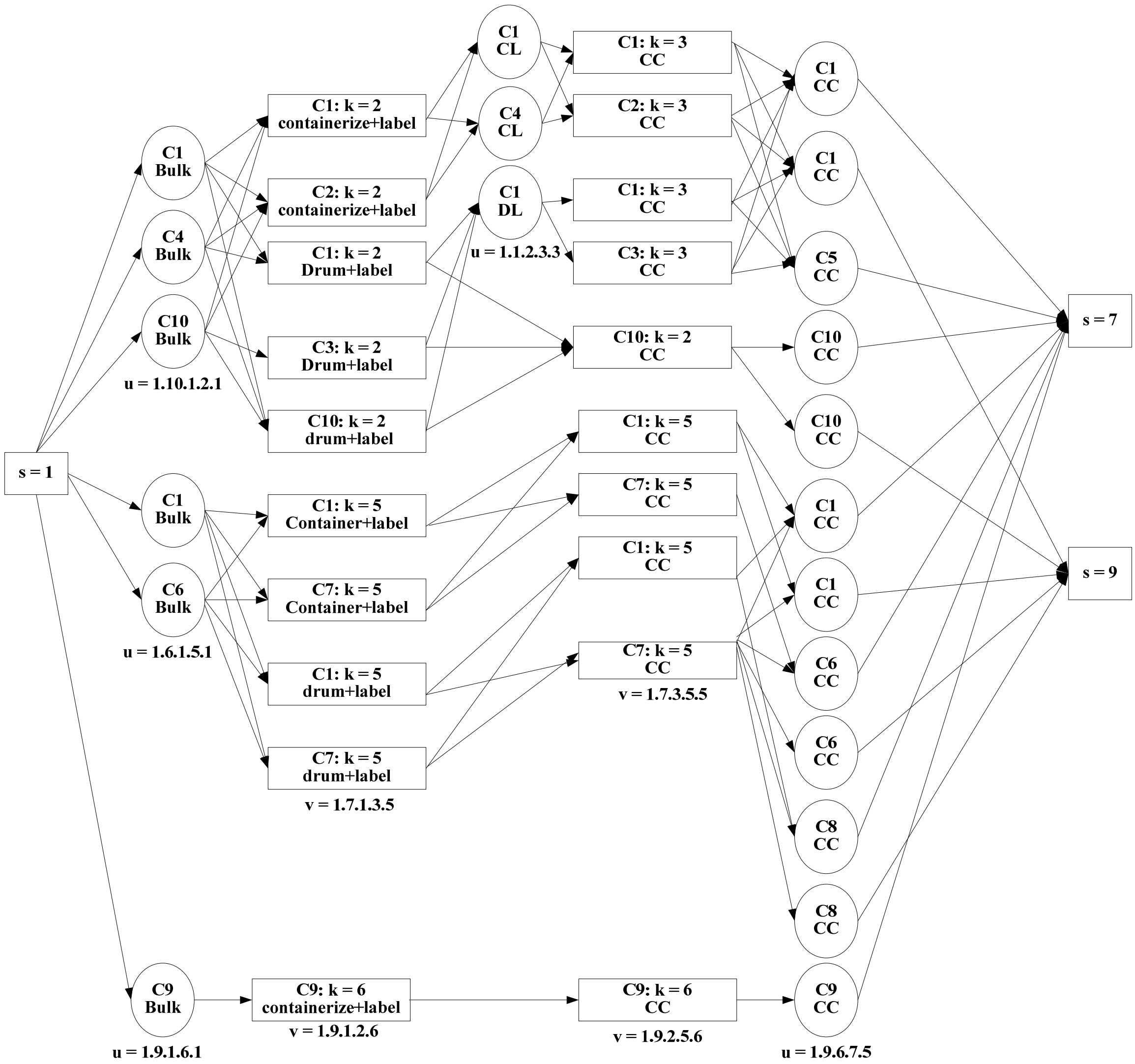

Figure 7.6: Receipe superstructure from site s = 1 for product A for Example 2, scenario 2 (1= bulk, 2 = container+label, 3 = drum+label, 5 = clear customs, CL = containerize+label form, DL = drum+label form, CC = clear customs). u = m.c.s.s′.n denotes the transport task that takes form n of material m from site s to site s′ via contract c. v = m.c.n.n′.k denotes the task that transforms form n of material m under contract c to produce form n′ at site k.

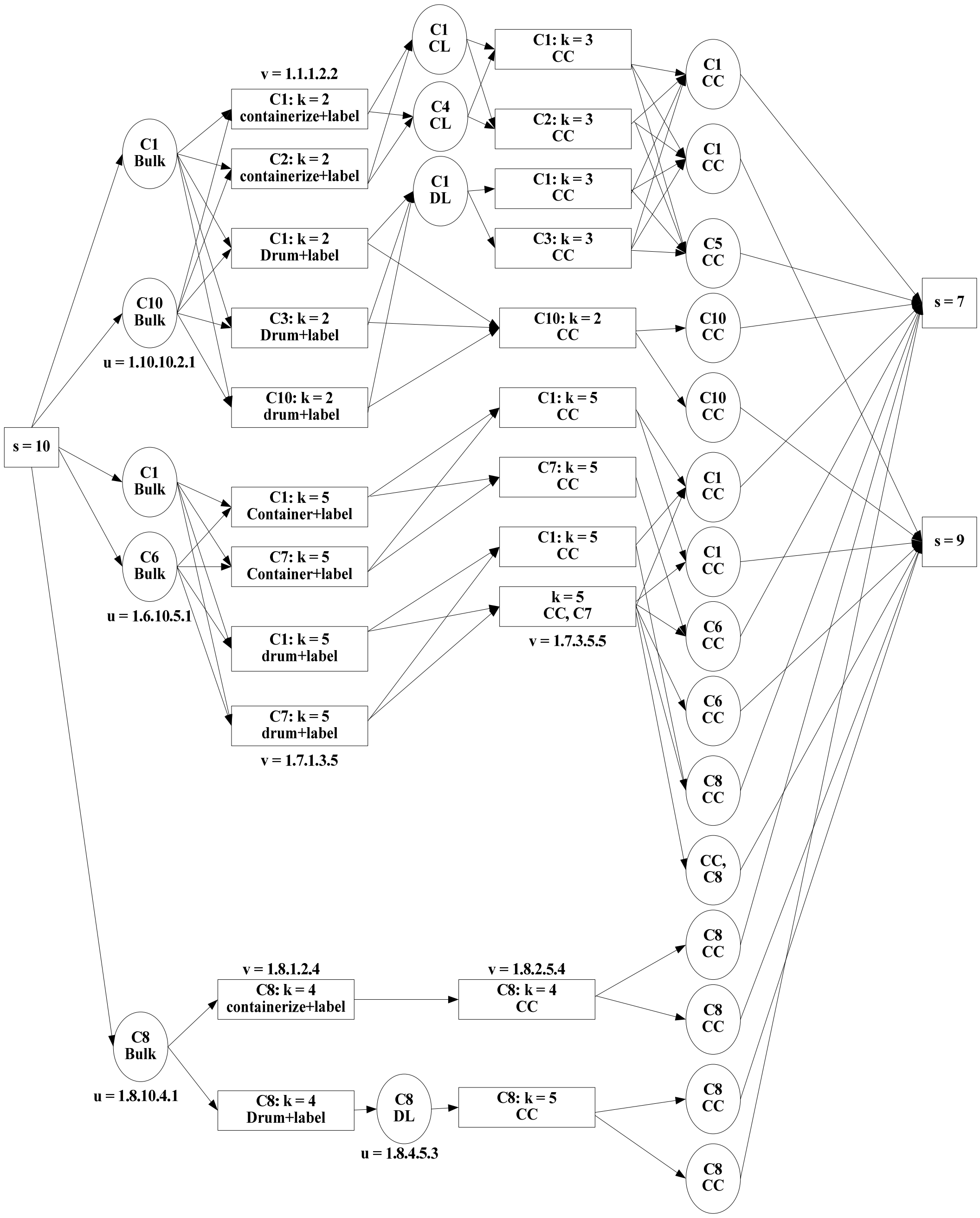

Figure 7.7: Recipe superstructure from site s = 10 for product A for Example 2, scenario 2 (1 = bulk, 2 = container+label, 3 = drum+label, 5 = clear customs, CL = containerize+label form, DL = drum+label form, CC= clear customs). u = m.c.s.s′.n denotes the transport task that takes form n of material m from site s to site s′ via contract c. v = m.c.n.n′.k denotes the task that transforms form n of material m under contract c to produce form n′ at site k.

The various sub-contracts for this example are given in Table 7.2 and they are treated as additional contracts for this example. Note that subcontracts have the same durations and fixed costs as that of the parent contract. In this example, C1 is the parent contract and C11, C12, C21, C22, etc. are subcontracts. The implication of selecting a separate contract is that each of its tasks must be served in some minimum amount. For this example, we set the minimum amount as 100 kton for each task/service. In scenario 2, in contrast, we do not break up a contract into contracts representing various combinations of its individual contracts, but set the lower limit on task amount as zero. This enables the company to select a contract, but still have the choice of selecting none, one, or more tasks from that contract.

7.3.1 Scenario 1

The MILP model for this problem has 2490 binary variables, 3789 constraints, and 5614 continuous variables. It required 31916 s of CPU time. The optimal plan includes nine contracts, namely C1, C4, C5, C6, C25, C27, C30, C31, and C32. Table 4 shows the profiles of logistics services under different contracts. The transport task from site s = 1 to site s = 2 is done via C1 and C4 in the first two years, but via C1 and C27 (subcontract of C4) in the third and fourth. While the selection of two contracts for the same task may not make an intuitive sense, as both require fixed costs, C4 (or C27) with its lower cost (5 k$/kton) in comparison to C1 (6 k$/kton) becomes more attractive, as its fixed cost of 7000 k$ is offset by using C4 (or C27) for more than 7000 kton. It is interesting to note that the optimal plan also includes combinations of in-house and outside contracts, and combinations of recipes. The optimal plan uses hub sites k = 2, 3, and 5. Note that the optimal plan does not include C10, even though C10 drums, labels, and clears customs at hub site k = 2 and involves no transport task.

Even the optimal solution for this rather small example shows a variety of interesting features such as one contract supplying services at multiple hub sites in multiple forms through multiple recipes and multiple contracts supplying services at a single hub site, multiple tasks via multiple contracts at a single hub site, etc. It is clear that such a solution is not necessarily intuitive and is difficult to obtain manually. Just to compare what a manual approach can achieve for this example, let us examine the prices of various contracts. First, note that C1 offers the lowest price. Also, the selection of multiple contracts incurs fixed costs, so it may seem logical to select C1 as the only contract supplying all services. Now, consider the demand at s = 7. The transport cost from s = 1 to s = 2 (6 k$/kton) is half of that from s = 10 to s = 2 (12 k$/kton). Hence, we would transport only the minimum amount from s = 10 to s = 2. Also, note that the material can transit through hub sites k = 2 or k = 5. Also, the material has to be containerized or drummed, labeled, and then must clear customs at the same or different sites. Let us compute the costs for various options for site s = 1.

1. Containerize+label at k = 2 and clear customs at k = 3: Cost = 6 + 10 + 4 + 2 + 20 = 42 k$/kton.
2. Drum+label at k = 2 and clear customs at k = 3: Cost = 6 + 7 + 5 + 1 + 20 = 39 k$/kton.
3. Containerize+label, and clear customs at k = 5: Cost = 8 + 11 + 3 + 18 = 40 k$/kton
4. Drum+label, and clear customs at k = 5: Cost = 8 + 8 + 2 + 18 = 36 k$/kton.

Of the above, the minimum cost to fulfill the demand at s = 7 is to use hub site k = 5. Hence, we route 11,900 kton of material using this option and the minimum amount (100 kton) through hub site k = 2. Using this intuitive logistics strategy, we get 2,897,200 k$ as the total logistics cost, which is 43.86% higher than the minimum cost (2,013,950 k$) from our model. In addition, such a manual approach will quickly become intractable, as the problem size and complexity increase. Furthermore, even if we were to obtain a solution somehow, it may be significantly worse than the best possible. This clearly illustrates the utility of the modeling approach presented in this work.

7.3.2 Scenario 2

In this scenario, we allow the partial selections of contracts, so we may not need to break full contracts. We still require that fixed costs are the same even for such partial selections. The MILP model for this problem has 1110 binary variables, 1761 constraints, and 2516 continuous variables. It required 6.29 s of CPU time. For this scenario, we find that the optimal cost is 2.0% lower (1,974,500 k$) than that for scenario 1. The optimal plan includes seven contracts, namely C1, C3, C4, C5, C6, C7, and C8 as compared to nine in scenario 1. Table 7.4 shows the profiles of services performed under different contracts. Note that C8 offers eight transport and four non-transport tasks. However, no task from C8 is selected in the optimal plan in the first four years. Only in the fifth year, one task of transport from $s = 5$ to $s = 7$ after clearing the customs is selected in the optimal plan. The reason for this is that C8 offers a lower cost (15 k$/kton) compared to all the other options (18 k$/kton for C1, and 15 k$/kton for C6) in the fifth year. Note that C6 is selected in the first year, but is unavailable in the fifth due to its contract length of four years. Similarly, the solution for scenario 1 was forced to transport 100 kton via hub site $k = 2$ due to the imposition of the lower limit, even though it was not cost effective to do so. In scenario 2, this amount goes to zero, as the limit became zero. Another reason for the cost reduction in this scenario is the fact that the inventory at the demand sites is zero in all years compared to 300 kton inventory at $s = 9$ in the fifth year for scenario 1.

The drastic reduction in computation time in scenario 2 compared to that in scenario 1 is a bit surprising. While treating partial contracts as separate contracts does increase the binary variables considerably, we suspect that the known unpredictability of MILP solution times due to numerical data could also be responsible for this huge reduction. We now consider a larger example based on simulated data for a large MNC.

7.4 Example 3

A MNC has two production sites (*j* = 1 and 10) that produce two bulk products (*m* = 1 and 2). The MNC delivers them to 10 customer sites (*i* = 7, 9, 11, 12, 13, 14, 15, 16, 17, and 18). *m* = 1 is containerized (or drummed)+labeled (*n* = 2 or 3), and clears customs (*n* = 5) and *m* = 2 is pelletized+containerized+labeled (*n* = 2), and clears customs (*n* = 5). Table 7.5 lists the production capacities, demands, holding costs, and quantity ranges for price-tiers. The MNC is evaluating 28 contracts (C1-C28, *c* = 1-28) of which C1 represents the in-house option. The planning horizon is five years with five identical periods. Table 7.6 lists the data for this example. Again, we use CPLEX v10.0.1 in GAMS 22.2 on a 3.00 GHz Pentium® PC with 2 GB of RAM.

For this example, we allow the partial selection of contracts. Our MILP model for this problem has 3380 binary variables, 5859 constraints, and 7989 continuous variables. However, it requires only 30.05 s of CPU time. Table 6.7 shows the execution of various logistics services. Of the 28 possible contracts, seven contracts (C1, C6, C8, C9, C14, C15, and C20) are selected in the optimal solution. Interestingly, C1, the in-house option, is used for all the required tasks, but the optimal plan includes other contracts too. Although C1 is selected in the first year, the transport from *s* = 1 to *s* = 2 for *m* = 1 via C1 is required only in the fifth year due to the flexibility in selecting a partial contract. It is possible for m = 1 to pass through hub sites s = 2, s = 3, and s = 5 under C1. However, for m = 1, C1 uses s = 5 for the first four years only, and s = 2 and s = 3 for the last year. The demand for m = 1 at s = 13 is filled by a mix of contracts C1, C8, and C14. For the first four years, C8 transports material from s = 10, containerizes+labels, clears customs at k = 4, and ships to the demand site. For the last year, the demand is filled via C1 and C14. C1 transports material from s = 1, containerizes+labels at k = 2, clears customs at k = 3, and then ships to the demand site. C14 only transports the material from site k = 5. C1 transports it from the production site, containerizes+labels, and clears customs at k = 5. Features such as one hub site performing services on one or more materials through different contracts, and one contract supplying the same or different services at multiple hub sites on multiple materials are also present. C1 containerizes+labels m = 1, and clears customs via hub site k = 5 during the first four years. During the fifth year, it uses k = 2 and at k = 5 for containerizing+labeling, but clears customs at k = 3 for materials that are containerized+labeled at k = 2 and at k = 5 for the materials that are containerized+labeled at k = 5. C8 containerizes+labels the material and clears customs at k = 4 during the first four years. Note that the optimal solution possesses an interesting variety in its selection of hub sites, contracts, and periods for various materials.

7.5 Example 4

Supply chains are dynamic and demand and price data rarely stay unchanged. While our model is static, it can be used in a reactive manner to handle disruptions (changes) of various types (demand, supply, capacities, contracts, prices, etc.) in supply chain dynamics. Clearly, optimal plans get quickly outdated and must be revised. To illustrate this, let us revise the optimal plan obtained for Example 3 after two years of execution due to the changes in demand. Thus, all the data of Example 3, except some demands and prices for some contracts (Table 7.8), apply for this example. It is very likely that new contract options may be available for consideration at the time of such revisions, and previous decisions such as in-house execution may need to be reviewed. Furthermore, the current contracts must be honored, and while the in-house option may not continue, its fixed cost must be zero. Note that the zero time for this example is the start of the third year in Example 1 and the horizon length is three years.

The optimal plan has seven contracts, namely C1, C6, C8, C9, C14, C15, and C20. C6 and C8 are current contracts and must be honored respectively for the first three and two years in this example. Thus, the contract length of C8 is two years and that of C6 is three years in this example. We set z_8 = 1, y_{81} = 1, y_{82} = 1, z_6 = 1, y_{61} = 1, y_{62} = 1, and y_{63} = 1. Note that the inventory at the end of the second year in Example 3 is not zero for production sites j =1 and j = 10, so we set the initial inventory appropriately in this example. Also, the fixed costs of C6 and C8 are zero, as they are current.

The revised optimal procurement plan selects three more contracts C13, C25, and C26 in addition to the seven current contracts. Table 7.9 shows the service profiles under the ten contracts (C1, C6, C8, C9, C13, C14, C15, C20, C25, and C26). In the first year, the total demand for m = 1 decreases from 170,000 kton to 47,600 kton. In Example 3, m = 1 was transported from the production sites (s = 1 and s = 10) to the hub site s = 5 (9 k$/kton and 11 k$/kton respectively) via C1, from s = 10 to s = 4 (10 k$/kton) via C8, and from s = 1 to s = 6 (9 k$/kton) via C14. Since the demand has reduced, the material is not transported from s = 10 to s = 5 via the in-house option (C1), as the cost is more (11 k$/kton).

Let us now examine the consequences of following the optimal procurement strategy obtained from Example 3 in the face of decreased demands. As per the plan in Example 3, the demand for material m = 1 at s = 17 during the fourth year is fulfilled via C1 through hub site s = 5. The material is transported from s = 1 to s = 5 (9 k$/kton), containerized+labeled and clears customs at s = 5 (18 k$/kton and 12 k$/kton), and is transported to s = 17 (20 k$/kton). The total cost for the material to reach s = 17 is 9 + 18 + 12 + 20 = 59 k$/kton. In the revised plan (Example 4), the demand at s = 17 during the second year (Note that fourth year in Example 3 is the same as second year in Example 4) is satisfied by a combination of contracts. The material transports under C14 from s = 1 to hub site s = 6 (9 k$/kton). It is drummed+labeled and clears customs at s = 6 (20 k$/kton and 10 k$/kton) via C25 and C26 (Prices reduced for C25 and C26) respectively, and is transported via C13 to s = 17 (15 k$/kton). The total cost in the revised plan is 9 + 20 + 10 + 15 = 54 k$/kton. The demand for m = 1 at s = 17 is 10,000 kton. Thus, the revised plan reduces the costs for m = 1 during the fourth year at s = 17 by (59–54)*10000 = 50,000 k$. The total cost for the revised plan is 8,415,400 k$, which is 3.03% lower than the cost for the original plan from Example 3.

7.6 Conclusion

We presented a systematic and quantitative decision-making formalism to address the integrated logistics needs of a MNC in a global business environment. Although our goal was to address the logistics in chemicals and related industries in particular, the methodology is general and applicable to other supply chains as well. The formalism involved a novel representation of logistics activities in terms of a recipe superstructure and a static MILP model based on that to select the optimal contracts that minimize the total logistics cost. It allows the flexibility of selecting partial contracts, which reduces the combinatorial complexity and computation time considerably, along with some reduction in costs under certain assumptions. The model not only accommodates existing contracts, but also allows new contracts to extend beyond the horizon. Thus, it is able to address in a reactive manner the various dynamic disruptions that normally arise in chemical supply chains. We also found that the full selection of contracts are not only costly, it is also computationally expensive. The CPU time is much larger in the case of full selection of contracts. Lastly, our model assumed zero inventory at the hub sites and allowed contracts to be selected only once in the planning horizon. These can be addressed via simple modification of our model.

Although, our discussion in this chapter was confined to bulk discounts, unit discounts (Chapter 5) can also be easily incorporated in the proposed model. The fact that our proposed deterministic model is computationally manageable even for a large-scale example provides a basis for future work involving supply chain uncertainties.. One limitation of our work is using cost as the sole selection criterion. Other non-quantifiable criteria for contract selection such as reliability, service quality, etc. are important and addressing them together in a quantitative model is a challenge that warrants further attention.

Table 7.1 Production capacities, customer demands (PQ_{mst} in 1000 kton), inventory holding costs (HC_{mst} k$/kton), and quantity ranges (QL_{wr} in 1000 kton) for price-tiers for Example 2

s	PQ_{1s1}	PQ_{1s2}	PQ_{1s3}	PQ_{1s4}	PQ_{1s5}	HC_{ms1} to HC_{ms5}
1	17	20	16	2	4	1
10	2	4	6	14	14	1
7	12	10	17	10	11	100
9	4	8	6	6	0	100
QL_{w1}= 0.1, QL_{w2} = 1, QL_{w3} = 10, QL_{w4} = 1000						

Table 7.2 Contracts (c), contract lengths (CL_c yr), fixed costs (Fx_c in million$), and sub-contracts (for scenario 1 of Example 2) for Examples 2 and 3

Example 2				Example 3								
c	CL_c	Fx_c	Subcontracts	c	CL_c	Fx_c	c	CL_c	Fx_c	c	CL_c	Fx_c
C1	5	14	C11 - C22	C1	5	200	C11	5	50	C21	2	10
C2	3	9	C23, C24	C2	3	40	C12	5	30	C22	3	10
C3	5	10	C25, C26	C3	5	30	C13	5	30	C23	5	10
C4	2	7	C27, C28	C4	2	30	C14	5	70	C24	5	10
C5	3	4	NA	C5	3	40	C15	4	30	C25	5	10
C6	4	5	C29, C30	C6	4	40	C16	3	30	C26	4	10
C7	4	7	C31, C32	C7	4	40	C17	2	30	C27	3	10
C8	4	8	C33, C34	C8	4	50	C18	4	30	C28	3	10
C9	4	6	C35, C36	C9	4	60	C19	4	30			
C10	3	7	C37, C38	C10	5	60	C20	3	60			

Table 7.3: Transport tasks *u* (denoted by *m.c.s.s'.n*), non-transport tasks *v* (denoted by *m.c.n.n'.k*), and their prices (p_{urt} and p_{vrt}, k$/kton) for Example 2

u	p_{urt}	*u*	p_{urt}	*u*	p_{urt}	*u*	p_{urt}
1.1.1.2.1	6	1.8.10.4.1	12	1.16.2.3.3	5	1.29.1.5.1	12
1.1.10.2.1	12	1.8.4.5.3	7	1.17.3.7.5	20	1.29.10.5.1	11
1.1.1.5.1	8	1.8.5.7.5	15	1.18.3.9.5	10	1.30.5.7.5	15
1.1.10.5.1	7	1.8.5.9.5	10	1.19.5.7.5	18	1.30.5.9.5	7
1.1.2.3.2	4	1.8.4.7.5	12	1.20.5.9.5	12	1.33.10.4.1	12
1.1.2.3.3	5	1.8.4.9.5	10	1.21.1.2.1	6	1.33.4.5.3	7
1.1.3.7.5	20	1.9.1.6.1	10	1.21.10.2.1	12	1.33.5.7.5	15
1.1.3.9.5	10	1.9.6.7.5	11	1.21.1.5.1	8	1.33.5.9.5	10
1.1.5.7.5	18	1.10.1.2.1	6	1.21.10.5.1	7	1.33.4.7.5	12
1.1.5.9.5	12	1.10.10.2.1	10	1.21.2.3.2	4	1.33.4.9.5	10
1.4.1.2.1	5	1.10.2.7.5	7	1.21.2.3.3	5	1.35.1.6.1	10
1.4.2.3.2	4	1.10.2.9.5	6	1.21.3.7.5	20	1.35.6.7.5	11
1.5.3.7.5	4	1.11.1.2.1	6	1.21.3.9.5	10	1.37.1.2.1	6
1.6.1.5.1	12	1.12.10.2.1	12	1.21.5.7.5	18	1.37.10.2.1	10
1.6.10.5.1	11	1.13.1.5.1	8	1.21.5.9.5	12	1.37.2.7.5	7
1.6.5.7.5	15	1.14.10.5.1	7	1.27.1.2.1	5	1.37.2.9.5	6
1.6.5.9.5	7	1.15.2.3.2	4	1.28.2.3.2	4		
v	p_{vrt}	*v*	p_{vrt}	*v*	p_{vrt}	*v*	p_{vrt}
1.1.1.2.2	10	1.7.1.2.5	5	1.22.1.2.2	10	1.31.1.2.5	5
1.1.1.3.2	7	1.7.2.5.5	1	1.22.1.3.2	7	1.31.2.5.5	1
1.1.2.5.3	2	1.7.1.3.5	4	1.22.2.5.3	2	1.32.1.3.5	4
1.1.3.5.3	1	1.7.3.5.5	2	1.22.3.5.3	1	1.32.3.5.5	2
1.1.1.2.5	11	1.8.1.2.4	22	1.22.1.2.5	11	1.34.1.2.4	22
1.1.2.5.5	3	1.8.1.3.4	26	1.22.2.5.5	3	1.34.1.3.4	26
1.1.1.3.5	8	1.8.2.5.4	12	1.22.1.3.5	8	1.34.2.5.4	12
1.1.3.5.5	2	1.8.3.5.5	13	1.22.3.5.5	2	1.34.3.5.5	13
1.2.1.2.2	8	1.9.1.2.6	11	1.23.1.2.2	8	1.36.1.2.6	11
1.2.2.5.3	2	1.9.2.5.6	3	1.24.2.5.3	2	1.36.2.5.6	3
1.3.1.3.2	5	1.10.1.3.2	10	1.25.1.3.2	5	1.38.1.3.2	10
1.3.3.5.3	1	1.10.3.5.2	12	1.26.3.5.3	1	1.38.3.5.2	12

Table 7.4: Tasks and amounts (100 kton) of materials processed via different contracts in scenarios 1 and 2 for Example 2

Scenario 1											
u	Q_{u1}	Q_{u2}	Q_{u3}	Q_{u4}	Q_{u5}	v	Q_{v1}	Q_{v2}	Q_{v3}	Q_{v4}	Q_{v5}
1.1.1.2.1	1	1	1	1	2	1.1.1.2.2	2	2	1	1	1
1.1.10.2.1	1	1	1	1	1	1.1.1.3.2	1	1	1	1	1
1.1.1.5.1	22	42	10	10	1	1.1.2.5.3	2	2	1	1	1
1.1.10.5.1	19	39	51	147	107	1.1.3.5.3	117	97	168	2	2
1.1.2.3.2	1	1	1	1	1	1.1.1.2.5	1	1	1	1	1
1.1.2.3.3	117	97	168	2	2	1.1.2.5.5	1	1	1	1	1
1.1.3.7.5	1	1	1	1	2	1.1.1.3.5	1	1	1	1	1
1.1.3.9.5	1	1	1	2	1	1.1.3.5.5	30	77	10	10	1
1.1.5.7.5	1	1	1	1	1	1.25.1.3.2	116	96	167	1	1
1.1.5.9.5	1	1	1	1	1	1.31.1.2.5		2	49	100	108
1.4.1.2.1	117	97				1.31.2.5.5		2	49	100	108
1.4.2.3.2	1	1				1.32.1.3.5	39	77	10	55	
1.5.3.7.5	117	97	167			1.32.3.5.5	10	1	1	46	
1.6.1.5.1					1						
1.6.10.5.1					1						
1.6.5.7.5					107						
1.6.5.9.5					1						
1.27.1.2.1			167	1							
1.30.5.7.5	1	1	1	1							
1.30.5.9.5	38	78	58	57							
Scenario 2											
u	Q_{u1}	Q_{u2}	Q_{u3}	Q_{u4}	Q_{u5}	v	Q_{v1}	Q_{v2}	Q_{v3}	Q_{v4}	Q_{v5}
1.1.1.2.1	120					1.1.3.5.3	110	100	169		
1.1.2.3.3	120	100	170			1.1.1.3.5	40				
1.1.1.5.1	20	49	10	1		1.1.3.5.5	40	10	40		10
1.1.10.5.1	20	31	50	159	110	1.3.1.3.2	120	100	170		
1.4.1.2.1	0	100	170			1.3.3.5.3	10		1		
1.5.3.7.5	120	100	170			1.7.1.2.5		10	10	10	100
1.6.5.7.5				100		1.7.2.5.5		10	10	10	100
1.6.5.9.5	40	80	60	60		1.7.1.3.5		70	50	150	10
1.8.5.7.5					110	1.7.3.5.5		60	10	150	

Table 7.5: Production capacities, customer demands (PQ_{mst} in 1000 kton), inventory holding costs (HC_{mst} k$/kton), and quantity ranges (QL_{wr} in 1000 kton) for price-tiers for Example 3

s	PQ_{1s1}	PQ_{1s2}	PQ_{1s3}	PQ_{1s4}	PQ_{1s5}	PQ_{2s1}	PQ_{2s2}	PQ_{2s3}	PQ_{2s4}	PQ_{2s5}
1	100	50	100	80	100	50	100	0	10	10
10	50	40	80	30	20	0	4	60	0	10
7, 9	12	10	17	10	11	4	8	6	1	1.1
11 - 18	12	10	17	10	11	4	1	6	1	1.1
	HC_{1s1}	HC_{1s2}	HC_{1s3}	HC_{1s4}	HC_{1s5}	HC_{2s1}	HC_{2s2}	HC_{2s3}	HC_{2s4}	HC_{2s5}
7, 9, 11-18	12	10	17	10	11	12	10	17	10	11
1, 10	1	1	1	1	1	1	1	1	1	1
	$QL_{w1} = 10$, $QL_{w2} = 100$, $QL_{w3} = 10000$									

Table 7.6: Transport tasks *u* (denoted by *m.c.s.s'.n*), non-transport tasks *v* (denoted by *m.c.n.n'.k*), and their prices (p_{urt} and p_{vrt}, k$/kton) for Example 3

u	p_{urt}	*u*	p_{urt}	*u*	p_{urt}	*u*	p_{urt}	*u*	p_{urt}
1.1.1.2.1	6	1.6.10.5.1	12	2.9.6.7.5	9	1.13.6.7.5	19	1.20.6.18.5	13
1.1.10.2.1	12	1.6.5.7.5	20	2.9.6.17.5	22	1.13.6.9.5	18	2.12.1.6.1	21
1.1.1.5.1	9	1.6.5.9.5	8	2.9.6.18.5	14	1.13.6.17.5	15	2.13.6.7.5	21
1.1.10.5.1	11	1.6.5.11.5	20	2.9.6.16.5	16	1.13.6.18.5	14	2.13.6.9.5	18
1.1.2.3.2	10	1.6.5.12.5	8	2.10.1.2.1	15	1.14.1.6.1	9	2.13.6.17.5	16
1.1.2.3.3	10	2.1.1.5.1	10	2.10.10.2.1	18	1.14.10.6.1	17	2.13.6.18.5	17
1.1.3.7.5	12	2.1.10.5.1	13	2.10.2.11.5	10	1.14.6.8.2	17	2.15.1.6.1	12
1.1.3.9.5	9	2.1.1.3.1	10	2.10.2.12.5	11	1.14.8.7.5	17	2.15.10.6.1	10
1.1.3.11.5	10	2.1.10.3.1	15	2.10.2.13.5	10	1.14.8.9.5	17	2.15.6.7.5	11
1.1.3.12.5	12	2.1.3.7.5	13	2.10.2.14.5	11	1.14.8.11.5	15	2.15.6.9.5	12
1.1.3.13.5	9	2.1.3.9.5	11	1.8.10.4.1	10	1.14.8.12.5	15	2.15.6.11.5	13
1.1.5.14.5	10	2.1.3.11.5	12	1.8.4.5.3	12	1.14.8.13.5	16	2.15.6.12.5	14
1.1.5.15.5	12	2.1.3.12.5	13	1.8.5.7.5	12	1.14.8.14.5	17	2.15.6.13.5	14
1.1.5.16.5	19	2.1.3.13.5	10	1.8.5.9.5	12	1.14.1.5.1	17	2.15.6.14.5	12
1.1.5.17.5	20	2.1.5.14.5	11	1.8.5.17.5	22	1.14.10.5.1	19	2.15.6.15.5	14
1.1.5.18.5	18	2.1.5.15.5	13	1.8.5.18.5	20	1.14.5.7.5	17	2.15.6.16.5	12
1.2.3.11.5	12	2.1.5.16.5	20	1.8.4.7.5	13	1.14.5.9.5	16	2.15.6.17.5	15
1.2.3.12.5	14	2.1.5.17.5	22	1.8.4.9.5	13	1.14.5.11.5	13	2.15.6.18.5	15
1.2.3.13.5	14	2.1.5.18.5	20	1.8.4.11.5	12	1.14.5.12.5	16	2.16.10.2.1	13
1.2.3.14.5	12	2.2.5.11.5	12	1.8.4.12.5	14	1.14.5.13.5	17	2.17.2.3.2	14
1.2.3.15.5	12	2.2.5.12.5	16	1.8.4.13.5	13	1.14.5.14.5	16	2.18.3.9.5	12
1.3.3.16.5	21	2.2.5.13.5	14	1.9.1.6.1	12	1.16.10.2.1	11	2.18.3.11.5	13
1.3.3.17.5	22	2.2.5.14.5	15	1.9.6.7.5	13	1.17.2.3.2	12	2.18.3.12.5	14
1.3.3.18.5	22	2.2.5.15.5	16	1.9.6.17.5	21	1.18.3.9.5	10	2.18.3.13.5	12
1.3.3.7.5	13	2.5.1.5.1	13	1.9.6.18.5	12	1.18.3.11.5	12	2.18.3.14.5	14
1.3.3.9.5	16	2.5.10.5.1	15	1.9.6.16.5	15	1.18.3.12.5	13	2.18.3.15.5	15
1.4.1.2.1	7	2.5.5.7.5	10	1.10.1.2.1	9	1.18.3.13.5	10	2.19.10.6.1	17
1.4.2.3.2	11	2.5.5.9.5	11	1.10.10.2.1	14	1.18.3.14.5	12	2.20.6.7.5	13
1.4.3.7.5	13	2.5.5.16.5	21	1.10.2.11.5	13	1.18.3.15.5	14	2.20.6.16.5	14
1.4.3.12.5	13	2.5.5.17.5	22	1.10.2.12.5	15	1.19.10.6.1	17	2.20.6.17.5	15
1.4.3.14.5	10	2.5.5.18.5	23	1.10.2.13.5	16	1.20.6.7.5	12	2.20.6.18.5	15
1.4.3.16.5	19	2.5.5.15.5	15	1.10.2.14.5	17	1.20.6.16.5	13	2.21.1.2.1	12
1.4.3.18.5	19	2.9.1.6.1	12	1.12.1.6.1	19	1.20.6.17.5	12	2.22.2.7.5	13
1.6.1.5.1	10								
v	p_{vrt}	*v*	p_{vrt}	*v*	p_{vrt}	*v*	p_{vrt}	*v*	p_{vrt}
1.1.1.2.2	20	1.3.1.3.3	27	1.9.1.2.6	21	1.23.1.2.2	24	2.7.1.2.5	21
1.1.1.3.2	25	1.3.3.5.3	12	1.9.2.5.6	15	1.24.2.5.3	11	2.7.2.5.5	16
1.1.2.5.3	11	1.7.1.2.5	22	1.10.1.3.2	28	1.25.1.3.6	27	2.9.1.2.6	19
1.1.3.5.3	9	1.7.2.5.5	13	1.10.3.5.2	12	1.26.3.5.6	9	2.9.2.5.6	11
1.1.1.2.5	18	1.7.1.3.5	28	1.11.1.3.6	27	2.1.1.2.5	21	2.10.1.2.2	21
1.1.2.5.5	12	1.7.3.5.5	14	1.11.3.5.6	12	2.1.2.5.5	11	2.10.2.5.2	12
1.1.1.3.5	26	1.8.1.2.4	17	1.14.1.2.6	22	2.1.1.2.3	22	2.15.1.2.6	21
1.1.3.5.5	9	1.8.1.3.4	22	1.14.2.5.8	11	2.1.2.5.3	12	2.15.2.5.6	11
1.2.1.2.3	25	1.8.2.5.4	12	1.14.1.3.5	23	2.2.1.2.5	22	2.27.1.2.2	24
1.2.2.5.3	12	1.8.3.5.5	13	1.14.3.5.5	11	2.2.2.5.5	12	2.28.2.5.2	12

Table 7.7: Tasks and amounts (1000 kton) of materials processed via different contracts in Example 3

u	Q_{u1}	Q_{u2}	Q_{u3}	Q_{u4}	Q_{u5}	v	Q_{v1}	Q_{v2}	Q_{v3}	Q_{v4}	Q_{v5}
1.1.1.2.1					10	1.1.1.2.2					10
1.1.1.5.1	54	51	100	60	100	1.1.2.5.3					10
1.1.10.5.1		9				1.1.1.2.5	54	60	100	60	100
1.1.2.3.2					10	1.1.2.5.5	54	60	100	60	100
1.1.3.13.5					10	1.8.1.2.4	50	30	51	30	
1.1.5.14.5	12	10	17	10	11	1.8.2.5.4	50	30	51	30	
1.1.5.15.5	12	10	17	10	11	1.9.1.2.6	16	10	19	10	
1.1.5.16.5	10	10	15	10	11	1.9.2.5.6	16	10	19	10	
1.1.5.17.5				10	11	2.1.1.2.5	8	2	1	2	2.2
1.1.5.18.5	10	10	17		11	2.1.1.2.3	16	1	6	1	1.1
1.6.5.9.5		10	17	10	11	2.1.2.5.3	16	1	6	1	1.1
1.6.5.12.5		10	17	10	11	2.1.2.5.5	8	2	1	2	2.2
1.8.10.4.1	50	30	51	30		2.9.1.2.6	16	21	53	7	
1.8.4.13.5	12	10	17	10		2.9.2.5.6	16	21	43	7	
1.8.5.9.5	10					2.15.1.2.6					7.7
1.8.4.7.5	12	10	17	10		2.15.2.5.6			10		7.7
1.8.4.9.5	2										
1.8.4.11.5	12	10	17	10		u	Q_{u1}	Q_{u2}	Q_{u3}	Q_{u4}	Q_{u5}
1.8.4.12.5	12					2.9.1.6.1	16	7		0	
1.9.6.18.5	2			10		2.9.6.7.5	4	8	6	1	
1.14.1.6.1	16	10	19	10		2.9.6.18.5	4	1	6	1	
1.14.5.7.5					11	2.15.1.6.1		10			
1.14.5.11.5					11	2.15.10.6.1		4	53	7	7.7
1.14.5.13.5					1	2.15.6.7.5					1.1
1.20.6.16.5	2		2			2.15.6.9.5		8	6	1	1.1
1.20.6.17.5	12	10	17			2.15.6.11.5		1	6	1	1.1
2.1.1.5.1	8	2	1	2	2.2	2.15.6.12.5		1	6	1	1.1
2.1.1.3.1	16	1	6	1	1.1	2.15.6.14.5		0	5		
2.1.3.9.5	4					2.15.6.15.5		0	6		
2.1.3.11.5	4					2.15.6.16.5		1	6	1	1.1
2.1.3.12.5	4					2.15.6.17.5		1	6	1	1.1
2.1.3.13.5	4	1	6	1	1.1	2.15.6.18.5					1.1
2.1.5.14.5	4	1	1	1	1.1	2.20.6.16.5	4				
2.1.5.15.5	4	1	0	1	1.1	2.20.6.17.5	4				

Table 7.8: Customer demands (PQ_{mst} in 100 kton), and updated contracts with tasks (v) and costs (p_{vrt} k$/kton) for Example 4

s	PQ_{1s1}	PQ_{1s2}	PQ_{1s3}	PQ_{2s1}	PQ_{2s2}	PQ_{2s3}	c	v	p_{vrt}
7	170	100	0	60	0	11	C23	1.23.1.2.2	20
9	170	0	110	0	10	11	C24	1.24.2.5.3	10
11	17	10	11	6	10	11	C25	1.25.1.3.6	20
12	17	0	11	6	10	11	C26	1.26.3.5.6	10
13	17	0	11	6	20	11	C27	2.27.1.2.2	20
14	17	0	11	100	0	0	C28	2.28.2.5.2	8
15	17	0	11	6	10	0			
16	17	100	11	6	10	0			
17	17	100	11	6	10	11			
18	17	100	0	6	20	11			
Note that all other contracts are the same as in Table 7.6									

Table 7.9: Tasks and amounts (100 kton) of materials processed via different contracts in Example 4

u	Q_{u1}	Q_{u2}	Q_{u3}	u	Q_{u1}	Q_{u2}	Q_{u3}	v	Q_{v1}	Q_{v2}	Q_{v3}
1.1.1.5.1	221	100	176	1.20.6.17.5	17			1.1.1.2.5	221	100	176
1.1.5.14.5	17		11	1.20.6.16.5	17			1.1.2.5.5	221	100	176
1.1.5.15.5	17		11	2.1.1.3.1			11	1.8.1.2.4	34	10	
1.1.5.16.5			11	2.1.3.13.5			11	1.8.2.5.4	34	10	
1.6.5.9.5	170		110	2.9.6.7.5	60			1.25.1.3.6	221	300	11
1.6.5.12.5	17		11	2.9.6.18.5	6	20		1.26.3.5.6	221	300	11
1.8.10.4.1	34	10		2.15.6.7.5	0	0	11				
1.8.4.13.5	17			2.15.6.9.5		10	11	2.1.1.2.3			11
1.8.5.7.5	0	100		2.15.10.6.1	202	100	66	2.1.2.5.3			11
1.8.4.11.5	17	10		2.15.6.11.5	6	10	11				
1.9.6.16.5		100		2.15.6.12.5	6	10	11	2.9.1.2.6	202	100	
1.9.6.18.5	17	100		2.15.6.13.5	6	20		2.9.2.5.6	102	100	
1.13.6.17.5		100	11	2.15.6.14.5	100			2.15.1.2.6			66
1.14.1.6.1	221	300	11	2.15.6.15.5	6	10		2.15.2.5.6	100		66
1.14.5.11.5			11	2.15.6.16.5	6	10					
1.14.5.13.5			11	2.15.6.17.5	6	10	11				
1.20.6.7.5	170			2.15.6.18.5	0	0	11				

CHAPTER 8. SELECTING CONTRACTS FOR THE SUPPLY OF RAW MATERIALS UNDER UNCERTAINTIES

Continuous change, uncertainty, and intense competition are the norms in today's volatile business environment. As mentioned earlier, uncertainty plays an important role in supply chains. Uncertainties in price, availability, demand, production costs, etc. complicate the task of a supply chain manager to meet customer demand on time. Hence, it is necessary to consider the impact of uncertainties in supply chain planning.

The objective of this chapter is to extend the model of selection of material suppliers and supply contracts (Chapter 5) under uncertain operating and economic conditions. An efficient deterministic MILP model explained in chapter 5 solves relatively quicker even for an industry-scale example, which enables us to use a scenario-based approach. In a scenario based approach, one could consider many scenarios without making the problem too large to solve. Thus, we adopt MILP model explained in chapter 5 for this work involving business uncertainties. We now proceed to consider the case where demands and prices are not known exactly but are subject to some uncertainty.

8.1 Scenario Generation

As mentioned earlier, scenario based approach attempts to capture uncertainty by representing it in terms of a moderate number of discrete realizations of the stochastic quantities, constituting distinct scenarios A question that needs to be addressed in this context concerns the generation of the scenarios. Mobasheri et al. (1989) describe scenario as a plausible possible states derived from the present state with consideration of potential major industry events. In our model, each scenario defines a set of possible outcomes over the planning horizon – demand or price realization for each material at each site during each period. For scenario generation, we allow three random levels (average, average+20%, and average–20%) of demands and purchase prices and assume that all scenarios are equally probable.

8.2 MILP Formulation

To capture the uncertainties in various parameters such as demands and prices, we use scenarios denoted by superscript i with α^i being the probability of scenario i. In this chapter, we consider uncertainties in demands and purchase prices. Thus, D^i_{mst} represents the demand of m at site s in scenario i during t and p^i_{mcr} as the price of m via contract c in price-tier r in scenario i. For the sake of brevity, we illustrate the major changes in the formulation of chapter 5 for just one type of contract. Others would follow accordingly. We select TQCFB (total quantity commitment contract with flexibility and multi-tier bulk discounts) as the contract for illustration. Thus, while the following discussion and constraints are in general valid for any contract type, some of them (as indicated in the subsequent discussion) are strictly valid for TQCFB contracts only.

For the scenario-based approach, we divide the main decision variables in the formulation of chapter 5 into two classes. The decisions related to contract selection and durations will be scenario-independent, and they are as follows.

$$ys_{ct} = \begin{cases} 1 & \text{if contract } c \text{ begins at the start of period } t \\ 0 & \text{otherwise} \end{cases}$$

$$z_c = \begin{cases} 1 & \text{if contract } c \text{ is selected} \\ 0 & \text{otherwise} \end{cases}$$

$$z_c = \sum_{t=1}^{T} ys_{ct} \quad (8.1)$$

$$y_{ct} = \begin{cases} 1 & \text{if contract } c \text{ is in effect during period } t \\ 0 & \text{otherwise} \end{cases}$$

$$y_{ct} = \sum_{t-CL_c+1}^{t} ys_{ct} \quad (8.2)$$

The remaining variables related to purchase and distribution profiles will be scenario-dependent, and they are as follows.

$$Q_{mc}^{i} = \sum_{t=1}^{T} q_{mct}^{i} \quad (8.3)$$

$$q_{mct}^{i} \leq y_{ct} q_{mct}^{U} \quad (8.4)$$

$$Q_{mc}^{i} \leq Q_{mc}^{U} z_c \quad (8.5)$$

$$\sum_{r=1}^{R_{mc}} \beta_{mcr}^{i} = z_c \quad (8.6)$$

$$Q_{mc}^{i} = \sum_{r=1}^{R_{mc}} (QL_{mc(r-1)} \beta_{mcr}^{i} + \Delta Q_{mcr}^{i}) \quad (8.7)$$

$$\Delta Q_{mcr}^{i} \leq \beta_{mcr}^{i} [QL_{mcr} - QL_{mc(r-1)}] \quad (8.8)$$

$$PC_{mc}^{i} = \pi_{mc} (QL_{mc1} \beta_{mc1}^{i} - \Delta Q_{mc1}^{i}) + \sum_{r=1}^{R_{mc}} p_{mcr}^{i} (QL_{mc(r-1)} \beta_{mcr}^{i} + \Delta Q_{mcr}^{i}) \quad (8.9)$$

$$q_{mct}^{i} = \sum_{s} S_{mcst}^{i} \quad (8.10)$$

$$\sum_{c,t} S_{mcst}^{i} \geq \sum_{t} D_{mst}^{i} \quad (8.11)$$

$$C = \sum_{m \in M_c} \sum_{c,s,i,t} \alpha^{i} PC_{mct}^{i} + \sum_{m \in M_c} \sum_{c,s,i,t} \alpha^{i} S_{mcst}^{i} LC_{mcst} + \sum_{m \in M_c} \sum_{c,s,i} \sum_{t} \alpha^{i} I_{mst}^{i} HC_{mst} \quad (8.12)$$

Note that eq. 8.9 is valid only for TQCFB contracts, while others are applicable for all contract types. Equations corresponding to other contract types can be modified from those given in chapter 5.

8.3 Example

We consider Example 1 of chapter 5 and allow three random levels (average, average+20%, and average–20%) of demands and purchase prices. In this example, the MNC has three plant sites (s = 1, 2, 3) that require two materials (m = 1, 2). The planning horizon involves five periods (t = 1, 2, 3, 4, 5 years; T = 5). The central procurement department is evaluating nineteen supply contracts: three TQC-FLB (C1, C2, C3), three TQC-FB (C4, C5, C6), three TQC-U (C7, C8, C9), three PQC-FU (C10, C11, C12), three PQC-B (C13, C14, C15), two TDC-FB (C16, C17), and two PDC-U (C18, C19). For an explanation of contract types, please refer chapter 5. We consider three cases. In Case 1, price is deterministic and only demands are uncertain. In Case 2, demands and spot prices are uncertain, but contract prices are fixed. In Case 3, demands as well as prices of all contracts are uncertain. Case 3 applies in a situation where for raw material prices may be pegged to the price of a fixed commodity. For instance, the price of liquefied natural gas (LNG) in many long-term supply contracts is pegged to the price of crude oil. We solve our model using CPLEX v10.0.1 in GAMS 22.2 (Brooke et al., 2005) on a 3.00 GHz Pentium® PC with 2 GB of RAM.

8.3.1 Case 1

We simulated hundred scenarios for demand levels randomly and assigned equal probabilities to them. The first scenario involves average demands, while the remaining ninety nine scenarios have demands at one of three levels randomly. For the average demand data, please refer to Table 5.2 of chapter 5.

For the deterministic case (scenario 1 – average demand), the optimal plan includes three contracts, namely C1 (TQC-FLB), C16 (TDC-FB), and C19 (PDC-U), and spot purchases at various times. Now, when we include various scenarios, the same contracts C1, C16, and C19 along with spot purchases are selected. These selected contracts are the first-stage decisions, while the second stage decisions involve quantities of materials purchased via different contracts, distribution of these materials to different sites, and their inventory levels. First stage decisions remain unchanged for deterministic and stochastic demands. Stochastic market demands results in an average procurement cost that is 0.67% (Gap of 0.5%) and 0.85% (Gap of 0.1%) lower than that for the deterministic case. The model solution time is 18.3 CPU s (Gap of 0.5%) compared to negligible (< 1) CPU s for the deterministic case. The increase in the computational time is due to increase in the number of constraints and variables which are reported in Table 8.1 However, computational time grows significantly (336.7 CPU s) if we reduce the gap from 0.5 percent to 0.1 percent.

8.3.2 Case 2

As in Case 1, we simulated hundred scenarios randomly and assigned equal probabilities to them. However, we allowed both demands and spot prices to be uncertain. The first scenario involves average demands and prices while the remaining ninety nine scenarios have demands and prices at one of three levels randomly. For the average spot price data, please refer Table 5.4 (contract C20 and C21 represent spot purchases for materials 1 and 2 respectively).

It is interesting to note that the optimal plan remains unchanged, namely C1 (TQC-FLB), C16 (TDC-FB), and C19 (PDC-U), and spot purchases same as that of the optimal plan of case 1 and of deterministic case. It is important to note that the numbers of variables and constraints are same in case 1 and case 2 as spot price uncertainty does not involve any extra variables. Now, the optimal cost is 58,344.1 K$ which is 0.36 % higher than the case 1. This may be due to spot price uncertainty as price may have increase from their average value for some scenarios and in case 1, we are considering average (deterministic) price for all the scenarios. According to Lababidi et al. (2004), this increase is known as the expected value of perfect information and refers to an increase in cost due to the presence of uncertainty. The computational cost is same as case 1 which is due to same number of variables and constraints.

8.3.3 Case 3

Here, we simulated thirty scenarios randomly and assigned equal probabilities to them. The first scenario involves average demands and prices, while the remaining twenty nine scenarios have demands and prices at one of three levels randomly. It is interesting to note that now four contracts C1, C16, C17, and C19 along with spot purchases are selected compared to three contracts (C1, C16, and C19) and spot purchases selected for deterministic, case 1, and case 2. Stochastic market demands and purchase prices results in an average procurement cost that is 6.4% lower than that of the deterministic case. The model solution time is 5.9 CPU s (Gap of 0.5%) compared to negligible (< 1) CPU s for the deterministic case. The overall computational time grows because of the increase in the number of constraints and variables which are reported in Table 8.1. However, computational time grows significantly (39.1 CPU s) if we reduce the gap from 0.5 percent to 0 percent. Even after the increase in computational cost, our proposed stochastic model is fast and can solve for large number of scenarios and for different uncertainties.

8.4 Discussion

We addressed the strategic and integrated sourcing and distribution of materials in a global and volatile business environment for a MNC, which are key planning decisions in many supply chains including the chemical. The proposed mixed-integer linear programming model selects the best contracts and suppliers that minimize the total procurement cost including the logistics and inventory costs. The model is tested by means of a number of case studies reflecting uncertainty in key parameters such as demand, price, etc. We considered two types of uncertainties together. Since our deterministic model is fast even for an industrial scale example, the scenario based approach is used to model uncertainties. In presence of demand and spot price uncertainty, deterministic and stochastic solutions are same. However, when demands and prices of all contracts are uncertain, the first stage decisions (i.e., the contracts selected, their start time, etc) were found to be different from that of deterministic results which concludes that deterministic models may result in unsatisfactory planning. Although the handling of uncertainty is demonstrated by considering uncertainties in demand and price, other uncertainties such as logistics cost, penalty, etc is incorporated in a simulated manner.

Table 8.1: Model and Solution Statistics

	Deterministic	Case 1		Case 3	
Gap	0%	0.5%	0.1%	0.5%	0%
0-1 variables	265	17,095		5,195	
Single variables	1227	101,910		30,720	
Constraints	841	72,715		21,895	
CPU time [s]	<1	18.3	336.7	5.9	39.1
Cost [K$]	58,523.90	58,136.20	58,025.98	55,007.30	54,946.68

CHAPTER 9. CONCLUSIONS AND RECOMMENDATIONS

Most chemical companies producing mature, undifferentiated products, effective supply chain management requires cost reductions. A major expenditure for such companies is the purchase of materials and logistics services. Thus, managing the procurement and distribution of these materials and services is important for effective supply chain management, and involves a variety of decisions and considerations. The aim of this work was to develop systematic and quantitative methods and tools to support complex decision-making in this and other areas of supply chain management. This work has made a significant contribution to advancing the science of decision support in supply chain management.

First, we developed a multi-agent platform MADE to simulate chemical supply chains and provide an agent middle-ware to support the development of multi-agent systems. MADE simplifies the development of agent applications and provides the developer with an integrated environment for quick and easy construction of a multi-agent model. It provides an easy to use platform to model the functions and activities within a supply chain. MADE can be used for modeling any supply chain with little or no modification. We demonstrated its successful application by modeling and simulating a refinery supply chain (PRISMS-MADE) and analyzing several case studies.

The decision support system provided by PRISMS-MADE highlighted important issues in managing chemical supply chains. One important and cost-intensive process is the timely and cost-effective procurement and distribution of raw materials. Thus, we addressed, in greater detail the strategic and integrated sourcing and distribution of materials, with the help of mathematical models in a global business environment for a MNC. Strategic sourcing of contracts offers several advantages and it is common practice in many industries, especially the chemical industry. We proposed a relatively comprehensive classification of material supply contracts which includes several key real-life contract features such as purchase commitments, commitment durations, purchase flexibility, variable contract lengths, product-bundling, and multi-tier bulk/unit prices and discounts. Our proposed multi-period mixed-integer linear programming model not only selects the best contracts and suppliers that minimize the total procurement cost including the logistics and inventory costs, but also assigns the suppliers and decides the supply distribution to various globally distributed sites of a MNC. It not only accommodates existing contracts, but also allows new contracts to extend beyond the horizon. This allows one to review the supply strategy and contracts periodically. In our preliminary models, we assumed that prices did not vary with time in TQC contracts and the commitment was for a single period in PQC contracts. Therefore, we subsequently revised our models to relax these two assumptions.

Our deterministic MILP model for supply contracts solves relatively quickly even for an industry-scale example, which allowed the use of a scenario based approach for addressing various demand and price uncertainties. The model was tested by means of a number of case studies reflecting uncertainty in key parameters such as demand, price, etc. We considered two types of uncertainties together. In the presence of demand and spot price uncertainty, deterministic and stochastic solutions are the same (i.e., the contracts selected, quantity purchased, their start times, etc.). However, when demands and prices of all contracts are uncertain, the first stage decisions (i.e., the contracts selected, their start times, etc.) were found to be different from deterministic results which concluded that deterministic models may result in unsatisfactory planning. We simulated 100 scenarios for demands and spot prices uncertainty and found that computational time grows significantly in comparison with the deterministic case which is due to increase in the number of constraints and variables. Even after the increase in computational cost, our proposed stochastic model can solve for a large number of scenarios and for different uncertainties. Although the handling of uncertainty was demonstrated by considering uncertainties in demand and price, other uncertainties such as logistics cost, penalty, etc can be incorporated in a similar manner.

To compliment our work on materials, we also presented a systematic framework for managing chemical logistics in an integrated manner. We developed a systematic and quantitative decision-making formalism to address the integrated logistics needs of a MNC in a global business environment. Although our goal was to address the logistics in chemicals and related industries in particular, the methodology is general and applicable to other supply chains as well. The formalism involved a novel representation of logistics activities in terms of a recipe superstructure and a static MILP model based to select the contracts that minimize the total logistics cost. It allows the flexibility of selecting partial contracts, which reduces the combinatorial complexity and computation time considerably, along with some reduction in costs under certain assumptions. The model not only accommodates existing contracts, but also allows new contracts to extend beyond the horizon. Thus, it is able to address in a reactive manner the various dynamic disruptions that normally arise in chemical supply chains. We also found that the full selection of contracts were not only costly, it was also computationally expensive. Lastly, our model assumed zero inventory at the hub sites and allowed contracts to be selected only once in the planning horizon.

9.1 Recommendations

Unhindered and timely material, information, and finance flow between different entities of supply chain is important. Blockage in any of these would lead to undesirable events like process shutdown, financial loss, under-supply or over-supply, etc. Hence, there is a greater need for risk and disruption management. The agent-based refinery supply chain model described earlier can be extended to provide decision support during disruptions. An agent-based disruption management system should be capable of detecting abnormal situations before they occur, diagnose the root cause, and propose corrective actions as required (Bansal et al., 2005). The agents that model the department can be endowed with additional capabilities (by including suitable threads to their Grafcets) to measure entity-specific key performance indicators (KPIs). These KPIs can also be monitored by the agents by comparing their day-to-day values against pre-planned limits. Alarms can be generated when a sustained deviation in any KPI is detected. Corrective agents can be proposed and scheduled into the supply chain operation as necessary.

Also, MADE can be extended to provide selection of supply and logistics contracts. An Optimizer agent can be developed in MADE that connects to GAMS to get the optimal contracts.

Our MILP model of global supply and distribution of materials allowed contracts to be selected only once in the planning horizon. This can be extended for multiple selections of same contracts. Also, cost is used as the sole selection criterion in the case of global supply. Usually, a company has other non-quantifiable criteria for contract selection such as reliability, service quality, etc. Addressing them together is a challenge. These extensions are also applicable for the selection of logistics contracts.

As MNC can purchase materials from suppliers with any contracts (supply contracts, customers can buy products from MNC through different types of contracts (sales contracts). Our model can be extended for sales contracts and for combination of supply contracts, sales contracts, and spot market.

The handling of uncertainty is demonstrated by considering uncertainties in demand and price in the MILP model of global supply and distribution of materials, other uncertainties such as logistics cost, penalty, etc can be incorporated in a similar manner. The effect of uncertainties in the selection of third-party logistics contracts can also be addressed in a similar manner. Also, our logistics contracts model assumed zero inventory at the hub sites. This can also be a future work.

We looked into the selection of supply and logistics contracts from the perspective of buyers, i.e, MNC. However, designing and selecting contracts from the seller's perspective can be a potential research area. The design of contracts includes deciding minimum commitment, duration of contract, penalty cost, price, etc. Selection of transport carrier can also be an interesting future work. Selection of an appropriate transport carrier is an important business decision, where a range of different service attributes offered by the transport supplier can be evaluated.

Another challenging research direction can be 3PLs (or 4PLs) collaboration. The key to collaboration lies in identifying and reducing the "hidden costs" that all 3PLs in a logistics system pay.

REFERENCES

AgentBuilder - An integrated tool suite for constructing intelligent software agents. http://www.agentbuilder.com

Aldea, A., Bañares-Alćantra, R., Jiménez, L., Moreno, A., Martínez, J., Riaño, D., (2004). The scope of application of multi-agent systems in the process industry: three case studies. Expert Systems with Applications, 26 (2004) 39 -47.

Andersson, D. (1997). Third Party Logistics-Outsourcing Logistics in Partnerships. Dissertation No. 34, Department of Management and Economics, 1997, Linköpings Universitet, Sweden.

Andersson, Dan, and Norrman, A., (2002). Procurement of logistics services – a minutes work or a multi-year project? European Journal of Purchasing and Supply Management, 8(1), pp 3-14.

Anupindi, R., Y. Bassok., (1999). Supply contracts with quantity commitments and stochastic demand. In: Tayur, S., Ganeshan, R., Magazine, M. (Eds.), Quantitative Models for Supply Chain Management. Kluwer Academic Publishers, Dordrecht, pp 199-232.

Bagchi, Prabir. K., (1989). Carrier Selection: the analytic hierarchy process. Logistics and Transportation Review, 25(1), pp 63-73.

Bagchi, P.K., Virum, H., (1998). Logistical alliances: trends and prospects in integrated Europe. Journal of Business Logistics, 19 (1), 191-213.

Bansal, M., Adhitya, A., Srinivasan, R., Karimi, I., (2005). An Online Decision Support Framework for Managing Abnormal Supply Chain Events, Presented in the European Symposium on Computer Aided Process Engineering – 15, Barcelona, Spain, May 29 – Jun, 2005.

Barber, K.S, Goel, A., Han, D. C., Kim, J., Lam, D. N., Liu, T.H., MacMohan, M., Martin, C.E., and Mckay, R., (2003). Infrastructure for Design, Deployment and Experimentation of Distributed Agent-based Systems: The Requirements, The Technologies, and an Example. Autonomous Agents and Multi-Agent Systems, 7, 49-69, 2003.

Beamon, B. M., (1998). Supply chain design and analysis: Models and methods. International Journal of Production Economics 55 (3), 281.

Bender, P.S., Brown, R.W., Isaac, M.H., and Shapiro, J.F., (1985) Improving purchasing productivity at IBM with a normative decision support system. Interfaces 1985, 15, 106-115.

Bhatnagar, R., Sohail, A.S., Millen, R., (1999). Third Party Logistics Services: A Singapore Perspective. International Journal of Physical Distribution & Logistics Management, 1999, 29, pp 569-587.

Bond, A. H., & Gasser, L., (1988). An analysis of problems and research in DAI. Readings in distributed artificial intelligence. San Mateo, CA: Morgan Kaufman.

Braithwaite, A., (2002) Achieving world class supply chain and logistics in the chemical industry. EPCA Logistics Meeting Monaco, November 2002.

Brooke, A., Kendrick, D., Meeraus, A., Raman, R., (2005). GAMS: A User's Guide.

Buffa, F.P., and Jackson, W.M., (1983) A goal programming model for purchase planning. Journal of Purchasing and Materials Management, 27-34.

Burton, T.T., (1988) JIT/repetitive sourcing strategies: "Tying the knot" With your suppliers. Production and Inventory Management Journal, 38-41.

Byrne, P.M., (1993) A new road map for contract logistics. Transportation & Distribution, April, pp. 58-62.

Chaudhry, S.S., Forst, F.G., Zydiak, J.L., (1991) A multicriteria approach to allocating order quantity among vendors. Production and Inventory Management Journal, 32, 82-85.

Chen, F.Y., Krass, D., (2001) Analysis of supply contracts with minimum total order quantity commitments and non-stationary demands. European Journal of Operational Research, 131, 309-323.

Chen, C., Wang, B., Lee, W., (2003). Multiobjective Optimization for a Multienterprise Supply Chain Network. Industrial Engineering Chemistry Research 42, 1879-1889.

Chen, C. L., Lee, W.C., (2004). Optimization of Multi-Echelon Supply Chain Networks with Uncertain Sales Process. Journal of Chemical Engineering of Japan, Vol. 37, No. 7, pp. 822-834.

Choudhary, A., Tiwari, M., Mukhopadhyay, S., (2004). Application of an analytical network process to strategic planning problems of a supply chain cell: case study of a pharmaceutical firm. Production Planning & Control Vol. 15, No. 1, Jan 2004, 13-26.

Cicirello, V.A., and Smith, S.F., (2004). Wasp-like Agents for Distributed Factory Coordination. Autonomous Agents and Multi-Agent Systems, 8, 237-266, 2004.

Cohen, M. A. & Lee, H. L., (1998). Strategic analysis of integrated production-distribution systems: Models and methods. Operations Research 36 (2), 216.

Cohen, M. A. & Moon, S., (1990). Impact of production scale economies, manufacturing complexity, and transportation costs on supply chain facility networks. Journal of Manufacturing and Operations Management 3, 269.

David, R., and Alla, H., (1992), Petri nets and Grafcet : tools for modelling discrete event systems, Prentice-Hall.

Davis, T., 1993. Effective Supply Chain Management. Sloan Manage. Rev., Summer, 35-46.

Dempsey, W.A., (1978). Vendor selection and the buying process. Journal of Purchasing, 2/1, 5-17.

De Souza, R., (2004). Logistics: Complexity, challenges and opportunities, Logistics & SCM, Inaugural Issue.

European Commission – Chemicals Introduction, http://www.europa.eu.int/comm/energy_transport/atlas/htmlu/chemintro.html

Fishhaut, Eric., (2003), Petrochemicals firms take a stand against oil price volatility. GlobalView Software, May.

FIPA Agent Management Specification. Foundation for Intelligent Physical Agents, (2002), http://www.fipa.org/specs/fipa0023/

FIPA-OS home page.

http://www.nortelnetworks.com/products/announcements/fipa/index.html/

Flores, R. Garcia., Wang, X.Z. & Goltz, G. E., (2000). Agent-based information flow for process industries' supply chain modelling. Computers & Chemical Engineering 24, 1135-1141

Frascatore, M.R., Mahmoodi, F., (2008). Long-term and penalty contracts in a two-stage supply chain with stochastic demand. European Journal of Operational Research, 184, 147-156,

Frazelle, E., (2002) *S*upply chain strategy: the logistics of supply chain management, New York, McGraw Hill Pub Co, 2002.

Foster, T.A. and Muller, E.J., (1990) Third parties: your passport to profits. Distribution, October, pp. 30-32.

Fox, M. S., Barbuceanu, M., and Teigen, R., (2000). Agent-Oriented Supply-Chain Management. The International Journal of Flexible Manufacturing Systems, 12, (2000): 165-188.

Ganeshan, R., Harrison, T.P., (1995). An introduction to Supply Chain Management; Technical Report; Department of Management Science and Information Systems, The Pennsylvania State University: University Park, PA.

Gaonkar, R., Viswanadham, N., (2004). A Conceptual and Analytical Framework for the Management of Risk in Supply Chains. Proceedings - IEEE International conference on Robotics and Automation, Volume 2004, Issue 3, 2004, Pages 2699-2704.

Ghodsypour, S.H., O'Brien, C., (1998) A decision support system for supplier selection using an integrated analytic hierarchy process and linear programming. International Journal of Production Economics, 56-57, 199-212.

Ghodsypour, S.H., O'Brien, C., (2001) The total cost of logistics in supplier selection, under conditions of multiple sourcing, multiple criteria and capacity constraint. International Journal of Production Economics, 73, 15-27.

Giannoccaro, I., Pontrandolfo, P., Scozzi, B., (2003). A Fuzzy Echelon Approach for Inventory Management in Supply Chains. European Journal of Operational Research, 149, 185-196.

Guillén, G., Mele, F., Bagajewicz, M., Espuña, A., Puigjaner, L., (2005). Multiobjective supply chain design under uncertainty. Chemical Engineering Science 60, 1535-1553.

Gupta, A., Maranas, Costas. D., (2000). A Two-stage Modeling and Solution Framework for Multisite Midterm Planning under Demand Uncertainty. Industrial & Engineering Chemistry Research, 39, 2000, 3799-3813.

Gupta, A., Maranas, C., Mcdonald, C., (2000). Mid-term supply chain planning under demand uncertainty: customer demand satisfaction and inventory management. Computers and Chemical Engineering 24 (2000), 2613-2621.

Gupta, A., Maranas, C., (2003). Managing demand uncertainty in supply chain planning. Computers and Chemical Engineering 27 (2003) 1219-1227.

Harrington, L., (1995) Logistics, agent for change: shaping the integrated supply chain. Transportation & Distribution, 1995a, January, pp. 30-34.

Hoffman, W., (2002). Better chemistry through technology. Supply Chain Technology News, May 2002.

http://people.hofstra.edu/geotrans/eng/ch3en/conc3en/ch3c1en.html accessed on 21 Jan 2008.

http://www.gensym.com/documents/g2_datasheet.pdf accessed on 17 Nov 2008.

JADE home page. http://jade.tilab.com/

Janssen, M., (2005). The architecture and business value of a semi-cooperative, agent-based supply chain management system. Electronic Commerce Research and Applications, 2005, Volume 4, Issue 4, pp 315-328.

Jeon, H., Petrie, C, Cutkosky, (2000) JATLite: A Java Agent Infrastructure with Message Routing. IEEE Internet Computing Vol. 4, No. 2: March-April 2000, pp 87-96.

Jetlund, A.S., Karimi, I.A., (2004). Improving the logistics of multi-compartment chemical tankers. Computers & Chemical Engineering, 2004, 28, 1267-1283.

Julka, N., Srinivasan, R., Karimi, I., (2002). Agent-based supply chain management-1: Framework. Computers and Chemical Engineering 26 (2002) 1755-1769.

Julka, N., Karimi, I., Srinivasan, R., (2002). Agent-based supply chain management-2: a refinery application. Computers and Chemical Engineering 26 (2002) 1771-1781.

Karimi, I.A., Sharafali, M., Mahalingam, H., (2005). Scheduling tank container movements for chemical logistics. AICHE, 51, 178-197.

Karimi, I., Srinivasan, R., Viswanadham, N., (2000). Chemical Supply Chains Supply Chain Mapping and Tool Development. The Logistic Institute-Asia Pacific, Chemicals Supply Chain Research, WP: TLI-AP/00/09, May 2000.

Karimi, I.A., Srinivasan, R., Han, P.L., (2002). Unlock supply chain improvements through effective logistics. Chemical Engineering Progress, 5, 32-38.

Karpak, B., Kumcu, E., Kasuganti, R.R., (2001). Purchasing materials in the supply chain: managing a multi-objective task. European Journal of Purchasing & Supply Management, 7, 209-216.

Kasilingam, R. G., Lee, C.P., (1996). Selection of Vendors- A Mixed-Integer Programming Approach. Computers ind. Engg, Vol *31*, No. ½, pp 347-350.

Kearney, A.T., (2000). Insight to impact: Results of the Fourth Quinquennial European Logistics Study. Brussels: European Logistics Association.

Kimbrough, S. O., Wu, D. J. & Zhong, F., (2002). Computers play the beer game: can artificial agents manage supply chains? Decision Support Systems 33 (2002) 323-333.

Khosla, R., Ichalkaranje, N., Jain, L., (), Design of Intelligent Multi-Agent Systems, Springer.

Krajewski, L.J., Ritzman, L.P., (1999). Operations Management- Strategy and Analysis. Addison Wesley, Reading, Mass 1999.

Lababidi, H., Ahmed, M., Alatiqi, I., Al-Enzi, A., (2004). Optimizing the Supply Chain of a Petrochemical Company under Uncertain Operating and Economic Conditions. Industrial Engineering Chemistry Research 2004, 43, 63-73.

Lambert, D.M., Stock, J.R., (1993). Strategic Logistics Management, Irwin, Homewood, IL.

Lambert, D.M., (2001). The Supply Chain Management and Logistics Controversy. In: Brewer, A.M., Button, K.J., Hensher, D.A., (Eds.), Handbook of Logistics and Supply-Chain Management. Pergamon Publishers, Netherland, pp 99 – 126.

Lambert, D. M. & Cooper, M.C., (2000). Issues in supply chain management. Industrial Marketing Management 29 (1), 65.

Lee, H. L. & Billington, C., (1993). Material management in decentralized supply chains. Operations Research 41 (5), 835.

Liang, W. Y. & Huang, C. C., (2006). Agent-based demand forecast in multi-echelon supply chain. Decision Support Systems 42, 390-407.

Lieb, R., and Randall, H., (1996). A comparison of the use of third party logistics services by large American manufacturers, 1991, 1994, and 1995. Journal of Business Logistics, 1996, 17(1), pp 305-320.

Liu, M. L., & Sahinidis, N. V., (1997). Process planning in a fuzzy environment. European Journal of Operational Research, 100, 142.

Maltz, Arnold B., and Ellram, Lisa M., (1997) Total cost of relationship: An analytical framework for the logistics outsourcing decision. Journal of Business Logistics, 18(1), pp 45-66.

Martínez-de-Albéniz, V., Simchi-Levi, D., (2005). A Portfolio Approach to Procurement Contracts. Production and Operations Management, Vol. *14*, No. 1, pp 90-114.

McGinnis, M.A., (1989). A comparative evaluation of freight transportation choice models. Transportation Journal, 29(2), pp 36-46.

Menon, M.K., McGinnis, M.A., Ackerman, K.B., (1998). Selection creteria for providers of third-party logistics services: an exploratory study. Journal of Business Logistics, 19 (1), 121-137.

Mishra, M., R. Srinivasan, and I. A. Karimi, (2003). Managing disruptions in refinery supply chain using an agent-based decision support system, Presented in the AIChE annual meeting, San Francisco, Nov 16-21.

Mobasheri, F., Orren, L. H., Sioshansi, F. P., (1989). Scenario Planning at Southern California Edison. Interfaces, 19, 31-44.

Mohanty, R.P., Deshmukh, S.G., (1993). Use of analytic hierarchic process for evaluating sources of supply. International Journal of Physical Distribution & Logistics Management, Vol. *23*, Issue. 3.

Mulvey, J. M., Rosenbaum, D. P., Shetty, B., (1997). Strategic Financial Risk Management and Operations Research. European Journal of Operational Research, 97, 1-16.

Nydick, R. L., Hill, R. P., (1992). Using the Analytic Hierarchy Process to Structure the Supplier Selection Procedure. International Journal of Purchasing and Materials Management, 28 (1), pp 31-36.

Papageorgiou, L., Rotstein, G., Shah, N., (2001). Strategic Supply Chain Optimization for the Pharmaceutical Industries. Industrial Engineering Chemistry Research 2001, 40, 275-286.

Park, M., Park, S., Mele, F.D., Grossmann, I.E., (2006). Modeling of Purchase and Sales Contracts in Supply Chain Optimization. Industrial Engineering Chemistry Research, 45 (14), pp 5013 – 5026.

Parunak, H.V.D., (1996): Applications of distributed artificial intelligentce in industry. In O'Hare and Jennings, eds., Foundations of Distributed Artificial Intelligence, John Willey & Sons.

Parunak, H.V.D., Savit, R., Riolo, R.L., (1998) Agent-Based Modeling vs. Equation-Based Modeling: A Case Study and User's Guide. Proceedings of Workshop on Multi-Agent Systems and Agent-Based Simulation (MABS'98), Springer: Berlin, 1998, pp 10-25. Available at http://www.erim.org/~vparunak/mabs98.pdf.

Pedersen, E.L., and Gray, Richard., (1998) The transport selection criteria of Norwegian exporters. International Journal of Physical Distribution & Logistics Management, 28(2), pp 108-120.

Perea, E., Grossmann, I., Ydstie, E., Tahmassebi, T., (2000). Dynamic modeling and classical control theory for supply chain management. Computers and Chemical Engineering 24, 1143-1149.

Petkov, S.B., Maranas, C.D., (1997). Multiperiod Planning and Scheduling of Multiproduct Batch Plants under Demand Uncertainty. Industrial & Engineering Chemistry Research, 36, 4864.

Petrovic, D., Roy, R., and Petrovic, R., (1998). Modeling and Simulation of a Supply Chain in an Uncertain Environment. European Journal of Operational Research, 109, 299-309.

Petrovic, D., Roy, R., and Petrovic, R., (1999). Supply Chain Modeling Using Fuzzy Sets. International Journal of Production Economics, 59, 443-453.

Qi, Xiangtong., Bard, J.F., Yu, G., (2004). Supply Chain coordination with demand disruptions. Omega, Volume 32, Issue 4, 2004, Pages 301-312.

R, Srinivasan, Mukta Bansal, and I.A. Karimi, A Multi-Agent Approach to Supply Chain Management in the Chemical Industry, In *Multiagent-Based Supply Chain*

Management Eds: B. Chaib-draa and J. P. Müller, Studies in Computational Intelligence, Vol 28, p419-448, 2006.

Rao, K., Young, R.R. and Novick, J.A., (1993). Third-party services in the logistics of global firms. Logistics and Transportation Review, Vol. 29 No. 4, pp. 363-70.

Razzaque, M.A., and Chang, C.S., (1998). Outsourcing of logistics functions: a literature survey. International Journal of Physical Distribution & Logistics Management, 28(2), pp 89-107.

Rosenthal, E.C., Zydiak, J.L., Chaudhary, S.S., (1995) Vendor Selection with Bundling. Decision Sciences, Volume *26* Number 1, 35-48.

Ryu, J.H., Dua, V., Pistikopoulos, E.N., (2004). A Bilevel Programming Framework for Enterprise-Wide Process Networks under Uncertainty. Computers and Chemical Engineering, 28, 1121-1129.

Saaty, T.L., (1980). Analytic Hierarchy Process, Mcraw-Hill, New York, NY, 1980.

Santoso, T., Ahmed, S., Goetschalckx, M., Shapiro, A., (2005). A Stochastic Programming Approach for Supply Chain Network Design under Uncertainty. European Journal of Operational Research, 167, 96-115.

Serenko, A., Detlor, B., (2002), Agent Toolkits: A general overview of the market and an assessment of instructor satisfaction with utilizing toolkits in the classroom.

Shah, N., (2005). Process industry supply chains: Advances and challenges. Computers and Chemical Engineering, 29, 1225-1235.

Sharma, D., Benton, W.C., and Srivastava, R., (1989). Competitive strategy and purchasing decisions in Proceedings of the 1989 Annual Conference of the Decision Sciences, Institute, 1088-1090.

Sheffi, Y., (1990). Third party logistics: present and future prospects. Journal of Business Logistics, Vol. 11 No. 2, pp. 27-39.

Sheffi, Y., (2001). Supply Chain Management under the Threat of International Terrorism. International Journal of Logistics Management 12 (2001) 1-11.

Sheffi, Y., Rice, J.B., Fleck, J.M., Caniato, F., (2003). Supply Chain Response to Global Terrorism: A situation scan, Presented in the EurOMA POMS Joint International Conference, Cernobbio.

Singhvi, A., Madhavan, k., Shenoy, U., (2004). Pinch analysis for aggregate production planning in supply chains. Computers and Chemical Engineering 28 (2004) 993-999.

Sink, H.L., Langley Jr., C.J., (1997). A managerial framework for the acquisition of third-party logistics services. Journal of Business Logistics, 18 (2), 163-187.

Sink, H.L., Langley Jr., C.J., and Gibson, B.J., (1996). Buyer observations of the US third-party logistics market. International Journal of Physical Distribution and Logistics Management, Vol. 26 No. 3, pp. 38-46.

Sridharan, R., (1995). The Capacitated Plant Location Problem. European Journal of Operational Research, 87, 203-213.

Sundaramoorthy, A., Karimi, I.A, (2005). A simpler better slot-based continuous-time formulation for short-term scheduling in multipurpose batch plants. Chemical Engineering Science, 60, 2679 – 2702.

Swaminathan, J. M., Smith, S. F. & Sadeh, N. M. (1998). Modeling Supply Chain Dynamics: A Multiagent Approach. Decision Sciences Volume 29 Number 3.

Sycara, K., Pannu, A., Williamson, M., and Zeng, D., (1996), Distributed intelligent agents, IEEE Expert 1996; 11(6): 36-46.

Sykuta, M.E., (1996). Futures trading and supply contracting in the oil refining industry. Journal of Corporate Finance, 2, 317-334.

Tay, H.L., Karimi, I.A., Peck, C.K, Peh, X.L., (2005). Contract Selection and Tank Allocation in a Terminaling and Storage Facility. Industrial Engineering of Chemistry Research, 44, 7435-7450.

Trunick, P.A., (1989). Outsourcing: A single source for many talents. Transportation & Distribution, July, pp. 20-23.

Tsay, A.A., Nahmias, S., Agrawal, N., (1999). Modeling supply chain contracts: a review. In: Tayur, S., Ganeshan, R., Magazine, M. (Eds.), Quantitative Models for Supply Chain Management. Kluwer Academic Publishers, Dordrecht, pp 300-336.

Tsiakis, P., Shah, N., Pantelides, C., (2001). Design of multi-echelon supply chain networks under demand uncertainty. Industrial Engineering Chemistry Research 2001, 40, 3585-3604.

Van Hoek, R., I., (2000). The purchasing and control of supplementary third-party logistics services. The Journal of Supply Chain Management, 2000, Fall, 14-26.

Verdicchio, M ., and Colombetti, M., (2002). Commitments for Agent-Based Supply Chain Management. ACM SIGecom Exchanges, Vol. 3, No. 1, 2002.

Weber, C.A., Current, J.R., Benton, W.C., (1991). Vendor selection criteria and methods. European Journal of Operational Research, 50, 2-18. chapter 2

Weiss, G., (1999). Multiagent systems. A modern approach to distributed artificial intelligence. Cambridge, MA: MIT Press

Whitfield, Mark, (2004). A Stronger link. European Chemical News, September 20-26, 2004

Williams, J. F., (1983). A hybrid algorithm for simultaneous scheduling of production and distribution in multi-echelon structures. Management Science 29 (1), 77.

Wilson, M.C., (2002), Transportation Disruptions in the Supply Chain: Simulator as a Decision Support Tool, Proceedings of the 31st Annual Logistics Educators Conference, 2002.

Woolridge, M., (2002), An Introduction to MultiAgent Systems, John Wiley & Sons.

Wooldridge, M. & Jennings, N. (1995). Intelligent agents: theory and practice. Knowledge Engineering Review 10 (2), 115.

Xu, Minghui., Qi, Xiangtong., Yu, G., Zhang, H., Gao, Chengxiu., (2003). The Demand Disruption Management Problem for a Supply Chain with Nonlinear Demand Functions. Journal of Systems Science and Systems Engineering, Volume 12, No.1 Pages 1-16.

Yee, T.F., Grossmann, I.E., Kravanja, Z., (1990). Simultaneous optimization models for heat integration – 1. Area and Energy targeting and modeling of multi-stream exchangers. Computers & Chemical Engineering, 1990, vol. 14, num10, 1151-1164.

Zeithaml, V.A., Parasuraman, A., Berry, L.L., (1985). Problems and strategies in service marketing. Journal of Marketing, 1985, 49, 33-46.

Zimmermann, H. J., (2000). An Application-Oriented View of Modeling Uncertainty. European Journal of Operational Research, 122, 190-198.

PUBLICATIONS

Mukta Bansal, A. Adhitya, R. Srinivasan, and I.A. Karimi, An Online Decision Support Framework for Managing Abnormal Supply Chain Events, In *Computer-aided Chemical Engineering*, Ed: L. Puigjaner and A. Espuna, Vol 20, pp 985-990, 2005.

R, Srinivasan, **Mukta Bansal**, and I.A. Karimi, A Multi-Agent Approach to Supply Chain Management in the Chemical Industry, In *Multiagent-Based Supply Chain Management* Eds: B. Chaib-draa and J. P. Müller, Studies in Computational Intelligence, Vol 28, p419-448, 2006.

Mukta Bansal, I. A. Karimi, R. Srinivasan, Optimal Contract Selection for the Global Supply and Distribution of Raw Materials, *Industrial & Engineering Chemistry Research*, 2007, Volume 46, 6522-39.

Mukta Bansal, I. A. Karimi, R. Srinivasan, Selection of Third-Party Service Contracts for Chemical Logistics, Submitted, *Industrial & Engineering Chemistry Research*, 2008

Mukta Bansal, I. A. Karimi, R. Srinivasan, Selecting Contracts for the Global Supply of Raw Materials under Uncertainties, *Manuscript in preparation*, 2008.

Mukta Bansal, R. Srinivasan, I. A. Karimi, G2MADE-A Multi-Agent Platform for Chemical Supply Chain Management, *Manuscript in preparation*, 2008.

Mukta Bansal, A. Adhitya, R. Srinivasan, and I.A. Karimi, An Online Decision Support Framework for Managing Abnormal Supply Chain Events, Presented in the *European Symposium on Computer Aided Process Engineering* – 15, Barcelona, Spain, May 29 – Jun, 2005

Mukta Bansal, I.A. Karimi, R. Srinivasan, (2006), Contract Selection for Raw Material Procurement, *INFORMS*, Hong Kong, June 25-28, 2006

Mukta Bansal, R. Srinivasan, and I.A. Karimi, Strategic Sourcing Based on Contract Selection, Presented at the *INFORMS Annual Meeting*, Pittsburgh, PA, Nov 5-8, 2006

Mukta Bansal, I.A. Karimi, and R. Srinivasan, Modeling and Selection of Supply Contracts, Presented at the *AIChE Annual Meeting*, San Francisco, CA, Nov 12-17, 2006

Mukta Bansal, I.A. Karimi, and R. Srinivasan, Selecting Third-Party Logistics Contracts for Chemical Companies, Presented at the *AIChE Annual Meeting*, San Francisco, CA, Nov 12-17, 2006

Mukta Bansal, I.A. Karimi, R. Srinivasan, (2007), Outsourcing and Optimization of Logistics Services for Chemical Companies, Presented at the *European Symposium on Computer Aided Process Engineering* – 17, Bucharest, Romania, May 27-30, 2007

Mukta Bansal, I.A. Karimi, R. Srinivasan, (2008), Optimal Contract Selection for the Global Supply Under Uncertainty, submitted at *FOCAPO*, Boston, June, 2008