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Thesis Title: Planning in Global Chemical Supply Chains with Regulatory Factors

Abstract

Both chemical supply chain operation and strategic problems have received extensive interest from researchers for some years now. However, most existing models that address these problems have limited application in the industry due to (1) omission of regulatory factors, (2) non-generic representation of regulatory factors, (3) unrealistic representation of problem parameters, or (4) omission of industrially relevant decision-making process constraints. This dissertation aims to address the existing deficiencies in the chemical supply chain research in three major ways. First, it introduces and classifies the major regulatory factors that can influence supply chain decisions of chemical companies. Second, it introduces five new chemical supply chain models which have better application potential than most existing ones in literature. Third, it introduces a novel solution methodology that is capable of addressing large scale stochastic supply chain design and operation problems with account of regulatory factors and risk control constraint.

Keywords: regulatory factors, capacity-expansion planning, production-distribution planning, stochastic programming

PLANNING IN GLOBAL CHEMICAL SUPPLY CHAINS WITH REGULATORY FACTORS

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NATIONAL UNIVERSITY OF SINGAPORE

2009

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A THESIS SUBMITTED

FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF CHEMICAL & BIOMOLECULAR ENGINEERING

NATIONAL UNIVERSITY OF SINGAPORE

2009

Acknowledgements

Undoubtedly, the successful completion of this doctoral research project has been accompanied by accumulation of debt of personal gratitude to a list of individuals and organizations.

My foremost regards goes to my supervisor Professor Karimi, to whom I shall be eternally grateful for (1) allowing me to embark on this journey and realize my dream without stretching my financial liability, and (2) providing me the total freedom to explore my ideas and realize my true potential. His ideas, comments, encouragement and guidance have undoubtedly played an instrumental role in meeting the objectives of this research project. I would also like to thank Prof Lakshminarayanan and Prof Gunawan for serving on my doctoral examination committee. Their constructive feedback and comments have helped tremendously in shaping the scope and direction of my research.

This research would not have been possible without the financial, administrative, technical and material support that I have received from National University of Singapore, Agency for Science, Technology & Research (A*STAR), Maritime and Port Authority of Singapore (MPA) and The Logistics Institute- Asia Pacific (TLI-AP). Special thanks also go to BMT Asia Pacific, Berlian Laju Tanker and GBLT Shipmanagement for generous support they have rendered during the course of my research work in TLI-AP.

Finally, I own my deepest gratitude to my family and friends. Without their support and encouragement, I would not have ventured in this journey. In particular, I am immensely grateful to my wife Cindy for her patience, sacrifice and support during this intense period of my life. I would also like to thank my daughters Jana and Janelle

for the love, joy and laughter they bring to the family since their arrival, and who have helped me tide over those frustrating moments of my academic pursuit.

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Summary

Most chemical companies need to operate with global perspective due to geographical spread of their manufacturing facilities and their cross-border material transactional activities. The current competitive and dynamic environment in which these companies across the globe are merging and streamlining their resources also accentuates the global nature of their businesses. Clearly, this makes it imperative that they make supply chain planning decisions with all the globally dispersed supply chain entities considered. In other words, the decisions should be on a global and integrated basis and must account for all key the regulatory factors. Essentially, the latter refer to the legislative instruments (duties, tariffs, taxes, etc.) that a government agency imposes on the ownership, imports, exports, accounts, and earnings of business operators within its jurisdiction. The primary goals of these factors are to boost a country's coffer or protect the interests of local businesses. Countries around the world may share similar types of regulatory factors, but the details of these regulations are extremely important and vary from country to country. Inevitably, they create a heterogeneous global network of business landscapes that have different levels of influence on the supply chain operations and bottom line performance of any business operator.

Both supply chain strategic and operation problems have received extensive attention from research workers for some years now. However, most existing models that address supply chain problems fail to account for any regulatory factors. This limits their application in the industry, especially by multinational companies, since solutions of these models are unlikely to remain optimal in the presence of appropriate regulatory factors. On the other hand, among the models that have been developed

with regulatory factors to address supply chain problems, there is ample room for improvement to enhance their applications in the industry. This improvement may appear in the form of (1) more realistic representations of regulatory factors and/or problem parameters, (2) more generic problem formulations, or (3) incorporating other critical decision-making process constraints so as to accommodate to the needs of companies with different operational characteristics and requirements.

On the whole, this dissertation aims to fill existing gap in chemical supply chain optimization research in three major ways. First, it introduces and classifies the major regulatory factors that can influence supply chain decisions of chemical companies. In addition, it presents a concise introduction and overview of not so well-known but important regulatory factors (i.e. duty drawback and carry-forward loss) which are relevant to the chemical companies. Second, it introduces five new models that address chemical supply chain problems. Essentially, these five new models distinguish themselves by their incorporation of industrially relevant regulatory factors which are omitted by most existing ones in the literature. Third, it introduces a novel solution methodology that is capable of addressing a large scale stochastic supply chain design and operation problems with account of regulatory factors and risk control constraint. In particular, the new algorithmic procedure exhibits a highly parallel solution structure which can be exploited for computational efficiency.

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Nomenclature

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a_{ft}	fixed cost of capacity expansion at f and t
ATP	after tax profits
b_{ft}	variable cost of capacity expansion or new construction at f and t
BFL_1	known bunker fuel level of the tanker at the end of its first leg prior to its departure to the next port or destination for refueling
BFL_k^χ	bunker fuel level of the tanker at the end of its k^{th} leg) in scenario χ prior to its departure to the next port or destination for refueling
BOM	bill of materials
c	customer facility
$\boldsymbol{C}$	set of characteristic scenarios
c_{ft}	fixed cost of constructing a facility at f and t
CB	MNC's capital budget for capacity expansion or new facility construction over planning horizon
CB_t	MNC's capital budget for capacity expansion or new facility construction at t
CE_t	MNC's capital expenditure during t
$CFL_{ntt'}^\chi$	nonnegative loss amount incurred by MNC in n for period t and that is available for tax rebate at the beginning of t' in scenario χ
CIF_{isft}	cost + insurance + freight charges of shipping a unit of material m_i from s to f at t
CIF_{isct}^χ	cost + insurance + freight charges of shipping a unit of material m_i from s to f at t in scenario χ
CO_{ifct}	cost that f incurs for outsourcing the production of a unit of m_i delivered to c at t
CO_{ifct}^χ	cost that f incurs for outsourcing the production of a unit of m_i delivered to c at t and χ
d	basis interval which is used to describe duration of a capacity project project
D_{ict}	demand of material m_i from by customer c during t

D_{ict}^{χ}	demand of material m_i from by customer c during t in scenario χ
DC_f	depreciation charge of f over planning horizon
DR_i	unloading rate (mass per unit time) for cargo i
e_{ft}^{χ}	currency exchange rate which is in units of a numeraire currency per unit of currency of facility f during t and χ
$\boldsymbol{EF}$	set of external facilities from which the MNC sources raw materials or to which it sells finished products
$\boldsymbol{EIF}$	set of existing facilities that the MNC owns
EPT_i	earliest pick up time of cargo i
ETA_k	arrival time of a port visit by a tanker at end of leg k
ETD_k	departure time of a tanker after its port visit at end of leg k
$\boldsymbol{F}_n$	set of facilities located in nation n
$\boldsymbol{F}_n'$	set of facilities located outside nation n
f	facility (internal or external; supplier, producer, or customer)
F_{ifct}	units of material m_i shipped from f to c during t
F_{ifct}^{χ}	units of material m_i shipped from f to c during t in scenario χ
F_{isft}	units of material m_i shipped from s to f during t
F_{isft}^{χ}	units of material m_i shipped from s to f during t in scenario χ
F_{ko}	additional fuel consumption due to voyage to refueling port if refueling option o of leg k is chosen
FC_k	total fuel consumed by tanker from start to end of leg k and is inclusive of those used for cargo loading, unloading, tank cleaning, waiting and inspection done at the end of leg k
g	facility (internal or external; supplier, producer, or customer)
G	set of cargos that are carried by the tanker
g_{fk}^{C}	quantum change in capital expenditure when Δq_{fk}^{C} exceeds zero
g_{fk}^{D}	quantum change in project duration when Δq_{fk}^{D} exceeds zero
G_{ifct}	units of i that f outsources for customer c during t
G_{ifgt}^{χ}	units of i that f outsources during period t and at scenario χ to meet the demand of customer g

G_{ifgct}	units of i that is outsourced by f to g to fulfill the order of c during t
G_{ift}^{U}	upper limit on the units of m_i that f can outsource during t
GI_f	gross income of f
GI_{ft}	gross income of f during t
GI_{ft}^{χ}	gross income of f during t and χ
h_{fk}^{C}	1, if $\Delta q_{fk}^{C} > 0$, 0 otherwise
h_{fk}^{D}	1, if $\Delta q_{fk}^{D} > 0$, 0 otherwise
i	material or cargo code
$\mathbf{I_k}$	set of cargos to be loaded onto the tanker at the end of its k^{th} leg
$I_{\chi l}$	number of times a scenario χ has been ranked l
I_{if}^{L}	lower limit on the inventory level of i at f
I_{if}^{U}	upper limit on the inventory level of i at f
I_{ift}	inventory level of a material i associated with an internal facility f at the end of a period t
IC_{ift}	inventory cost of unit material m_i per unit time period during t
ID_{isft}	import duty imposed on material m_i that going from s to f during t
$\boldsymbol{IF}$	facilities owned by the MNC currently or in future
$\boldsymbol{IM_f}$	incoming materials consumed by f
j	material code
k	order of linear segment a capacity expansion cost and duration profiles
K	total number of port visits
K_f^{C}	number of linear segment a capacity expansion cost profile
K_f^{D}	number of linear segment a capacity expansion duration profile
L_f	project life of capital expenditure at f
LPT_i	latest pick up time of cargo i
LR_i	loading rate (mass per unit time) for cargo i
M	number of subintervals in t
m_i	name of material with code i
MC_{ft}	variable production cost of manufacturing one unit of $\pi(f)$ by f at t
MD_{ft}^{χ}	MD claim for f at t and χ
MaxP_{χ}	maximum possible probability of scenario χ in the incidence matrix

MaxRank_{χ}	maximum l ($1 \le l \le NS$) with $I_{\chi l}>0$
MinRank_{χ}	minimum l ($1 \le l \le NS$) with $I_{\chi l}>0$
MP_{jt}	open market value of j during t
MP_{jt}^{χ}	open market value of j during t and χ
MPD_k	maximum permissible delay in arrival of tanker at a port at the end of leg k
n	nation or country
N	number of countries
$\bar{N}_{nt}$	nonnegative loss upper bound of the MNC in n during t
$NDC_{f\tau t}$	depreciation charge of f during t due to capital expenditure during τ
$NDC_{ft\eta}$	depreciation charge of f during η^{th} interval of t due to capital expenditure incurred for capacity expansion or new construction at the start of planning horizon
NE_{nt}^{χ}	nonnegative loss of the MNC in nation n during t and χ
NS	number of scenarios of uncertain parameter realizations
$\boldsymbol{OM}_f$	outgoing materials produced by f
OC_{ifgct}	cost incurred by f for every unit of m_i that is outsourced to g to fulfill the order of c at t
ODC_{ft}	old depreciation charge of f during t due to (old) investments committed before $t = 0$
P	number of first stage solution generated in the initialization step of SCA
P_{ifgt}	unit selling price (exclusive of insurance and freight) of material m_i charged by f to g during t
P_{isct}^{χ}	unit selling price (exclusive of insurance and freight) of material m_i charged by s to c during t and χ
$\bar{P}_{nt}$	profit upper bound of the MNC in n during t
P_o	unit fuel price of refueling option o at end of first leg
P_{ko}^{χ}	unit fuel price of refueling option o at end of leg k in scenario χ
PC_f	total project cost of capacity expansion at f
PC_k	port due payable for the tanker for its visit of the port at leg k
PD_f	total project duration of capacity expansion at f
PE_{nt}^{χ}	profit of the MNC in nation n during t and χ

$\Delta PD_{ft\eta}$	1, if capacity expansion at f expends the η^{th} interval of t, 0 otherwise
$\underline{Q}$	minimum fuel level of tanker
$\overline{Q}$	maximum fuel level or fuel tank capacity of tanker
$Q_{\min}$	minimum refueling quantity
Q_o	amount (tonnes) of bunker fuel to be purchased by the tanker at the end of its first leg
Q_{ko}^{χ}	amount (tonnes) of bunker fuel to be purchased by the tanker at the end of leg k from option o in scenario χ
q_f	amount of capacity expansion or construction at facility f
q_f^L	lower limit on expansion size at facility f
Δq_{fk}^C	amount of capacity expansion or construction at f based on the kth segment of the capacity expansion cost profile
$\Delta \overline{q}_{fk}^C$	upper limit of Δq_{fk}^C
Δq_{fk}^D	amount of capacity expansion or construction at f based on the kth segment of the capacity expansion duration profile
$\Delta \overline{q}_{fk}^D$	upper limit of Δq_{fk}^D
Δq_{ft}	amount of capacity expansion or construction at f during t, which is beyond the minimum allowed level
Q_{ft}	production capacity of f at t
$Q_{ft\eta}$	production capacity of f at η^{th} interval of t
Q_{f0}	initial capacity of f at time zero
Q_f^L	lower limit on the size of new facility f
Q_f^U	upper limit on the capacity at f
$q_{sfijt\tau}$	units of i that an internal facility f imports from supplier s at t and it subsequently consumes to manufacture j at τ
$q_{sfij0\tau}$	units of i that an internal facility f imports from supplier s prior to the start of horizon and it subsequently consumes to manufacture j at τ
r	annual interest rate
$r_{fci\tau\theta}$	units of i that is manufactured by f using imported materials at τ and that is subsequently exported to c at θ

R^{C}_{fk}	slope of linear segment k in the capacity expansion cost profile
R_{jft}	market value of j relative to those of all finished products of f during t
$\overline{RFT}_o$	maximum allowable refueling time of refueling option o
$\underline{RFT_o}$	minimum allowable refueling time of refueling option o
RR_{ko}	refueling rate (mass per unit time) of refueling option o at end of leg k
RT_k	amount of time that a tanker spends at a port at the end of leg k
$RV_{jf\tau}$	relative value of j among all finished products of f during τ
RV^{χ}_{jft}	relative value of j among all finished products of f during t in scenario χ
s	supplier facility
$\boldsymbol{S}$	set of critical lower tail-end scenarios
S_{ist}	amount of material m_i that supplier s can supply to the MNC during t
SR_i	sale revenue generated by carrying the cargo i from its origin to destination
t	fiscal year
T	number of fiscal years in the planning horizon
T_1	known arrival time of the tanker to its first port of visit
T_2	time at which the tanker arrives at a port at the end its second leg
T_{adm}	total inspection time needed by the tanker at any port
T^{χ}_{k}	time at which the tanker arrives at a port at the end its k^{th} leg in scenario χ
TCC	time chartering cost ($/day) of the tanker
TI_n	taxable income of the MNC in nation n
TI_{nt}	taxable income of the MNC in nation n during t
TIP^{χ}_{nt}	taxable income payable by MNC in n at the end of t and in χ
TR_n	corporate tax rate in nation n
TR_{nt}	corporate tax rate in nation n during fiscal year t
TT_k	time (days) that the tanker takes to sail from end of leg k to the next port
$\mathbf{U_k}$	set of cargos to be unloaded by tanker at the end of its k^{th} leg
V_i	weight of cargo i
W^{χ}_{ijsft}	units of i that are eligible for MD claim by f due to its import from s during t in scenario χ

x_o	1, if bunkering option o at the end of tanker's first leg is used, 0 otherwise
x_{ko}^{χ}	1, if bunkering option o at the end of tanker's k^th^ leg is used in scenario χ, 0 otherwise
x_{ift}	units of material m_i consumed or produced by f during t
X_{ft}	units of $\pi(f)$ consumed or produced by f during t
X_{ft}^{χ}	units of $\pi(f)$ consumed or produced by f during t in scenario χ
X_f^L	lower limit on the units of $\pi(f)$ consumed or produced by f at every t
X_f^U	upper limit on the units of $\pi(f)$ consumed or produced by f at every t
y_{χ}	1, if χ is chosen as a characteristic scenario, 0 otherwise
y_f	1, if the MNC expands capacity at f, 0 otherwise
y_{ft}	1, if the MNC expands capacity at f during t, 0 otherwise
YP_{nt}^{χ}	1, if $PE_{nt}^{\chi} - NE_{nt}^{\chi} \geq 0$, 0 otherwise
z_{ft}	1, if the MNC builds a new facility f during t, 0 otherwise
Z^{χ}	1, if $\sum_n \sum_t PE_{nt}^{\chi} - NE_{nt}^{\chi} \geq \upsilon$, 0 otherwise

Greek letters

α	minimum number of scenarios that needs to be accounted in the risk control constraint
α_{isf}	fraction of i in the inventory of f at the start of the horizon that f procured from s
β	target average daily profit of decision-makers in TBPP
ε_{nt}^{χ}	currency exchange rate which is in units of a numeraire currency per unit of currency of nation n during t and χ
κ	maximum probability of NPV falling below or equal to v set by the decision makers
ξ	maximum probability of average daily profit falling less than or equal to β
θ_{χ}	spread ratio scenario χ

$\delta(f)$	number of years for each expansion or construction activity at f
δ_k^χ	reduction in port time at the end of leg k in scenario χ
μ	constant bunker consumption rate (mass per unit time) of the tanker for waiting at port
η	index for subinterval of t
ρ	maximum possible return that the MNC can earn over the planning horizon
$\pi(f)$	primary product associated with f
π_{ko}	fixed price (due to port dues and other administrative expenses, etc) of arranging refueling option o at the end of leg k
σ_{if}	coefficient of material m_i in the mass balance equation of f
σ_{ko}	additional voyage cum port administrative time to be incurred by tanker if refueling option o at end of leg k is employed
φ	predetermined maximum number of characteristic scenarios to be chosen for a given problem
φ_f	binary parameter that is 1 if $Q_{f0} > 0$, and 0 otherwise
γ_{ift}	fraction of material m_i that f imports from the foreign supplier during period t
ψ_χ	probability of occurrence of scenario χ
τ	fiscal year
τ_{ko}	additional fuel consumption due to the voyage to the refueling destination if refueling option o of leg k is chosen
χ	scenario of uncertain parameter realizations
ν	pre-specified VAR set by decision maker
ω_n	the number of years that corporate losses can be carried forward based on the loss carry-forward policy of n

Abbreviations

2SSMIP	Two-Stage Stochastic Mixed-Integer Programming
ASEAN	Association of South-East Asian Nations
CARICOM	Canada and Caribbean Community and Common Market

CEP	Capacity Expansion Problem
CETA	Central European Trade Agreement
CIF	Cost, Insurance and Freight
CLT	Critical lower Tail-end
CPI	Chemical Process Industry
DCEP	Deterministic Capacity Expansion Problem
DPDP	Deterministic Production-Distribution Problem
dwt	Deadweight Ton
ENPV	Expected Net Present Value
EPZ	Export Processing Zone
EU	European Union
FDS	Fixed Drawback System
FOB	free-on-board
FTA	Free Trade Agreement
IDS	Individual Drawback System
IMF	International Monetary Fund
IP	Integer Programming
LAP	Location-Allocation Problem
LP	Linear Programming
M&A	Mergers and Acquisitions
MD	Manufacturing Drawback
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MNC	Multinational Company
NAFTA	North American Free Trade Agreement

NLP	Nonlinear Programming
NPV	Net Present Value
OA	Outer Approximation
PDP	Production-Distribution Problem
RMD	Rejected Merchandise Drawback
SCA	Scenario-Condensation Approach
SCEP	Stochastic Capacity Expansion Problem
SPDP	Stochastic Production-Distribution Problem
TBPP	Tanker Bunkering Planning Problem
UMD	Unused Merchandise Drawback
USSFTA	United States – Singapore Free Trade Agreement
VAR	Value-at-Risk
WTO	World Trade Organization

1. Introduction

Since the industrial revolution in the late 18th and early 19th century, the contribution of the chemical industry to the global economic growth has been increasingly significant. The global chemical trade, which hit more than US$1.24 trillion in 2006, has achieved an impressive 14% average annualized growth between 2000 and 2006 (see Table 1.1). Correspondingly, the demand for logistical support by the chemical industry has also increased over the years. Heideloff et al. (2005) stated that the capacity of ships (300 gross tons and over) that primarily support the global chemical industry and comprise oil, chemical, and liquid gas tankers, grew 3% annually between 2001 and 2005 to reach 368.4 million deadweight ton (dwt) at the beginning of 2005. In addition, the world has also been witnessing a flurry of expansion in chemical terminaling and storage facilities that include the bulk liquid terminals as reported by Markarian (2000) to accommodate the rise in the global demand of chemical products and seaborne chemical trade. Recently, Royal Vopak have decided to continue the Phase 4 capacity expansion project of their Banyan terminal which is expected to be completed in June 2009. The terminal will then have a total capacity of 1,245,000m^3. After officially opening a new tank farm of 380,000m^3 at the Fujairah terminal in February 2008, Royal Vopak are now evaluating the feasibility of expanding it by another 1,200,000m^3 with construction of new jetties that have four to six docking spaces.

Evidently, the growth in the fleet of ships and the expansion of port facilities supporting the chemical industry that takes place in tandem with the growth of global chemical industry both expands and complicates the global chemical supply chain network. Efficient and cost-effective management of chemical supply chains is clearly a major challenge to global chemical companies and is crucial to their financial success since the logistics costs can be as high as 20% or more of purchasing costs (Karimi et al., 2002).

Table 1.1: Shares of manufacturing exports among clusters and their annual growths

manufacturing clusters	value of manufacturing exports in 2006 (US$ billions)	annual percentage change		
		2000-2006	2005	2006
iron and steel	374	17	17	18
chemicals	1248	14	12	13
office and telecom equipment	1451	7	11	13
automotive products	1016	10	7	10
textiles	219	5	5	7
clothing	311	8	7	12

Data source: International trade statistics 2007 by World Trade Organization

1.1 Unique Characteristics of Chemical Supply Chains

The field of chemical supply chain management has received extensive attention from researchers for some years now. Though chemical supply chains do share similar operational features as those of other industries (such as the consumer electronics, automotive industries, etc), they possess several characteristics which make them distinctively different from others. Clearly, understanding of these distinctive characteristics enables supply chain practitioners and researchers to appreciate the unique set of constraints and challenges that they have to contend. This is extremely crucial prior to the formulation and execution of any strategies that aim to manage chemical supply chain efficiently and effectively. Based on their areas of impact on supply chain decisions, we classify these distinguishing chemical supply chain characteristics into four main categories, namely material sourcing, manufacturing operation, demand and transportation management. For each of these categories, we now describe concisely the distinguishing characteristics of chemical supply chains.

1.1.1 Material Sourcing

Many chemical companies, including those in the oil & gas, petrochemicals businesses, usually source their raw materials in bulk. Moreover, many of these raw materials have been commoditized and are traded extensively in many exchanges around the world on a 24x7 basis. This is a sharp contrast compared to manufacturing companies of other industries where extensive commodity trading is virtually non-existent. As a result, opportunistic buying is often practiced in the chemical industry to exploit any significant cost saving opportunity. Hence, it is crucial that material sourcing decisions are made with good visibility of activities at the trading exchanges as this ensures appropriate reaction is undertaken whenever a good trading deal arrives. But the option of exploiting any of such cost-saving opportunity must be exercised with caution as highly discounted raw materials may become highly discounted finished products when demand is at a level that does not justify additional production.

Though many of the raw materials that chemical companies procure have been commoditized, variability in the qualities and compositions of these materials is an industry norm. Moreover, most chemical manufacturing processes entail product blending and multiple-recipes (to be discussed in greater detail in the subsequent section) which inevitably make their outputs strongly dependent on the content of the raw materials used. Therefore, many material sourcing decisions have to be made with assistance of support tools that are able to evaluate usefulness of materials based on assay results and plant capabilities. Such tools are usually not employed in non-chemical industry because the latter consists of manufacturing processes that mostly do not involve product blending.

1.1.2 Manufacturing Operations

Many manufacturing processes of manufacturing plants essentially entail chemical reactions that are carried out in batch, continuous or semi-continuous operation modes with non-discrete products. They usually have multiple options of manufacturing recipes with complex nonlinear relationships between their raw materials and finished product, and several of these reactions even consist of multiple products being generated simultaneously. As such, numerous products and their variants of many chemical plants can be created from the same feedstock through blending of various constituents and the use of different process routes. Inevitably, production planning of their manufacturing processes has to contend raw material variability and product (including by-products) distribution issues which are usually addressed by feedstock blending and/or tweaking of process conditions and routes. Moreover, chemical plants usually store their non-discrete materials (raw materials, intermediate and finished products) in common storage tanks according to their identities or characteristics and not based on materials sources or product reaction pathways. Therefore, it is operationally impossible to link or tag each finished product to its corresponding raw material or process route. This limitation hinders root cause finding effort especially when product quality issues arise. On the other hand, the majority of manufacturers from non-chemical industries do not have to contend with this limitation since each of their manufacturing processes basically entails (1) production of discrete parts, (2) a fixed bill of materials (BOM), (3) single-product output, and (3) assembly-type processes.

Typically, chemical manufacturing facilities consist of complex networks of interconnected operating units for blending, separations, reactions and packaging. Operation of these facilities requires tanks of various sizes to be setup within operating units and between units for temporary storage of raw materials, work-in-progress (WIP), and finished goods inventory. In addition, the immiscibility and incompatibility of the wide array of products used or produced in chemical plants (due to their properties) mean the different products can only be stored in different tanks that have different storage requirements. Process planning of chemical plants must recognize the limitations posed by real-time filling and emptying of all tanks in the system to avoid tank overflows and to respect cleaning requirements for product changeovers or maintenance. Inevitably, this makes production planning of manufacturing plants in chemical industry more complex than that in other industries since most of their manufacturing plants do not have to contend with complex constraints pertinent tank management.

A majority of the finished products of chemical plants serve as raw materials to manufacturing plants in chemical and other industries (i.e. most chemical companies conduct business-to-business (B2B) sales). In order to serve the needs of such wide variety of industries, most chemical plants produce in bulk and adopt a make-to-stock approach. Therefore, they usually have to maintain higher inventories in their supply chain networks compared to non-chemical manufacturers. A majority of the latter manufacturers adopt a make-to-order approach and they have leaner inventory levels to meet demands of downstream users which primarily consist of distribution centers, retail outlets or individual end users.

All manufacturers distinguish their products based on their selected attributes. In non-chemical industries, these attributes are generally restricted to a limited set to tell apart different models, designs and model-specific options. However, attributes can assume an infinite range of values in chemical industry. This is because customers of chemical manufacturers usually specify their needs as "at least" or "no more than" a certain value of a given attribute. Thus, chemical manufacturers exploit this situation by substituting products of one quality (more or less of some attribute) with a product of higher quality when production efficiencies favor such a "give away". Inevitably, production planning of chemical plants requires an understanding of product substitution and the rules of acceptable product replacements. Such a requirement is usually not necessary among manufacturers from non-chemical industries.

1.1.3 Demand Management

As highlighted in the previous section, products of chemical plants can assume an infinite possible range of attributes. Fortunately, customer orders are usually expressed in terms of "at least" or "no more than" certain value of a given attribute. Therefore, demand-forecasting that chemical companies undertake not only have to be attribute-based, management of customer orders also require understanding of the underlying principle of substitution as well as the rules of acceptable product replacements as in production planning. In contrast, demand forecasting that non-chemical manufacturers undertake is based on their respective predetermined lists (i.e. finite number) of finished products which are differentiated by their designated store-keeping-units (SKUs). Essentially, no principle of substitution or rules of acceptable product replacements are required in order to manage their customer demands.

1.1.4 Transportation Management

Due to the nature of their manufacturing operations, many chemical manufacturers have to coordinate their inbound and outbound transportation of materials (raw materials and finished products) in bulk. These manufacturers employ a wide variety of transportation modes which include pipelines, tanker ships, tanker rail cars and tanker trucks to support the movement of their materials. The latter are usually hazardous in nature and their movement is usually governed by regulatory policies (that are legislated to address environmental, safety and security concerns) such as those imposed on the movement and tracking of hazardous materials. In addition, the immiscibility and incompatibility of these materials also mean that the transportation tools chosen to move them are subjected to maintenance requirements such as those pertinent to mandatory tank cleaning. In contrast, most manufacturers from non-chemical industry deal with raw materials and finished product that are chemically inert which are not subjected to aforementioned regulatory or maintenance requirements. Moreover, their inbound and outbound transportation of materials are usually undertaken in volumes that are much smaller than those of their counterparts in the chemical industry. Evidently, transportation management of products across chemical supply chains is more complex than supply chains in non-chemical industry.

1.2 Global Chemical Manufacturers

Most chemical companies are global in nature primarily due to the multinational spread of their manufacturing facilities as well as their extensive international product trading activities. Over the years, this global characteristic has been accentuated by the growth in value of world merchandise exports made by the chemical industry (see Table 1.1). The chemicals cluster has been the primary engine of export growth in global manufacturing industry in recent years. It is one of the few manufacturing clusters that achieved strong double digit annual growth in world merchandise exports from 2000 to 2006. Since only a quarter of outputs (Arora et al., 1998) made by the chemical industry goes directly to the individual consumers, the majority of chemical exports is utilized as raw materials by manufacturers from both chemical and non-chemical industries. With most chemical manufacturers relying on their counterparts in the same industry for raw materials, it is evident that chemical companies import their raw materials as significantly as they export their finished products. On the whole, the markets, in which chemical companies compete and source their raw materials, are not confined to countries or regions that host their manufacturing facilities.

Despite enjoying healthy growth in total export value in recent years, it is not all bed of roses for the chemical companies. The economic downturn that hit the Asian region in 1997 and subsequently the economic powerhouses like US, Europe and Japan in early 2000s has spawned a flurry of mergers and acquisitions (M&As) in the chemical industry (see Figure 1.1). M&As of chemical companies are primarily motivated by the opportunity of realizing cost synergies that accompanies any successful unification of these companies. Examples of major recent M&As include the mergers of Exxon and Mobil, Chevron and Texaco, and the acquisitions of Aventis CropScience by Bayer, Dupont Textiles & Interiors by Koch Industries, Albright & Wilson by Rhodia, BTP by Clariant and Aventis by Sanofi-Synthelabo. In recent years, sales of chemical businesses have remained active as reported by Chang (2004) and Walsh (2005). Inevitably, these M&A in the chemical industry have extended further the global roots of chemical businesses.

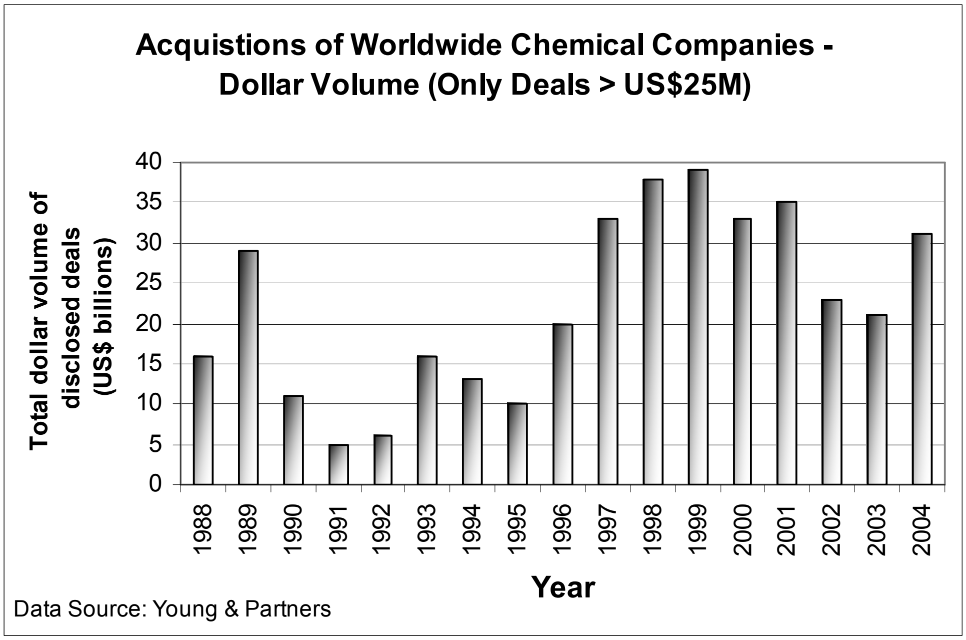

Figure 1.1: Dollar volume of acquisitions of chemical companies

Given the global nature of chemical manufacturing business, it is only natural that the operation of chemical companies and their earnings are influenced by the legislative measures and international trade policies imposed by different government agencies. Though it appears that the signing of multilateral and bilateral trade agreements (such as North American Free Trade Agreement, Central European Trade Agreement, United States - Singapore Free Trade Agreement, etc) attempt to level the playing field of the global business operators, the opposing forces of protectionism and trade disagreements still do persist to ensure a heterogeneous network of trade barriers around the globe. Examples of such protectionist measures include the import quotas imposed by Canada (on beef and veal) and India (on milk powder) to protect their respective domestic agricultural and diary industries, the refusal of China to revalue its currency (renminbi) to protect the competitiveness of its local exporters, etc. In addition to the several international trade disputes such as the one between US and

European Union (EU) over US's anti-dumping law (also known as Byrd amendment), the recent collapse of the World Trade Organization talk at Potsdam (2007), is a testimony to the divisions among the nations on regulating the world trade. With the diversity of regulatory measures imposed by multi-national government agencies that may either promote or discourage international trade and investments, it is critical that chemical companies appropriately account for all key legislative measures and international trade policies in their supply chain planning decisions.

1.3 Importance of Regulatory Factors

Evidently, a majority of the chemical companies exhibits at least one of the following three major global characteristics: (1) they own multiple manufacturing facilities which are based in different countries; (2) their manufacturing facilities source their raw materials from overseas to meet their production needs; (3) their manufacturing facilities export their finished products to overseas markets. Thus, it is imperative for chemical companies to adopt a global perspective both in designing their supply chain network of suppliers, manufacturing plants, distribution centers, customers and in managing the flow of materials and information across these supply chain entities. Essentially, a global perspective consists of two primary elements. The first element entails a holistic view whereby all globally dispersed supply chain entities are considered as an integrated unit during the process of supply chain planning. In supply chain planning context, a holistic view requires collective account of all related supply chain entities in design and management of material and information flows among them as opposed to a localized approach where only a subset of these entities is accounted. The importance of adopting a holistic view in supply chain planning has been recognized and much deliberated in the supply chain management textbooks where the concept has been coined as supply chain integration (Simchi-Levi et al., 2000), collaborative logistics (Frazelle, 2002), etc. The second element of global perspective requires appropriate accounting of all key regulatory factors. Unlike the first element, the significance of regulatory factors in supply chain planning has yet to receive the recognition it deserves despite the obvious and considerable impact of regulatory policies on manufacturers' business operations and bottom-line performances.

As in our recent paper (Oh and Karimi, 2004), we define regulatory factors as the legislative instruments that a government agency imposes on the ownership, imports, exports, accounts, and earnings of business operators within its jurisdiction. Table 1.2 presents a glossary of some common regulatory factors such as import tariffs (or duties), corporate taxes, duty drawback, offset requirements, quantitative import restrictions, etc. The primary goals of these factors are to boost a country's coffer or protect the interests of local businesses. We classify them into two types: domestic and international. In Table 1.2, local content rule and corporate taxes are domestic regulatory factors, while the others are international. The former govern business operations and trade activities within a country, while the latter regulate the transnational movement of goods and funds across international boundaries. The former is a characteristic of a country alone, while the latter depends on the two countries involved in a business transaction. Though countries around the globe impose similar types of regulatory policies, details of these policies tend to vary from country to country. Inevitably, this creates a heterogeneous network of global business landscape that manufacturers, including those in the chemical industry, have to contend with.

Table 1.2: A glossary of key regulatory factors (from Oh and Karimi, 2004)

Factor	**Description**	**Remarks and/or Examples**
Corporate Tax	Tax imposed by the local revenue authority on the chargeable income of a locally registered company	Varies from country to country (Ireland 12.5%, Italy 38.25%, Switzerland 24.1%, etc.).
Duty Drawback	Refund of import duty, when one exports a good with changed or unchanged conditions after having imported it or its components	Three main types: (1) rejected merchandise drawback (2) unused merchandise drawback (3) manufacture drawback.
Duty Relief	Refund of import duty, when one imports a good that is manufactured using locally produced materials	All European Union countries have this custom incentive
Import Duty	Tax imposed by the local custom authority on dutiable goods imported into a country	Varies between countries and depends on the country of origin of imported goods.
Local Content	Minimum percentage (in dollar value) of the components of a finished product, which must be made in the host country where the manufacturing plant is located	Philippines requires manufacturers in the auto industry to source 40% of the raw materials from domestic suppliers.
Offset Requirement	Minimum value of goods and services that must be expended in a country in exchange for the sale of products in the same country	Australia requires 70%.
Quantitative Import Restriction	Restrictions on the quantities of products imported into a country	Canada imposes a quota of 76,409 tonnes on its import of beef and veal. Beyond this limit, it imposes an import tariff of 26.5%.

1.4 Previous Work on Chemical Supply Chain Modeling

Generally, supply chain planning problems can be classified into two main categories, namely supply chain design and supply chain operation problems. The former are strategic in nature and affect the long term performance of a company. In contrast, supply chain operation problems are associated with the day-to-day to mid-term management and coordination of supply chain activities. Based on this problem classification, we sub-divide the review of models that have been developed to address these supply chain planning problems as shown in the following two sections. In addition, it must be noted that there is also a further sub-classification of both supply chain design and operation problems based on presence or absence of uncertainty in the problem parameters like product prices, demands, currency exchange rates, etc. Essentially, a deterministic problem assumes fixed parameters over a given planning horizon, while a stochastic problem allows uncertainty in some parameters.

1.4.1 Supply Chain Design Models

A supply chain design problem (SCDP) entails changing or fine-tuning a company's supply chain configuration, e.g. locations of new facilities, expansions of existing facilities to improve the company's overall performance, etc. The last may be measured in terms of company's revenue, market share, customer service level or downside risk against fluctuating currency exchange rate. SCDPs are strategic in scope and their solutions usually require substantial capital investments and have long lasting implications on a company's future operational and logistical decisions. Therefore, each SCDP is normally approached with an aggregated view of the entire supply chain and with a planning horizon of years, or even decades. Among the SCDPs that have been addressed in the academic literature, two main categories of SCDPs have been identified. The first one entails the location and allocation problems (LAPs) which involve determination of new facility locations and allocation of new and existing facility capacities to various demand locations. Alfred Weber was among the pioneers who address LAP when his work "*Über den Standort der Industrie*" (which is subsequently published in English as Theory of the location of industries in 1929) was published in 1909. It took almost another 50 years before LAPs receive more attention from researchers and they began to develop models that could represent the LAPs more realistically than Weber's pioneer model and also with more efficient solution methodologies (see Appendix A for list of selected publications that address LAPs). The second category of SCDPs consists of capacity expansion problems (CEPs) which also involve planning for the new facility locations. But a CEP differs from a LAP by the former problem's need to determine the schedules and sizes of facility constructions as well as capacity expansions to meet the projected growth in demand over a given planning horizon. CEPs have received extensive researchers' attention since the late 1950s (see Appendix B for list of selected publications that address CEPs).

1.4.2 Supply Chain Operation Models

Supply chain operation problems (SCOPs) deal with the operational aspects of supply chain management and they usually have planning horizons in terms of months, weeks, or even days. Each of these problems has the objective meeting the strategic goals of a company in a given configuration of supply chain. In general, SCOPs involve business functions such as the procurement, production, and distribution departments, which require sound planning to ensure smooth operation within each group and seamless integration across them. As such, we restrict our review only on models that have been developed to address such integrated problems which involve multiple supply chain activities (i.e. procurement, production, and distribution) and omit those models that have been developed individually to support for each of these activities. Evidently, modeling SCOPs require extensive information from key supply chain entities to characterize the entire supply chain.

The supply chain operation problems have received wide spread attention from the operations research and chemical engineering communities since the early 1980s (see Appendix C). Progressively, the industrial realism of these models that have been developed to emulate real supply chain operation problems has improved significantly over the years. This is clearly demonstrated by the evolution of models that capture the complexity of real life supply chain operation problems over the years. Evidently, more dimensions in the form of multiple facilities, multiple products, multiple transportation options or multiple echelons distribution network have been integrated into supply chain operation models in recently published works (after 2000) than in the older papers. Such integrative models have evolved not only due to the need to improve the models' industrial realism but also to capitalize the benefits of approaching supply chain operation problems holistically.

1.4.3 Comments

Voluminous of optimization models that address various types of chemical SCDPs and SCOPs have been published. However, it is surprising to note that chemical supply chain planning models incorporated with regulatory factors are few and far between despite the significant impact that regulatory factors have on business operations and performance. Till end of 2003, only few supply chain models from chemical engineering literature (Computers and Chemical Engineering, Industrial and Engineering Chemistry Research) have accounted for the impact of regulatory factor(s) in their solutions. One such model is that of van den Heever et al. (2001) and it is a mixed integer nonlinear programming (MINLP) model developed to address hydrocarbon field management problem. Its formulation accounts for taxes, tariffs and royalty rules imposed by governments on companies which are exploring their hydrocarbon fields. The authors also introduced a heuristic algorithm that is based on Lagrangean decomposition concept to solve their model. Another supply chain model with account of regulatory factors that is presented in chemical engineering journal is that of Papageorgiou et al. (2001) who reported a multi-period mixed integer linear programming (MILP) model for managing product portfolio in the pharmaceutical industry. Their model, which addresses product development and introduction along with deterministic capacity planning, accounts for the effect of corporate taxes.

Though the number of supply chain models incorporated with regulatory factors found in non-chemical engineering literature is higher than that in chemical engineering literature, the difference is only marginal. Moreover, application of these models that have accounted for regulatory factors in the chemical industry is limited due to non-generic representation of regulatory factors or omission of other key regulatory factors. For example, Cohen et al. (1989), Arntzen et al. (1995), and Goetschalckx et al. (2002) have all included some of the regulatory factors into their models to address SCOPs. Cohen et al. (1989) presented a normative model framework to maximize the after-tax profit of a global firm in the presence an uncertain currency exchange rate. They included corporate taxes, import tariffs, and local content rules in their formulation. Arntzen et al. (1995) introduced a MILP model that accounted for import tariffs, duty drawbacks, duty relief, local content rules, and offset requirements to represent a SCOP of a multinational company (MNC). Goetschalckx et al. (2002) addressed a SCOP simultaneously with LAP for a group of enterprises with the objective of maximizing the total after-tax profit in the presence of import tariffs. Now, it is apparent that at least one critical regulatory factor is omitted in each of the three aforementioned models. Savings offered by duty drawback regulations are not accounted for in the models of Cohen et al. (1989) and Goetschalckx et al. (2001). Though Artzen et al. (1995) have accounted for the effect of duty drawback regulations in their work, they conspicuously omitted corporate taxes in their formulation even though the former has significant impact on the bottom line performance of any business operator. It appears that the model developed by

Arntzen et al. (1995) is most comprehensively incorporated with regulatory factors among the three models. Nevertheless, it still has limited applications in the chemical industry due to two primary reasons. First, their model does not offer sufficient in-depth data on duty drawback distribution that is essential for inventory management and duty refund claims. Second, the formulation of duty drawbacks in their model is valid only for single-product manufacturing processes. Therefore, many of the upstream chemical companies with multi-product manufacturing processes where multiple products are manufactured simultaneously cannot employ the model by Arzten et al (1995) without making significant changes to it. Note that we define a multi-product manufacturing operation as a manufacturing process that produces multiple products simultaneously. That is to be distinguished from manufacturing processes that manufacture multiple products sequentially. We discuss later in greater details on the differences in duty drawback computations for single-product and multi-product manufacturing processes.

From the above discussion, we conclude that majority of the existing models for various supply chain problems are useful only in a local (national) context and are not appropriate for supply chain planning with (1) substantial transnational movements of goods and merchandise and (2) multi-nationally located supply chain entities. The failure to incorporate key regulatory factors into supply chain planning has virtually prevented their application in practice. An optimal solution to a supply chain problem with a local focus will generally not be optimal, when one integrates several regulatory factors into the problem. Therefore, it is extremely crucial to account for all the relevant regulatory factors in the operational and strategic planning activities of any business. On the other hand, the handful of models that have incorporated regulatory factors to address supply chain planning problems have limited application in the chemical industry. This can be attributed to either omission of other key regulatory factors or non-generic representation of regulatory factors in these models. Thus, ample room of opportunity remains available for researchers to come up with more industrially relevant and applicable chemical supply chain planning models.

1.5 Complexity of Modeling Regulatory Factors

Essentially, there are two major challenges that researchers have to contend when they account for regulatory factors in their supply chain models. First, they have to embark on the unenviable task of poring through voluminous multinational legislative documents, which stipulate the regulatory measures of their respective countries that in turn may affect the supply chain operations and bottom line performance of the business operator concerned. This is mandatory due to the variety of regulatory policies imposed by different countries as well as the need to identify the key regulatory factors which researchers feel are critical in their supply chain planning problems. The arduous job of interpreting correctly all pertinent regulatory factors is also complicated by the fact that the regulatory measures and trade policies are usually strewn with legislative lingo. As a result, these documents are difficult to be understood, especially by those who are not legally trained. In cases when the companies own facilities that are located in countries where their native languages are different from those of researchers, the latter also have to deal with language barrier that may further hinder their comprehension of foreign regulatory terms and conditions. For example, the official customs documents that stipulate import and export procedures in Malaysia, Thailand and China are only available in Bahasa Malaysia, Thai and Chinese respectively. Accurate interpretation of regulatory policies is essential for (1) assessing the importance of each regulatory factor in the supply chain problems, and (2) accurate representation of this factor in the mathematical formulation. Therefore, it is vital that resources are appropriately allocated to ensure all major regulatory factors involved in a supply chain problem are identified, studied and interpreted correctly before any attempt is made to account for them in a mathematical model.

The second major challenge that confronts researchers when they attempt to account for regulatory factors in their supply chain models is the complexity of their resultant models. The inclusion of regulatory factors in a supply chain model requires introduction of more variables and constraints, which in turn need more computational effort to solve the model, than one without the account of regulatory factors. This is clearly illustrated by our new stochastic capacity-expansion and deterministic production-distribution planning models that are to be introduced later. For instance, in the latter deterministic model, we deploy variables with five and six indices so that the duty drawbacks can be computed accurately in multi-product manufacturing operations. These variables also ensure sufficient production and inventory planning data are derived from the model's solution so that drawbacks can be duly claimed in accordance to pertinent regulations. However, the inclusion of variables with five and six indices inevitably mean that considerable computer memory resources are required to generate the model, especially when (1) the number of products, manufacturing facilities or time periods is large, and (2) the model is extended to account for uncertainty in some business parameters. When the computing hardware fails to meet memory requirements, a scenario which is often encountered in many practical supply chain problems, no solution can be obtained. As such, innovation in the area of solution methodology development is also needed before one can successfully solve such large scale problems.

1.6 Thesis Focus and Organization

From above discussion, it is clear that there is research gap in chemical supply chain optimization which is primarily attributed to the lack of models that have accounted for regulatory factors adequately. Basically, this project aims to fill this gap in three major ways. First, it introduces and classifies the major regulatory factors that can influence supply chain decisions of chemical companies. Second, it introduces five new models that address chemical supply chain problems. Essentially, four of these new models distinguish themselves from existing ones in the literature by their incorporation of industrially relevant regulatory factors which have widely been omitted by others. The fifth new model in turn addresses a supply chain operational problem which has so far received little or no attention from academic researchers. Third, it introduces a novel solution methodology that is capable of addressing large scale stochastic supply chain problem with risk control constraints.

The rest of the thesis is organized as follows. A chapter is allocated to each of the five new supply chain models which are developed to address deterministic capacity expansion, deterministic production-distribution, extended deterministic capacity expansion, stochastic capacity expansion planning problems, and stochastic tanker refueling planning problem respectively. Essentially, each of these five chapters entails a description of the problem involved and a presentation of the model formulation. Note that the extended deterministic capacity expansion problem basically differs from the aforementioned deterministic capacity expansion problem by the account of two more regulatory factors and a more realistic representation of the relationship between capacity expansion duration and expansion size. In the chapter that is allocated to stochastic capacity expansion planning problem with risk control constraints, a practical and novel solution methodology is also introduced. To demonstrate the robustness and effectiveness of the new algorithmic procedure to address other supply chain problems which share similar characteristics with stochastic capacity expansion planning problem with risk control constraints, we also apply it to solve a stochastic tanker refueling planning problem. In the concluding chapter, details of future opportunities in chemical supply chain research are evaluated and discussed.

2. Deterministic Capacity Expansion Problem

Manufacturing in the chemical process industry (CPI) often involves high temperatures, high pressures, and corrosive chemicals. It requires a high degree of automation and control to ensure product quality and safe operations. Most chemical plants have large production capacities to attain the necessary economies of scales. Clearly, it is not surprising that the CPI is a highly capital-intensive industry. Several major chemical companies spend more than US$500 million annually on capital expenditure, while many oil companies spend in excess of US$1 billion.

Because capacity expansion planning decisions can predestine up to eighty percent of the total cost (Harrison, 2001) of a company, they have a direct and huge impact on the company's long-term competitiveness. Moreover, the huge capital investments in the CPI make the sound and effective planning of capacity expansions extremely crucial for the continued success of chemical companies. Capacity expansion planning involves a strategic planning of timings, locations, and sizes of future capacity expansions with decisions such as when and which existing facilities should be shutdown; when, where and of what capacities new facilities should be constructed; or when, which and by how much existing facilities should be expanded. The companies normally make these decisions based on the forecasts of the demands, prices, and availabilities of raw materials, and the technology obsolescence of final products. Clearly, the quality of these strategic decisions depends on (1) the accuracy of the forecasts, and (2) the effectiveness of the planning techniques that assist the business decision processes. Most chemical and manufacturing companies are global. The current competitive and dynamic environment in which companies across the globe are merging and streamlining their resources also accentuates the global nature of their businesses. Clearly, this makes it imperative for them to adopt a global perspective on the expansion decisions, i.e. consider all potential sites across the globe, and account for regulatory factors.

Due to the variety and complexity of the bilateral and multi-lateral international trade factors and domestic regulatory factors, it is natural that an expansion decision that ignores these factors or fails to account for their effects correctly would be misplaced or misguided. Based on the work of Oh and Karimi (2004)., this chapter aims to highlight the critical role of the regulatory factors in capacity expansion planning and presents a deterministic capacity expansion problem (DCEP) model that addresses the two simplest and probably the most important regulatory factors, namely the import tariff (an international regulatory factor) and corporate tax (a domestic regulatory factor). Furthermore, the proposed DCEP model not only distinguishes itself from the previous work by allowing variable-size capacity expansions and new constructions, but also accounts for two domestic and international regulatory factors. In addition, the deterministic model also provides an effective basis for to handling uncertainty in problem parameters. Finally, this chapter shows the importance of accommodating the regulatory factors when addressing CEPs.

In what follows, we first review extensively the existing work on capacity expansion planning to highlight the scarcity of literature that considers the regulatory factors. We then describe a DCEP that accounts for import tariff and corporate tax, and present a mixed-integer linear programming (MILP) formulation for its solution. Subsequently, we demonstrate with a case study the vital need for incorporating these regulatory factors in the capacity expansion decisions.

2.1 Literature Review

So far, the literature on the manufacturing industry in general and the CPI in particular has addressed two types of capacity expansion planning problems, namely deterministic and stochastic. The deterministic problem assumes fixed parameters over a given planning horizon, while the stochastic problem allows uncertainty in some parameters. The work on capacity expansion planning began in the late 1950s. Since then, many researchers have addressed this topic.

Wagner and Whitin (1959) presented a forward algorithm for the DCEP. In a later work, Veinott and Wagner (1962a) demonstrated how to solve an important class of DCEPs as an ordinary or reduced transshipment problem. For this class, Veinott and Wagner (1962b) also proposed a special algorithm that is more efficient than the linear programming algorithm. Barchi et al. (1975) formulated an integer programming model to represent a DCEP that involves the determination of both production and expansion plans with no backordering over given horizons. Hiller and Shapiro (1986) introduced a MILP model to represent a DCEP with learning effects. These learning effects include the reduction in unit manufacturing costs with cumulative production figures as well as the decrease in market prices of the finished products over time.

Sahinidis et al.(1989) presented a multi-period model to address the DCEP in the CPI. The model determines new processes, expansion plans, and shutdown policies to maximize the net present value of the project given the forecasts of prices and demands of the chemicals over a long planning horizon. Though the authors stated that their problem parameters accounted for the effect of taxes, they failed to consider explicitly profit-based corporate taxes and origin-destination based import tariffs in their formulation. In a follow-up work, Sahinidis and Grossmann (1992) developed two reformulations for the same DCEP, which allow much faster solutions than the original model. Li and Tirupati (1994) addressed a DCEP that includes technology types (flexible versus dedicated facilities) as decision variables. Such problems abound in industries such as steel and consumer electronics, where the tradeoff between adding expensive flexible facilities and relatively cheaper dedicated facilities is crucial in capacity expansion planning. Lee et al. (2000) developed a mixed integer nonlinear programming model (MINLP) that integrates the DCEP with production and distribution considerations. They made the MINLP model convex by using an exponential transformation for the variables to eliminate the bilinear terms, and used the outer approximation (OA) algorithm for its solution. Papageorgiou et al. (2001) reported a multi-period MILP model for managing product portfolio in the pharmaceutical industry. Their model addresses product development and introduction along with deterministic capacity planning. Although they do account for the effect of corporate tax in their model, their capacity planning assumes pre-specified sizes and costs for every possible expansion or new facility construction.

We see from the above discussion that barring one work (2001) that incorporates corporate taxes, there have been very few attempts made so far to consider the effects of other regulatory factors, especially the international ones such as import tariff, in the CEPs prior to the publication of Oh and Karimi (2004). However, the same is not true for other classes of supply chain problems such as the location-allocation problems (LAPs) and the production-distribution problems (PDPs). The LAPs involve the selection of new facility locations and the allocation of production from different plants to various demand locations. We treat them as different from the CEPs, because they do not explicitly plan for the capacity expansion at the facilities. The PDPs entail the determination of production schedules for the manufacturing plants and the distribution plans for products across the entire value chain from suppliers, production plants, distribution centers, to customers.

Cohen et al. (1989), Arntzen et al. (1995), and Goetschalckx et al. (2002) have all included some of the regulatory factors in their PDPs. Cohen et al. (1989) reported a normative model framework to maximize the after-tax profit of an entire global firm in the presence an uncertain currency exchange rate. They included corporate tax, tariff, and local content rule. Arntzen et al. (1995) introduced a comprehensive MILP model that integrated corporate tax, import tariff, duty drawback, duty relief, local content rule, and offset requirement to represent a PDP for a multinational corporation. Goetschalckx et al. (2002) addressed a simultaneous LAP-PDP for a group of enterprises with the objective of maximizing the total after-tax profit in the presence of import tariffs.

From the above discussion, we conclude that most of the models and methodologies developed prior to the publication of Oh and Karimi (2004) for the CEPs are useful only in a local (national) context and are not appropriate for expansion planning with substantial transnational movements of goods and merchandise. The failure to incorporate key regulatory factors into capacity expansion planning has virtually prevented their application in practice. Therefore, it is extremely crucial to account for all the relevant regulatory factors in the strategic planning activity of any business. An optimal solution to a CEP with a local focus will generally not be optimal, when one integrates several regulatory factors into the CEP.

2.2 Problem Description

A MNC owns or can potentially build in future a set ***IF*** of processing facilities ($f \in$ ***IF***) in countries across the globe. We divide the facilities into two groups: ***EIF*** being the set of existing facilities and ***FIF*** being the set of future (new) facilities such that ***IF*** = ***EIF*** ∪ ***FIF***. These internal facilities of the MNC either manufacture useful products from some raw materials (or wastes) or simply treat wastes without producing any useful products. In addition to interacting with each other in terms of receiving/supplying materials to each other, they ($f \in$ ***IF***) also interact with another set ***EF*** of external facilities ($f \in$ ***EF***) that do not belong (or are external) to the MNC. We define ***F*** = ***IF*** ∪ ***EF***, and assume that the location and the incoming and outgoing materials for each $f \in$ ***F*** (whether existing or future, internal or external) are prefixed and known. Multiple facilities may exist at the same location or plant site. For instance, an existing plant site currently produces *B* and *C* from *A*, and *E* from *C* and *D*. The site has sufficient space to build two more processes: one to produce *G* from *C* and *F*, and the other to produce *J* from *H*. Then, we model this plant site as four separate facilities (f = 1, 2, 3, 4) as follows.

(f = 1) $A \rightarrow B + C$

(f = 2) $C + D \rightarrow E$

(f = 3) $C + F \rightarrow G$

(f = 4) $H \rightarrow I$

Facilities 1 and 2 exist now, while 3 and 4 are new that the company may or may not build.

For each $f \in$ ***F***, we group its associated materials (raw materials, products, byproducts, wastes, etc.) into two sets. $\boldsymbol{IM_f}$ denotes the set of incoming materials m_i ($i \in \boldsymbol{IM_f}$) consumed by f, and $\boldsymbol{OM_f}$ denoting the set of outgoing materials m_i ($i \in \boldsymbol{OM_f}$) produced by f. Note that we include only the materials that are relevant in terms of interaction among the facilities. For instance, suppose that an external facility f produces *C* and *D* from *A* and *B*. However, the MNC neither supplies currently or ponders supplying at any time *A* or *B* to *f* nor needs currently or ponders needing at any time *D* from *f* at any of its internal facilities. Then, we simply set $\boldsymbol{IM}_f$ as a null set, and $\boldsymbol{OM}_f = \{C\}$. Similarly, $\boldsymbol{IM}_f$ for an internal facility *f* may not include products (e.g. waste products) that are inconsequential, unless we also treat the waste disposal site as a separate facility by itself. Finally, for each *internal* facility *f* ($f \in \boldsymbol{IF}$), we designate one material $\pi(f)$ as a primary material, and define the current production capacity (Q_{f0}) of *f* as the rate (ton per fiscal year) at which *f* uses or produces $\pi(f)$ at time zero. Note that $\pi(f)$ can be an either incoming or outgoing material, and all future internal facilities ($f \in \boldsymbol{FIF}$) have $Q_{f0} = 0$.

Considering a global problem, we let all facilities be located in *N* different nations ($n = 1, 2, \ldots, N$) or countries, and define $\boldsymbol{F}_n$ as the set of facilities situated in nation *n* ($f \in \boldsymbol{F}_n$, $\boldsymbol{F}_1 \cup \boldsymbol{F}_2 \cup \ldots \cup \boldsymbol{F}_N = \boldsymbol{F}$, and $\boldsymbol{F}_n \cap \boldsymbol{F}_{n'}$ = null set for $n \neq n'$). The legislations of a host country *n* normally imposes several restrictions on the ownership, imports, exports, accounts, earnings, etc. of the facilities located in its jurisdiction ($f \in \boldsymbol{F}_n$). The internal facilities of each country *n* ($f \in \boldsymbol{IF} \cap \boldsymbol{F}_n$) pay corporate and other taxes collectively to the country's revenue authorities at the end of each fiscal year. Based on the sales forecast from the marketing division, the MNC wishes to develop an optimum, strategic, and global capacity expansion plan over a planning horizon of *T* fiscal years or periods ($t = 1, 2, \ldots, T$). The objective of this plan is to maximize the net present value (NPV) of the company's net cash flows over the planning horizon.

The desired expansion plan must determine:

(a) Time, location and amount of capacity expansion of each $f \in \boldsymbol{IF}$

(b) Actual flows of all materials to and from each $f \in \boldsymbol{F}$ during each *t*

We make the following assumptions for the above DCEP.

1. All business intelligence data that are crucial for generating a reliable capacity expansion plan are available. These include the forecasts for product demands, raw material requirements, raw material prices, product prices, transportation costs, operating costs, fixed and variable capacity expansion costs, capacity expansion limits, annual interest rates, import duties, and corporate taxes of all internal manufacturing facilities, and the capacities of all external supplier facilities over the T periods (fiscal years).
2. The fluctuations in currency exchange rates over the T periods are already accounted for in the business intelligence data. Hence, we express all expenditures and returns in terms of a numeraire currency.
3. Expansion-related construction activities do not affect the available production capacity of any internal facility f at any time.
4. All activities related to the capacity expansion or new plant construction at any $f \in \boldsymbol{IF}$ require $\delta(f)$ periods before the expanded or new capacity becomes available. For instance, if $\delta(f) = 3$, and the capacity expansion or new construction begins at the start of $t = 1$, then the expanded or new capacity is available only during and after $t = 4$.
5. An expansion or new construction cannot begin while an expansion or construction is underway. In other words, if $\delta(f) = 3$ and an expansion or construction begins at $t = 1$, then another expansion or construction cannot begin until after the end of $t = 3$.
6. The fixed costs for the expansion of an existing facility and for the construction of a new facility are different, but their linear variable costs are the same.
7. No inventory is carried forward from one period to the next at any internal facility f. This is reasonable, since the length (one year) of each period in the planning horizon is sufficiently long.

8. Every internal facility f is liable for the tariffs on all its imports from facilities that are outside its own country. The import tariff is levied based on the cost, insurance, and freight (CIF) cost (see Karimi et al., 2002 for more detailed CIF description) of imports at f. This refers to the total value of goods including the purchase, insurance, and freight costs incurred in bringing them to the delivery facility.
9. The mass balance for each internal facility f is given by,

$$\sum_{i \in \boldsymbol{IM}_f} \sigma_{if} m_i = \sum_{i \in \boldsymbol{OM}_f} \sigma_{if} m_i \qquad f \in \boldsymbol{IF} \qquad (2.1)$$

   where, m_i denotes material i that f consumes or produces, and σ_{if} is analogous to the stoichiometric coefficient of a species i in a reaction except that the above balance is in terms of mass (ton) rather than moles. For example, if a facility f consumes 2 kg of A and 1 kg of B to produce 1.8 kg of C and 1.2 kg of D, then $\sigma_{Af} = 2$, $\sigma_{Bf} = 1$, $\sigma_{Cf} = 1.8$, and $\sigma_{Df} = 1.2$. This facility could have either any of A, B, C, and D as the primary designated material.
10. For both the expansion of an internal existing facility and the construction of a new internal facility, depreciation is computed using the same formula.
11. Each internal facility has a constant lower limit on its production rate over the entire planning horizon. Thus, a facility, once it exists, must operate at or above that rate, and cannot shut down.
12. Products are shipped directly from the internal facilities to the customers and the latter bear the costs of materials, insurance, freight, and import duties.

We now present a formulation for the above stated DCEP. Unless stated otherwise, the indexes (f, t, i, etc.) assume their full ranges of values.

2.3 Model Formulation

The major task in developing the expansion plan is to decide the times, locations, and amounts of capacity expansion of each internal facility. To model these decisions, we define q_{ft} as the amount (ton) by which the capacity of facility $f \in \boldsymbol{IF}$ increases during period t and the following two binary variables and a simplifying notation:

$$y_{ft} = \begin{cases} 1 & \text{if the capacity of a facility } f \text{ expands during period } t \\ 0 & \text{otherwise} \end{cases} \qquad f \in \boldsymbol{IF}$$

$$z_{ft} = \begin{cases} 1 & \text{if a future facility } f \text{ begins construction during } t \\ 0 & \text{otherwise} \end{cases} \qquad f \in \boldsymbol{FIF}$$

$$\xi_{ft} = \begin{cases} z_{ft} & \text{if } f \in \boldsymbol{FIF} \\ 0 & \text{otherwise} \end{cases} \qquad f \in \boldsymbol{IF}$$

Assumption 4 tells us that there is no incentive to begin an expansion or new construction near the end of the horizon. Thus, $y_{ft} = 0$ for $f \in \boldsymbol{IF}$ and $t > T\text{–}\delta(f)$, and $z_{ft} = 0$ for $f \in \boldsymbol{FIF}$ and $t > T\text{–}\delta(f)$. Similarly, a future internal facility $f \in \boldsymbol{FIF}$ cannot start an expansion during the first $\delta(f)$ periods, because it must be built first, so $y_{ft} = 0$ for $f \in \boldsymbol{FIF}$ and $t \leq \delta(f)$.

Now, the MNC cannot build a future facility $f \in \boldsymbol{FIF}$ more than once during the planning horizon, so we have,

$$z_{f1} + z_{f2} + z_{f3} + \ldots + z_{f[T\text{–}\delta(f)]} \leq 1 \qquad f \in \boldsymbol{FIF} \qquad (2.2)$$

Similarly, it cannot expand the capacity of a future facility $f \in \boldsymbol{FIF}$, until it has built it. Therefore, we get,

$$y_{ft} \leq z_{f1} + z_{f2} + z_{f3} + \ldots + z_{f[t\text{–}\delta(f)]} \qquad f \in \boldsymbol{FIF},\ \delta(f) < t \leq T\text{–}\delta(f) \qquad (2.3)$$

Assumption 5 tells us that if the MNC begins expanding an existing facility $f \in$ ***EIF*** during a period t, or if it begins constructing or expanding a future internal facility $f \in$ ***FIF*** during a period t, then it cannot begin another expansion during the $\delta(f)$ periods including and after period t, so we obtain,

$$y_{ft} + \xi_{ft} + y_{f(t+1)} + \ldots + y_{f[t+\delta(f)-1]} \le 1 \qquad f \in \boldsymbol{IF},\ t \le T-\delta(f) \qquad (2.4)$$

If the MNC does not begin expanding a facility $f \in$ ***IF*** during a period t, then the amount of expansion (q_{ft}) must be zero. Therefore, we get,

$$q_{ft} \le y_{ft}(Q_f^U - Q_{f0}) \qquad f \in \boldsymbol{IF} \qquad (2.5a)$$

where, Q_f^U is the maximum capacity that $f \in$ ***IF*** can possibly have. Similarly, if an expansion or new construction occurs at $f \in$ ***IF***, then the capacity must expand by at least some lower limit, i.e.,

$$q_{ft} \ge y_{ft}\, q_f^L + \xi_{ft} Q_f^L \qquad f \in \boldsymbol{IF} \qquad (2.5b)$$

where, q_f^L is the minimum incremental expansion allowed at $f \in$ ***IF***, and Q_f^L is the minimum capacity of a new construction at $f \in$ ***FIF***. Using eqs. (2.4a,b), we write,

$$q_{ft} = y_{ft}\, q_f^L + \xi_{ft} Q_f^L + \Delta q_{ft} \qquad f \in \boldsymbol{IF} \qquad (2.6)$$

$$\Delta q_{ft} \le y_{ft}(Q_f^U - Q_{f0} - q_f^L) + \xi_{ft}(Q_f^U - Q_f^L) \qquad f \in \boldsymbol{IF} \qquad (2.7)$$

$$Q_{ft} = Q_{f(t-1)} + y_{f[t-\delta(f)]}q_f^L + \xi_{f[t-\delta(f)]}Q_f^L + \Delta q_{f[t-\delta(f)]} \qquad f \in \boldsymbol{IF} \qquad (2.8)$$

where, Q_{ft} is the capacity of $f \in \boldsymbol{IF}$ during period t with an upper limit of Q_f^U. The lower and upper limits on capacities are in line with the industrial practice and are based on economic analysis and space availability.

To model the incoming and outgoing flows of materials for the facilities, we let F_{isct} denote the quantity of material i that facility $s \in \boldsymbol{F}$ sells to facility $c \in \boldsymbol{F}$ during period t, where $s \neq c$. Note that F_{isct} is a non-negative variable that exists only for $i \in \boldsymbol{OM}_s \cap \boldsymbol{IM}_c$. Since inventory does not carry over from one period to the next, the material amounts consumed (produced) must match the incoming (outgoing) material flows. Therefore, if x_{ift} and X_{ft} respectively denote the actual consumption/production levels (ton/year) of materials m_i and $\pi(f)$ at an internal facility $f \in \boldsymbol{IF}$ during t, then we must have,

$$\sigma_{\pi(f)f}\, x_{ift} = \sigma_{if}\, X_{ft} \qquad f \in \boldsymbol{IF},\ i \in \boldsymbol{OM}_f \cup \boldsymbol{IM}_f \qquad (2.9)$$

$$\sigma_{if}\, X_{ft} = \sigma_{\pi(f)f}\left(\sum_{c \ni i \in \boldsymbol{IM}_c} F_{ifct} + \sum_{s \ni i \in \boldsymbol{OM}_s} F_{isft} \right) \qquad f \in \boldsymbol{IF},\ i \in \boldsymbol{OM}_f \cup \boldsymbol{IM}_f \qquad (2.10)$$

Note that only one of the two sums in the above equation can be nonzero, as we do not allow any facility f to send and receive the same material during any t. Furthermore, a facility $f \in \boldsymbol{IF}$ cannot process more than its capacity, so using eq. (2.8), we have,

$$X_{ft} \leq Q_{ft} \qquad f \in \boldsymbol{IF} \qquad (2.11)$$

Conversely, each facility $f \in \boldsymbol{IF}$ must respect a lower limit on its production rate.

$$X_{ft} \geq X_f^L \left(\varphi_f + \sum_{\tau=1}^{t-\delta(f)} z_{f\tau} \right) \qquad f \in \boldsymbol{IF} \qquad (2.12)$$

where $\varphi_f = 1$ for $f \in \boldsymbol{EIF}$ and 0 for $f \in \boldsymbol{FIF}$.

For each external facility $f \in \boldsymbol{EF}$, we define D_{ift} ($i \in \boldsymbol{IM}_f$) as the maximum quantity of i, which f can accept during t, and S_{ift} ($i \in \boldsymbol{OM}_f$) as the maximum amount of i, which f can supply during t. Clearly, $D_{ift}*S_{ift} = 0$, as we forbid simultaneous receipt and supply of the same material by any f. To ensure that delivery does not exceed demand, and supply does not exceed capacity, we use,

$$\sum_{f \in \boldsymbol{IF} \ni i \in \boldsymbol{OM}_f} F_{ifgt} + \sum_{f \in \boldsymbol{IF} \ni i \in \boldsymbol{IM}_f} F_{igft} \leq D_{igt} + S_{igt} \qquad g \in \boldsymbol{EF},\ i \in \boldsymbol{OM}_g \cup \boldsymbol{IM}_g \qquad (2.13)$$

Again, note that only one of the two terms on each side can exist in the above constraint.

Whether it is an expansion or new construction, the MNC will need to do some capital expenditure. Let CE_t and CB_t denote respectively the MNC's actual capital expenditure and allotted capital budget for period t, then we have,

$$CE_t = \sum_{f \in \boldsymbol{IF}} [a_{ft} y_{ft} + b_{ft}(y_{ft} q_f^L + \xi_{ft} Q_f^L + \Delta q_{ft}) + c_{ft} z_{ft}] \qquad (2.14)$$

where, a_{ft} is the fixed cost of expansion of an existing facility $f \in \boldsymbol{EIF}$ during t, c_{ft} is the fixed cost of construction of a new facility $f \in \boldsymbol{FIF}$ during t, and b_{ft} is the variable cost of expansion or new construction at an internal facility $f \in \boldsymbol{IF}$ during t. Using the previous equation, we ensure that the cumulative capital expenditure does not exceed the cumulative allotted budget, i.e.,

$$\sum_{\tau \le t} \sum_{f \in \boldsymbol{IF}} [a_{f\tau} y_{f\tau} + c_{f\tau} \xi_{f\tau} + b_{f\tau} (y_{f\tau} q_f^L + \xi_{f\tau} Q_f^L + \Delta q_{f\tau})] \le \sum_{\tau \le t} CB_\tau \tag{2.15}$$

Now, to compute the MNC's collective corporate taxes during each t in each host nation n, we need the taxable incomes of the MNC's facilities in that nation n. The taxable income is gross income minus depreciation, and gross income is sales minus operating expense. The operating expense is the sum of procurement and manufacturing (or variable production) costs. To this end, let P_{isct}, CIF_{isct}, and ID_{isct} denote respectively the purchase price ($/ton), CIF cost ($/ton), and import duty ($/$ of CIF cost) of material m_i ($i \in \boldsymbol{OM}_s \cap \boldsymbol{IM}_c$) sold by $s \in \boldsymbol{F}$ to $c \in \boldsymbol{F}$ during t. Then, the gross income GI_{ft} of $f \in \boldsymbol{IF}$ is,

$$GI_{ft} = -MC_{ft} X_{ft} + \sum_{i \in \boldsymbol{OM}_f} \sum_{c \ni i \in \boldsymbol{IM}_c} (P_{ifct} F_{ifct}) - \sum_{i \in \boldsymbol{IM}_f} \sum_{s \ni i \in \boldsymbol{OM}_s} (1 + ID_{isft}) CIF_{isft} F_{isft} \tag{2.16}$$

where, MC_{ft} is the manufacturing cost [$/ton of $\pi(f)$] of $f \in \boldsymbol{IF}$ during t.

Depreciation is an amount that the MNC charges itself for recovering its capital investment. Various methods exist for computing depreciation, and acceptable methods differ from country to country. In this paper, we use the simplest method for computing depreciation, which is the straight-line method. Now, during the planning horizon, two depreciation charges will occur. One arising from the (old) investments before t = 0, and the other arising from the (new) ones after t = 0. Let the former charge be ODC_{ft}, while for the latter, we define $NDC_{f\tau t}$ as the depreciation charge during t for the capital investment at $f \in \boldsymbol{IF}$ during year $\tau = 1, 2, \ldots, T–\delta(f)$. Then, we obtain,

$$NDC_{f\tau t}= \begin{cases} [a_{f\tau} y_{f\tau} + c_{f\tau}\xi_{f\tau} + b_{f\tau}(y_{f\tau} q_f^L + \xi_{f\tau} Q_f^L + \Delta q_{f\tau})]/L_f & \tau + \delta(f) \le t \le \min[\tau + L_f, T] \\ 0 & \text{otherwise} \end{cases}$$

$$1 \le \tau \le T–\delta(f), f \in \boldsymbol{IF} \qquad (2.17)$$

where, L_f denotes the project life (years) for all capital expenditure at $f \in \boldsymbol{IF}$, which begins after the new facility or expanded capacity becomes available for production. Using eqs. (2.16) and (2.17), we obtain the taxable income TI_{nt} of the MNC in nation n during t as,

$$TI_{nt} \ge \sum_{f \in \boldsymbol{IF} \cap \boldsymbol{F}_n} \left[\sum_{i \in \boldsymbol{OM}_f} \sum_{c \ni i \in \boldsymbol{IM}_c} P_{ifct} F_{ifct} - \sum_{i \in \boldsymbol{IM}_f} \sum_{s \ni i \in \boldsymbol{OM}_s} (1 + ID_{isft}) CIF_{isft} F_{isft} \right.$$
$$\left. - MC_{ft} X_{ft}^{\chi} - ODC_{ft} - \sum_{\tau=1}^{t-\delta(f)} NDC_{f\tau t} \right] \qquad (2.18)$$

where, eq. (2.17) gives $NDC_{f\tau t}$. Note that TI_{nt} is a nonnegative variable. If the tax rate (\$/\$ of taxable income) is TR_{nt} (non-negative) for nation n during t, then the corporate tax for the MNC during t is $TR_{nt}TI_{nt}$. With this, the NPV of the net cash flow for the MNC is,

$$\text{NPV} = \sum_{f\in \boldsymbol{IF}}\sum_{t}\frac{-MC_{ft}X_{ft} + \sum_{i\in \boldsymbol{OM}_f}\sum_{c\ni i\in \boldsymbol{IM}_c} P_{ifct}F_{ifct} - \sum_{i\in \boldsymbol{IM}_f}\sum_{s\ni i\in \boldsymbol{OM}_s}(1+ID_{isft})CIF_{isft}F_{isft}}{(1+r)^t}$$

$$-\sum_{f\in \boldsymbol{IF}}\sum_{t}\frac{[a_{ft}y_{ft} + c_{ft}\xi_{ft} + b_{ft}(y_{ft}q_f^L + \xi_{ft}Q_f^L + \Delta q_{ft})]}{(1+r)^t} - \sum_{n}\sum_{t}\frac{TI_{nt}TR_{nt}}{(1+r)^t} \qquad (2.19)$$

where, r is the annual interest rate (fraction).

This completes our formulation for the DCEP in the presence of corporate taxes and import duties as the regulatory factors. It comprises maximizing NPV (2.19) subject to eqs. (2.2) to (2.5), (2.7), (2.8), (2.10) to (2.13), (2.15), (2.17), and (2.18). We now illustrate our model with a realistic example and demonstrate the significant impact of regulatory factors.

2.4 Case Study

A MNC currently owns six facilities (***EIF*** = {F1 to F6}) and is considering six new facilities (***FIF*** = {F7 to F12}) for possible capacity expansion over the next ten fiscal years (t = 1, 2, …, T = 10) to meet the growth forecasts in the global demands of its products. The MNC classifies its facilities as primary or secondary. The primary upstream processing facilities supply raw materials to the secondary downstream facilities (see Figure 2.1 for the material flows among these facilities). Figure 2.2 shows an existing industrial setting with material flows similar to those in this case study. Here, a crude distillation unit is the primary facility, while steam reformer, catalytic reformer, and steam cracker are the secondary facilities. Table 2.1 lists the initial capacity (Q_{f0}), capacity limits (q_f^L, Q_f^L, Q_f^U), minimum production limits (X_f^L), manufacturing costs (MC_{ft}), expansion cost coefficients (a_{ft}, b_{ft}, c_{ft}), primary materials [$\pi(f)$], mass balance (σ_{if}), etc. for each facility.

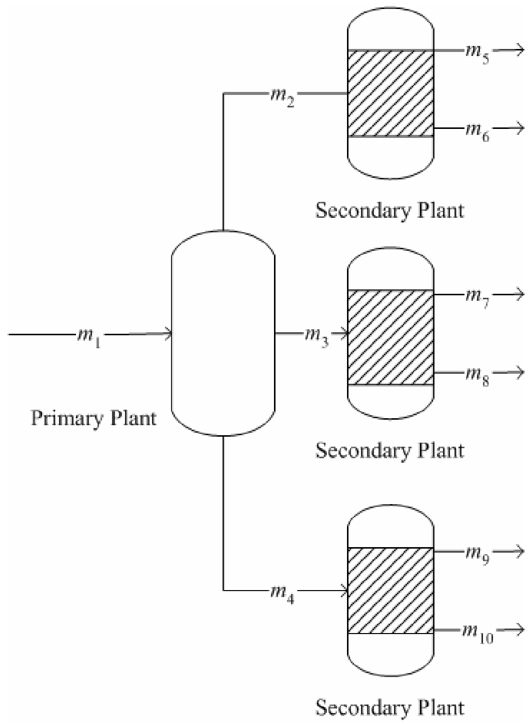

Figure 2.1: Material flows among the facilities in the case study

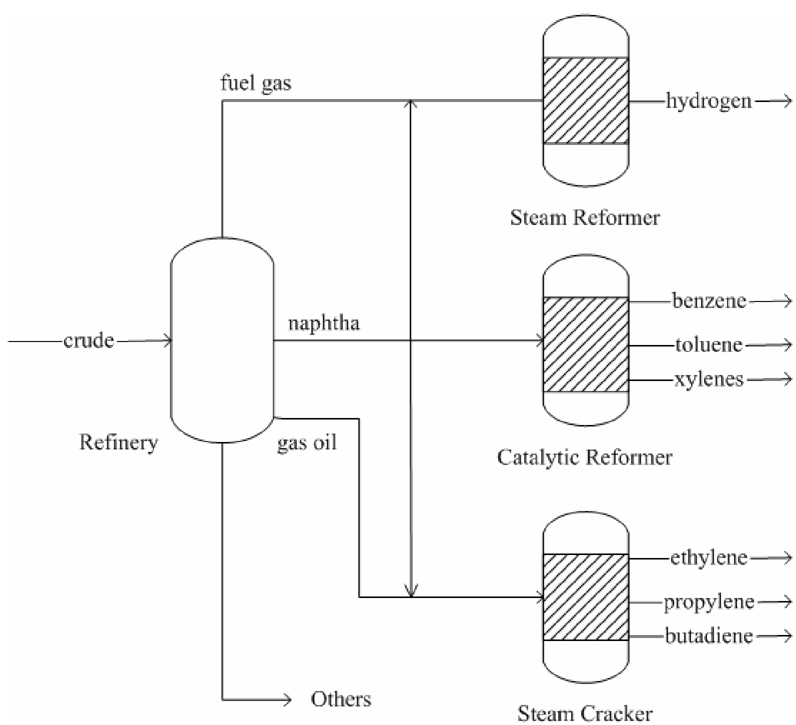

Figure 2.2: Material flows among the facilities of a typical petrochemical plant

Table 2.1: Types, initial capacities (ton/day), capacity limits (ton/day), mass balances, primary materials, project lives, periods for expansion or new construction, annual interest rates, depreciation charges (k$), minimum production limits (ton/day), manufacturing costs ($/kg), and coefficients (k$/ton) in expansion cost expressions for the MNC's facilities in case study

Facility (f)	$\pi(f)$	Initial Cap. (Q_{f0})	Max Cap. (Q_f^U)	Min Exp. (q_f^L)	Min Const. (Q_f^L)	Min Prod. (X_f^L)	MC_{f1}	a_{f1}	b_{f1}	c_{f1}	Depreciation Charges (ODC_{ft})
F1	m_2	90	120	25	-	40	0.581	220	10	330	160.7
F2	m_2	80	100	25	-	30	0.687	450	30	675	410.8
F3	m_5	40	80	25	-	20	0.720	300	20	450	369.1
F4	m_5	25	100	25	-	15	0.580	300	20	450	318.2
F5	m_7	30	70	25	-	30	1.025	500	10	750	321.1
F6	m_9	25	80	40	-	25	0.956	270	10	405	133.3
F7	m_2	0	150	30	40	30	1.222	200	20	300	0.0
F8	m_5	0	90	25	40	25	0.685	350	30	525	0.0
F9	m_7	0	120	40	60	40	1.112	480	30	720	0.0
F10	m_7	0	120	45	60	45	0.915	280	20	420	0.0
F11	m_9	0	85	25	30	25	0.825	550	20	825	0.0
F12	m_9	0	120	25	30	25	0.788	300	20	450	0.0

Mass balances:
F1, F2, and F7: $m_1 = 0.3m_2 + 0.3m_3 + 0.3m_4 + 0.1m_{11}$
F3, F4, and F8: $m_2 = 0.5m_5 + 0.4m_6 + 0.1m_{12}$
F5, F9, and F10: $m_3 = 0.6m_7 + 0.35m_8 + 0.05m_{13}$
F6, F11, and F12: $m_4 = 0.3m_9 + 0.65m_{10} + 0.05m_{14}$

F1, F2 and F7 are primary facilities, while all others are secondary. Each fiscal year has 300 production days at all facilities. All manufacturing costs (MC_{ft}) and expansion cost coefficients (a_{ft}, b_{ft}, and c_{ft}) increase by 3% each year. L_f (project life) = 15 years and $\delta(f)$ = 2 years for all constructions. The annual interest rate is constant at 6% for all facilities. All old depreciation charges (ODC_{ft}) are constant over the entire planning horizon.

External facilities comprise ten customers (C1 to C10) and eight suppliers (S1 to S8), thus ***EF*** = {C1 to C10, S1 to S8}. These customers and suppliers are the key external business partners to whom the MNC sells its products and from whom it sources raw materials respectively. The twelve internal facilities (***IF*** = {F1 to F12}) and the eighteen external facilities (customers and suppliers) are geographically spread across ten nations (n = N1 to N10): $\boldsymbol{F}_{\text{N1}}$ = {C1, S1, F9}, $\boldsymbol{F}_{\text{N2}}$ = {C2, S2, F1, F3}, $\boldsymbol{F}_{\text{N3}}$ = {C3, F8}, and so on as in Table 2.2.

Table 2.2: Locations of internal (MNC's own facilities) and external facilities (other suppliers and customers) in case study

Nation (n)	**Facilities** Customer	Supplier	MNC's	**Corporate Tax Rates** 100*TR_{nt} (Years t)
N1	C1	S1	F9	21% (1-10)
N2	C2	S2	F1, F3	38% (1-10)
N3	C3	-	F8	18% (1-10)
N4	C4	S3	-	-
N5	C5	S4	F2, F4	40% (1-10)
N6	C6	-	-	-
N7	C7	S5	F5	24% (1-10)
N8	C8	S6	F7, F10, F12	40% (1-3), 38% (4-6), 36% (7-10)
N9	C9	S7	F6	26% (1-10)
N10	C10	S8	F11	0% (1-4), 36% (5-10)

Table 2.2 also lists the corporate tax rate for each nation. The tax rates are constant over the ten years for all nations except N8, which has announced plans to cut corporate tax rate from 40% to 38% and then to 36% from the fourth and seventh years onwards respectively. In a bid to attract foreign direct investments (FDI), N10 has offered to waive the corporate tax for the next four fiscal years, if the MNC were to invest in new facilities at the start of the planning horizon.

Table 2.3 shows the import duties for material flows among the suppliers and internal facilities. Since the customers bear the import duties on their product purchases, they are of no concern to the MNC. The import duties of all products are constant over the planning horizon with one exception. From the third year onwards, a bilateral free trade agreement (FTA) between N5 and N8 is expected to commence officially, which will waive the import tariffs on product flows between them.

Table 2.4 lists the purchase and CIF costs as charged by the eight suppliers of raw materials, and the transfer prices charged by the MNC's internal facilities. The transfer prices (the price that an internal facility charges to another internal facility) at each period is fixed according to the material type regardless of which internal facility is the seller or buyer. This is required by the revenue authorities to prevent a company from manipulating transfer prices to save taxes. We use a 3% annual inflation rate for all cost data and prices in this example. Table 2.5 gives the demand rate expressions for the products consumed by the ten customers. For most customers, we use a linearly increasing demand rate for each product, so that most of Table 2.5 gives only the demands for years 1 and 10. For three customers, we express the demand rates as nonlinear functions of year. Figure 2.3 shows the demand rate profiles of material m_9 for the customers over the ten years. Table 2.6 lists the projected supply levels of materials from various suppliers. In all cases, we assume supply level to increase linearly with time.

Table 2.3: Percent import duties ($100ID_{isft}$) on raw material flows (m_i, i = 1 to 4) from F1, F2, F7, and S1 through S8 to internal facilities (F1 through F12).

Importing Facility	**Material** m_i (i)	**Exporting Facility (% Import duty)**
F1	1	S2 (0%), others (5%)
F2	1	S4 (0%), others (10%)
F3	2	F1 (0%), S2 (0%), others (35%)
F4	2	F2 (0%), S4 (0%), others (80%)
F5	3	S5 (0%), others (55%)
F6	4	S7 (0%), others (65%)
F7	1	S6 (0%), others (70%)
F8	2	All (60%)
F9	3	S1 (0%), others (45%)
F10	3	F7 (0%), S6 (0%), others (65%)
F11	4	S8 (0%), others (30%)
F12	4	F7 (0%), S6 (0%), others (30%)

Bilateral free trade agreement between N5 and N8 will commence from year three onwards. This means that the import duties on the material trade between S4, F2, F4 in N5 and S6, F7, F10, F12 in N8 will be zero for $t \geq 3$.

Table 2.4: Purchase costs (P_{isf1} \$/kg) and IF (insurance+freight) costs ($CIF_{isf1}–P_{isf1}$ \$/kg) of materials between facilities for year 1 (t = 1)

	To											
	Material m_1			Material m_2			Material m_3			Material m_4		
From	F1	F2	F7	F3	F4	F8	F5	F9	F10	F6	F11	F12
F1	-	-	-	0.210	0.210	0.210	0.440	0.440	0.440	0.180	0.180	0.180
				0.012	0.027	0.023	0.033	0.033	0.039	0.021	0.023	0.024
F2	-	-	-	0.210	0.210	0.210	0.440	0.440	0.440	0.180	0.180	0.180
				0.022	0.008	0.028	0.034	0.034	0.033	0.024	0.027	0.028
F7	-	-	-	0.210	0.210	0.210	0.440	0.440	0.440	0.180	0.180	0.180
				0.021	0.024	0.021	0.031	0.033	0.011	0.020	0.019	0.011
S1	0.510	0.510	0.510	2.280	2.280	2.280	1.410	1.410	1.410	1.550	1.550	1.550
	0.039	0.033	0.037	0.106	0.095	0.131	0.063	0.032	0.062	0.064	0.082	0.085
S2	1.780	1.780	1.780	1.170	1.170	1.170	0.750	0.750	0.750	1.210	1.210	1.210
	0.040	0.086	0.102	0.037	0.068	0.064	0.046	0.035	0.048	0.072	0.067	0.064
S3	1.730	1.730	1.730	1.760	1.760	1.760	0.990	0.990	0.990	1.860	1.860	1.860
	0.064	0.082	0.095	0.092	0.107	0.073	0.051	0.048	0.048	0.074	0.084	0.108
S4	0.880	0.880	0.880	0.860	0.860	0.860	1.750	1.750	1.750	2.160	2.160	2.160
	0.040	0.019	0.039	0.043	0.018	0.051	0.100	0.084	0.076	0.099	0.086	0.089
S5	0.770	0.770	0.770	0.670	0.670	0.670	0.950	0.950	0.950	1.700	1.700	1.700
	0.048	0.042	0.041	0.036	0.038	0.048	0.024	0.050	0.046	0.092	0.076	0.102
S6	1.400	1.400	1.400	1.380	1.380	1.380	0.750	0.750	0.750	2.110	2.110	2.110
	0.079	0.085	0.039	0.087	0.076	0.068	0.040	0.048	0.015	0.114	0.095	0.052
S7	1.120	1.120	1.120	2.400	2.400	2.400	1.930	1.930	1.930	0.730	0.730	0.730
	0.050	0.055	0.060	0.129	0.098	0.122	0.085	0.091	0.074	0.018	0.046	0.045
S8	1.040	1.040	1.040	1.960	1.960	1.960	0.820	0.820	0.820	0.800	0.800	0.800
	0.068	0.060	0.053	0.087	0.085	0.114	0.050	0.043	0.037	0.049	0.019	0.044

First row for each origin is the purchase cost, while the second is the IF cost. All costs increase by 3% each year due to inflation.

Table 2.5: Linear ranges or expressions for demands (D_{ict} ton/day) of materials (m_i, i = 2 to 10) and their selling prices ($/kg) in case study

i	Selling Price	Customer c									
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
2	1.24	85.8 213.8	$\frac{176.12t + 9.27}{0.45t + 0.55}$	117.4 147.1	142.9 222.2	91.9 262.0	98.9 230.3	$\frac{86.68t + 15.09}{0.35t + 0.65}$	92.0 246.1	$\frac{143.82t + 20.4}{0.38t + 0.62}$	135.6 204.7
3	1.49	81.2 211.8	$\frac{101.75t + 18.07}{0.35t + 0.65}$	108.9 196.9	145.4 207.6	85.1 230.6	95.2 326.0	$\frac{101.41t + 14.11}{0.38t + 0.62}$	82.4 279.0	$\frac{158.64t + 27.05}{0.35t + 0.65}$	123.3 186.5
4	1.48	84.6 280.5	$\frac{100.83t + 24.7}{0.3t + 0.7}$	102.8 188.9	104.0 182.1	85.4 307.5	81.1 336.1	$\frac{137.89t + 12.05}{0.42t + 0.58}$	88.9 337.6	$\frac{176.45t + 6.18}{0.47t + 0.53}$	129.0 143.8
5	3.98	95.8 281.7	$\frac{175.19t + 22.51}{0.39t + 0.61}$	133.6 154.1	136.7 201.8	99.8 283.7	83.5 328.3	$\frac{119.05t + 8.57}{0.43t + 0.57}$	94.7 342.5	$\frac{96.46t + 13.29}{0.38t + 0.62}$	105.4 164.4
6	3.45	86.2 300.3	$\frac{133.48t + 29.81}{0.32t + 0.68}$	129.0 182.4	146.7 223.8	83.0 218.0	96.2 317.7	$\frac{159.78t + 25.14}{0.36t + 0.64}$	87.6 319.7	$\frac{125.69t + 11.4}{0.42t + 0.58}$	123.7 175.0
7	4.12	95.5 294.8	$\frac{109.25t + 17.01}{0.37t + 0.63}$	112.9 192.1	108.0 129.9	83.5 223.8	99.2 287.8	$\frac{114.04t + 15.72}{0.38t + 0.62}$	84.6 298.6	$\frac{124.68t + 8.16}{0.44t + 0.56}$	147.2 160.2
8	4.43	93.5 239.2	$\frac{137.93t + 0.04}{0.5t + 0.5}$	122.9 161.5	112.8 180.0	95.6 343.8	82.5 260.9	$\frac{104.55t + 19.95}{0.34t + 0.66}$	80.3 349.5	$\frac{148.15t + 23.02}{0.37t + 0.63}$	115.8 148.1
9	2.80	86.5 210.9	$\frac{173.32t + 20.12}{0.4t + 0.6}$	138.2 150.3	131.5 146.5	95.6 312.0	95.2 263.5	$\frac{161.65t + 32.01}{0.33t + 0.67}$	81.4 235.8	$\frac{141.87t + 23.12}{0.36t + 0.64}$	143.9 165.9
10	3.36	88.7 215.6	$\frac{144.54t + 2.15}{0.49t + 0.51}$	121.6 210.7	135.7 206.7	83.3 217.5	99.7 311.8	$\frac{149.71t + 7.1}{0.45t + 0.55}$	85.5 250.2	$\frac{117.97t + 5.84}{0.45t + 0.55}$	130.5 196.0

The demand rates for C2, C7 and C9 are given as functions of t. For all others, the first row is the demand rate for year 1, while the second is for year 10, and the demand rates for the interim years are linear extrapolations. Figure 4 illustrates the variety of demand profiles of m_9 for the customers over the horizon. All prices increase by 3% each year.

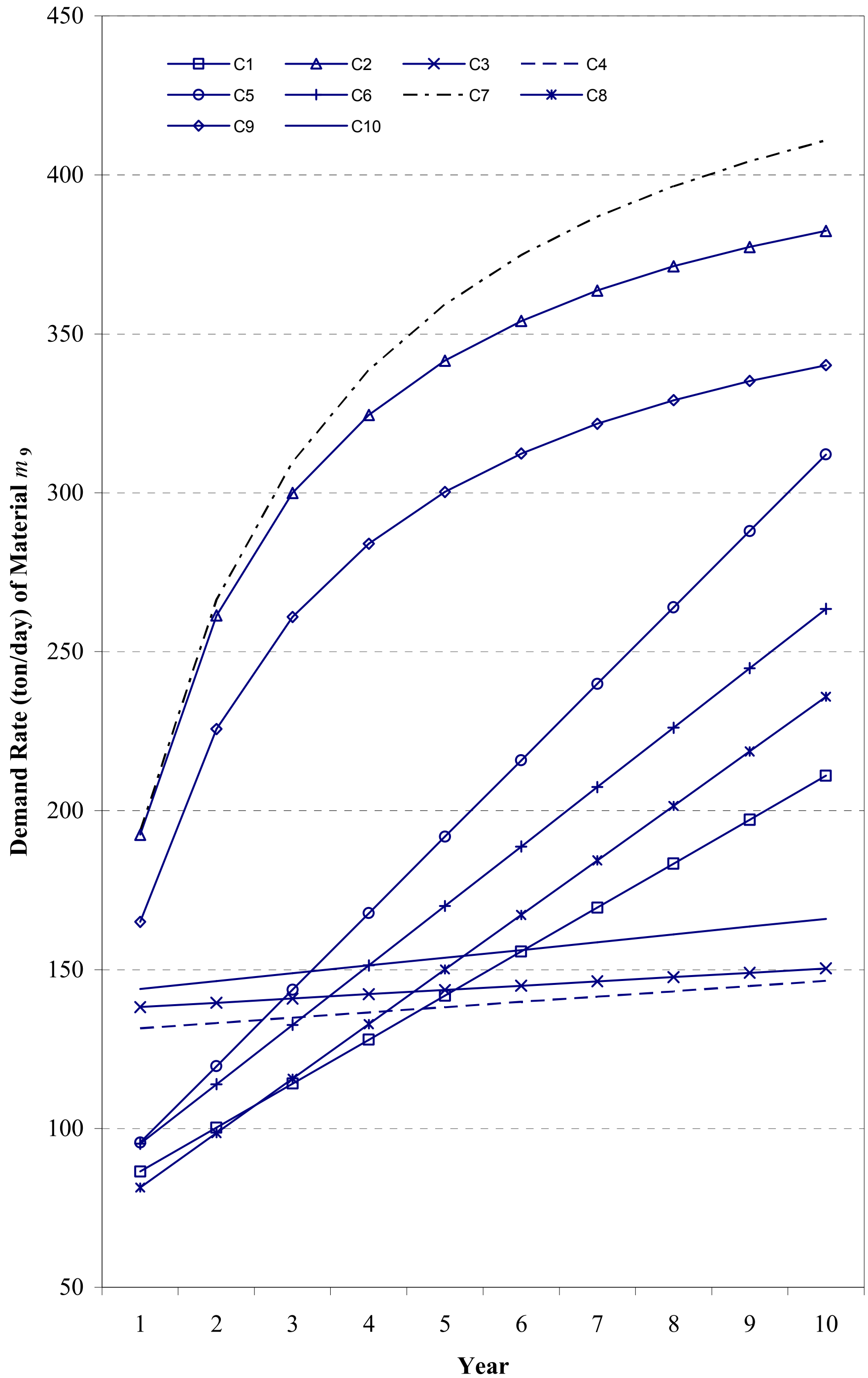

Figure 2.3: Demand rate profiles of material m_9 for the customers

Table 2.6: Linear ranges of projected supplies (S_{ist} ton/day) of materials (m_i, i = 1 to 4) from the external suppliers in case study

i	Supplier s							
	S1	S2	S3	S4	S5	S6	S7	S8
1	149.3	111.3	249.0	226.7	150.0	100.8	205.0	239.9
	296.0	284.1	311.6	248.6	257.6	254.6	256.8	249.2
2	102.3	119.1	247.4	220.1	108.0	132.3	220.6	216.3
	224.3	242.1	274.5	308.3	229.6	244.5	257.5	280.5
3	110.4	129.2	222.9	213.1	118.9	146.0	231.4	204.9
	260.7	243.2	230.2	294.6	281.5	268.4	288.2	243.5
4	134.7	141.7	227.2	221.5	125.1	123.1	220.2	202.8
	279.2	314.8	229.2	304.0	279.0	263.8	252.1	227.1

First row is the supplier's capacity for year 1, while the second is for year 10. The capacities for the interim years are linear extrapolations.

The MNC has allocated \$10 million for all expansion-related activities during the first year (CB_1 = 10 M\$). Furthermore, it has allocated another \$12 million (CB_6 = 12 M\$) for the same purpose during the sixth year of the planning horizon.

Using the above data and information, we solved our model for two cases. In case 1, we included the two regulatory factors, namely the corporate taxes and the import duties. In case 2, we did not, so we omitted eq. (2.13), all TI_{nt}, and set ID_{isft} = TR_{nt} = 0. We used CPLEX 8.1 solver within GAMS (Distribution 21.2) running on a Windows XP workstation with a Pentium 4 Xeon (2.8 GHz) processor. The model for case 1 involved 17,139 continuous variables, 144 binary variables, 2750 constraints, and 35,607 nonzeros, while that for case 2 involved 17,059 continuous variables, 144 binary variables, 2670 constraints, and 30,739 nonzeros. CPLEX solved case 1 in 0.874 s and gave the maximum NPV of \$4.53 billion, while it solved case 2 in 0.952 s and gave a NPV of \$4.13 billion.

Figure 2.4 shows the optimal expansion plans for the two cases. Clearly, the regulatory factors make the two solutions significantly different. For example, the case 1 solution suggests the construction of a new facility (F11) in N10 during the first year to capitalize on the tax-free window offered by N10 for the first four fiscal years. In contrast, the case 2 solution suggests the same construction in the sixth fiscal year. This is clearly due to the omission of the corporate tax in case 2. Because of this, the case 1 solution suggests the construction of a new facility (F12) during the sixth year, while the case 2 solution suggests the same during the first year. However, apart from these, the decisions of expansion vs. new construction and their locations are identical for both scenarios except for F3 during year 1. The case 1 solution suggests a larger expansion than case 2. This is probably due to the budget constraint. In case 2, the budget is used for the construction of secondary facility F12 (120 ton/day), which leaves less for the expansion of F3. In case 2, a smaller secondary facility F11 (85 ton/day) is built, so more is available for the expansion for F3.

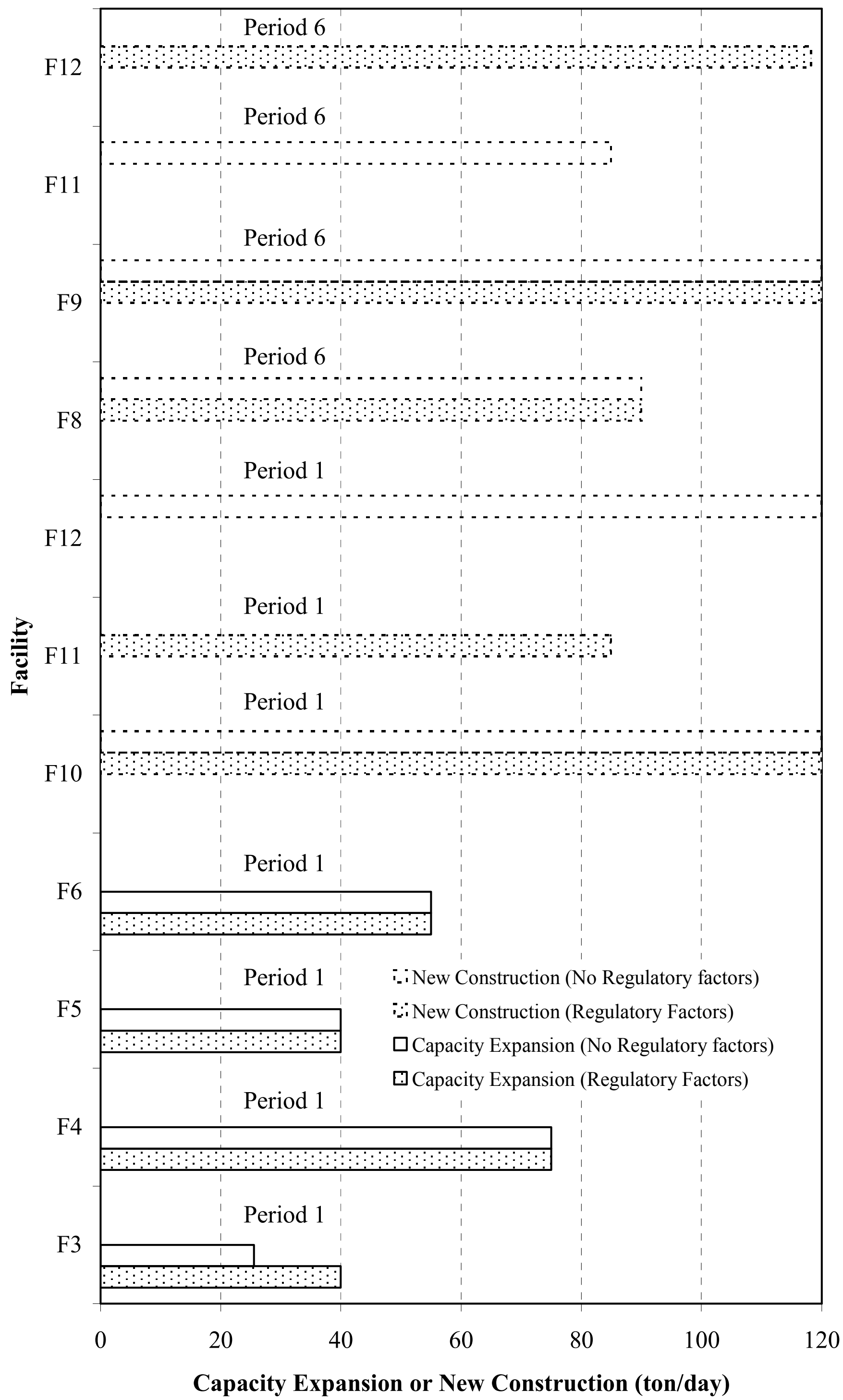

Figure 2.4: Expansion plans of the two scenarios. Shaded bars denote the plans for case 1 with regulatory factors, while the clear bars denote the plans for case 2. Bars with dashed borders denote new constructions, while those with continuous borders denote capacity expansions.

Although the two solutions differ in many other details (see Oh and Karimi, 2004), the striking difference is in their NPVs. Case 2 gives a NPV of $4.15 billion after we deduct the corporate taxes and import tariffs based on its solution. On the other hand, case 1 gives a NPV of $4.53 billion. The omission of the two regulatory factors in the capacity-planning model has obviously misguided the MNC to a significantly inferior solution. This clearly demonstrates the tremendous impact of the regulatory factors on capacity planning decisions, and the vital need for incorporating them in capacity planning models for global chemical supply chains.

Table 2.7 lists the NPVs of various components of the MNC's net cash flows in the two solutions. The total sales revenue in case 1 is about 4% lower than that in case 2, because case 1 has greater internal sales than case 2 as shown in Table 2.8. Internal sales are $60.6 million (111.5 kton of m_2 and 306 kton of m_4) in case 1 compared to $23.3 million (171.8 kton of m_4) in case 2. Internal sales are the sales by an internal facility to other internal facilities, while external sales are the ones to the external facilities. Greater internal sales in case 1 lower the sales revenue, since the inter-company transfer prices for products are normally lower than their open market prices. In spite of this, the NPV for case 1 is 9.6% higher than that of case 2. This is because the cost savings from lower manufacturing costs, material costs, transportation costs, import duties, and corporate taxes exceed the shortfall in the total sales revenue for case 1. In absolute terms, import tariffs and corporate taxes are the top two contributors to the $396 million difference in the NPVs of the two cases. This is a clear testimony to the need for incorporating the regulatory factors (domestic and international) in capacity expansion planning.

Table 2.7: NPVs of cash flow components in M$ and percent differences based on the case 2 results

Component	**Case 1 (M$)**	**Case 2 (M$)**	**Difference (M$)**	**Difference (%)**
Sales	11,656	12,157	–501	–4.1
Manufacturing costs	1,408	1,419	–11	–0.8
Material costs	3,251	3,501	–250	–7.1
Insurance+Freight costs	128	155	–27	–17.2
Import duties	303	640	–337	–52.7
Capital expenditures	17.89	17.69	0.20	1.1
Corporate taxes	2,022	2,295	–272	–11.9
NPV of net cash flow	4,525	4,130	396	9.6

The differences are percents of the NPVs for case 2.

Table 2.8: Breakdown of sales and amounts of each material (mi, i = 2 to 10) for the internal facilities in the two cases

Material m_i (i)	Case 1		Case 2	
	Internal Sales M$ (Quantity kton)	External Sales M$ (Quantity kton)	Internal Sales M$ (Quantity kton)	External Sales M$ (Quantity kton)
2	17.7 (111.5)	418.1 (393.9)	0 (0)	522.4 (505.4)
3	0 (0)	624.7 (505.4)	0 (0)	624.7 (505.4)
4	43.0 (306.0)	260.4 (199.4)	23.3 (171.8)	426.6 (333.7)
5	0 (0)	1,773.1 (552.0)	0 (0)	1,661.4 (517.2)
6	0 (0)	1,228.8 (441.6)	0 (0)	1,151.3 (413.8)
7	0 (0)	1,920.6 (582.0)	0 (0)	1,920.6 (582.0)
8	0 (0)	1,204.1 (339.5)	0 (0)	1,204.1 (339.5)
9	0 (0)	1,158.0 (517.4)	0 (0)	1,285.1 (571.5)
10	0 (0)	3,007.3 (1,121.0)	0 (0)	3,337.5 (1,238.3)
Total	60.6	11,595.1	23.3	12,133.6

Internal sales are sales among the internal facilities, while external sales are the sales by the internal facilities to the external facilities.

2.5 Discussion

This chapter has presented a new MILP model for the deterministic capacity expansion planning and material sourcing in global chemical supply chains. The proposed model treats the sizes of capacity expansions and new facility capacities as decision variables rather than pre-specified fixed numbers, and incorporates key supply chain operation decisions such as the sourcing of raw materials and the actual facility production rates, which can critically affect the strategic capacity planning decisions. Although developed with a perspective of the CPI, the model's generic nature makes it applicable to the deterministic capacity expansion planning in other manufacturing industries. For instance, by a simple modification or addition of some constraints, the proposed model can easily accommodate the requirements associated with new product development and introduction in the pharmaceutical industry and the decisions about technology selection (flexible versus dedicated facility) in consumer electronics industry. It must also be highlighted that the aforementioned DCEP model can also be modified easily to handle other extensions of the basic capacity expansion problem which are of relevance to the industry. These extensions include the account of delivery via distribution centers, outsourcing of production, and presence of uncertainty in problem parameters.

3. Deterministic Production-Distribution Problem

A normative production-distribution problem (PDP) is a supply chain operation problem which entails the determination of production plans of manufacturing facilities and the distribution plans of products across their supply chain network. PDPs arise mainly because all manufacturing companies, including those in the chemical industry, are driven by the goal of meeting customer demands in a most profitable way. Essentially, production-distribution planning decisions determine the flow plans of raw materials and finished products across all supply chain entities of a manufacturing company as well as the production levels of its manufacturing facilities over a given planning horizon. Manufacturing companies normally base their production-distribution planning decisions on available business data such as customer orders, product prices, production costs, available production capacities, suppliers' production capacities, forecasted orders and product prices, etc. Basically, the quality of production-distribution planning decisions depends strongly on (1) the accuracy of available and forecasted business data, and (2) the effectiveness of the planning techniques that assist the business decision making processes.

Despite the variety and complexity of regulatory factors imposed by different government bodies, it is surprising that many of the existing models in the literature that have addressed production-distribution problems (PDPs) fail to account for the effect of these regulatory factors. On the other hand, among the few production-distribution models that have accounted for regulatory factors, only one of them has considered duty drawback prior to the publication of Oh and Karimi (2006). This is especially astounding, since duty drawback regulations have been legislated in majority of the countries around the globe for many years and the global manufacturing companies can garner significant cost savings from duty drawback schemes. Moreover, the only production-distribution model that has accounted for duty drawback prior to the publication of Oh and Karimi (2006) is not suitable for all clusters of manufacturing industry. Inevitably, this limits its application in practice, particularly among the multi-product chemical manufacturing companies.

This chapter aims to address the deficiencies in the production-distribution planning research in three ways. First, it introduces the main concepts of duty drawback regulations and highlights their importance in production-distribution planning. Second, it presents a new deterministic model that accounts for three main regulatory factors, namely corporate taxes, import duties, and duty drawbacks to address the PDPs in the multi-product chemical industry. The new model not only ensures that duty drawbacks are duly claimed in accordance with the drawback regulations, a critical feature that previous work has overlooked, but also provides an effective basis for handling uncertainty in problem parameters. Finally, we use our model to solve a realistic problem to illustrate the importance of incorporating regulatory factors when addressing the PDPs.

3.1 Literature Review

The PDPs have received some attention in the operations research literature for the last two decades. We classify the PDPs according to whether the problem formulation considers regulatory factors. For brevity, we use a suffix R (i.e. PDP-R) to denote a PDP that addresses regulatory factors. On the other hand, PDP-C refers to a conventional PDP that ignores them. Based on this classification, we identify two main classes of PDPs and review the past work in these two classes.

Williams (1981) was one of the pioneers to venture into an in-depth research on the deterministic PDP-C (DPDP-C). His problem consisted of a conjoined assembly-arborescence network of production and distribution facilities. He proposed seven heuristic algorithms to solve this problem and compared them. Cohen and Moon (1991) reported a MILP model to address a special class of DPDP-C that has a concave cost function due to the economy of scale and diseconomy of scope. They also developed a solution algorithm based on Benders decomposition to solve their model. Martin et al. (1993) presented a large-scale linear programming (LP) model to represent a DPDP-C of a company in flat glass business. Without reporting any mathematical formulation, the authors claimed that their model accounted for the operational issues of running the flat glass business. Chandra and Fisher (1994) presented a computational study to illustrate the value of solving the production and distribution problems as an integrated problem (i.e. DPDP-C) relative to solving them separately. They studied a wide range of conditions by varying the problem parameters such as the numbers of products and customers and the length of planning horizon. Dhaenens-Flipo and Finke (2001) developed a multiperiod MILP model to represent a DPDP-C in which each production facility produces multiple products sequentially. Their model accounts for the possibility of product switch at the individual production lines within each period of the planning horizon. The entire problem is formulated as a network flow problem with relatively few binary variables to keep the real-size problems computationally manageable.

The DPDPs have received limited attention from the chemical engineering community. Wilkinson et al. (1996) presented a large-scale DPDP-C that considers important features such as finite intermediate storage in the form of multipurpose storage silos and equipment changeovers among multiple products with different recipes and packaging needs. Recently, Gjerdrum et al. (2001) approached a DPDP-C with intercompany transfer prices as model decision variables. They used a separable programming approach that uses logarithmic differentiation and approximations of the variables in the objective function to solve the resultant MINLP model. van den Heever et al. (2001) accounted for taxes, tariffs, and royalties rigorously in a multiperiod MINLP model for the strategic design and production planning of hydrocarbon field infrastructures. They proposed a Lagrangean decomposition heuristic that solves their model more efficiently compared to a full-space search for solution. They clearly demonstrated the significant savings obtained by embedding taxes, tariffs, and royalties within an optimization model as opposed to considering them after the fact, a message that this paper also shares strongly. Jackson and Grossmann (2003) introduced a multiperiod nonlinear programming (NLP) model for the planning and coordination of production and distribution activities of geographically distributed multiplant facilities. They proposed two solution methodologies (namely the spatial and temporal decomposition schemes) based on Lagrangean decomposition to solve the large-scale nonlinear problem. Chen et al. (2003) presented a MINLP model for a DPDP-C with multiple objectives such as maximizing the profit of each member enterprise, the customer service level, and minimizing safe inventory level. To cope with the multiple objectives that have different dimensions, they expressed each of these objectives as a fuzzy function based on fuzzy set concept. They also introduced a 2-phase fuzzy decision method to solve the model, which has the objective of maximizing the overall degree of satisfaction for the multiple fuzzy objectives.

Prior to the publication of Oh and Karimi (2006), Arntzen et al. (1995) presented probably the most comprehensive model for a DPDP-R in the computer industry. Their model incorporated several regulatory factors that influence the operations and profitability of a company. These include import tariff, duty drawback, duty relief, local content rule, and offset requirement. They minimized a composite function of weighted activity time and costs and proposed a solution algorithm that uses row-factorization to solve their model. Vidal and Goetschalckx (2001) presented an alternative approach to address a DPDP-R by taking the intercompany transfer prices and transportation cost allocations between subsidiaries to be the decision variables. Their model accounted for the effects of corporate tax and import tariff, and they used a heuristic algorithm based on successive linear programming. They sought to maximize the after-tax profit of the multinational company.

From the discussion in the current and previous subsections, we conclude that research on DPDPs with regulatory factors is still in its infancy, and few models and methodologies account for regulatory factors in the PDPs. More surprisingly, even though duty drawback can represent significant savings for many manufacturing companies, only one production-distribution model (Arntzen et al., 1995) has attempted to include this regulatory factor. However, the model has limited application in the manufacturing industry for two main reasons. First, it was developed for the computer-maker companies that generally have single-product manufacturing operations. Since duty drawback computations for single-product and multi-product manufacturing operations are different, their model is not applicable to all manufacturing companies. In this dissertation, we define multi-product manufacturing operation explicitly as a manufacturing process that manufactures multiple products simultaneously. This is to be distinguished from manufacturing processes that manufacture multiple products sequentially. An example of a multi-product manufacturing company is a typical petrochemical company that owns an oil refinery and petrochemical plants as shown in Figure 2.2. Second, their model does not use sufficiently in-depth data on manufacturing drawback distribution that is essential for duty refund claims. The manufacturing drawbacks in their model are explicitly based on the total import and export quantities over the planning horizon and do not identify the linkages between the batches of imported materials and exported finished products. As such, their model solution does not provide details that are crucial for inventory management and duty drawback claims, especially when product substitution (see Appendix D) is not permitted.

This completes our review of past work on the PDPs. We now present an overview of the duty drawback regulations to introduce their key concepts and to highlight their importance in PDPs.

3.2 What is Duty Drawback?

When a company imports a material, it may pay duties to the customs or revenue authorities based on the quantity or value of that material. The underlying goal of levying such a duty on imported materials is to boost a country's coffer or protect the interests of local businesses. However, consider for example a manufacturer who imports various PC parts, pays duties, assembles PCs, and exports them. Although import duties are good for the country, they are not good for this manufacturer, as he could be at a disadvantage in the global market due to his extra costs from import duties. Thus, discouraging imports and encouraging exports involve a tradeoff that most countries must balance. This led to the idea of duty drawback, which is a refund of import duty, when the material is destroyed, exported, or consumed as a raw material to produce an exported material. Its primary goal is to assist domestic manufacturers to compete in foreign markets. The World Trade Organization (WTO)

Agreement on Subsidies and Countervailing Measures clearly reflects the relevance of duty drawback in the world economy and its global acceptance. The agreement contains specific provisions that allow WTO members to offer duty drawback. It also specifies the conditions that could make duty drawback an impermissible export subsidy so that errant countries could be subject to the disciplines of WTO, which has a history of being less forgiving to government policies that subsidize exporters.

3.2.1 Types of Duty Drawback

The types of duty drawback vary from country to country. However, three most common types of duty drawback as defined in The US Code of Federal Regulations (Title 19, Part 191) are:

(1) Rejected merchandise drawback (RMD): This is available to the importers who paid duty on the merchandise that does not meet the quality specifications originally stated in the purchase order.

(2) Unused merchandise drawback (UMD): This is available to the exporters who send abroad the merchandise that was imported, but neither used nor altered.

(3) Manufacturing drawback (MD): This is available to the manufacturing companies that export the merchandise produced using the imported raw materials.

For a manufacturer with extensive international trading activities, MD would be of primary interest, as it would normally represent the most savings among all drawback types.

3.2.2 Importance of Duty Drawback

Increasingly, more countries are participating in bilateral and multilateral free trade agreements (FTAs) or are in the midst of negotiating such agreements. Some examples of signed free trade pacts are the North American Free Trade Agreement (NAFTA), the Central European Trade Agreement (CETA), and the United States – Singapore Free Trade Agreement (USSFTA). Examples of on-going FTA negotiations include those between United States and Thailand, China and Singapore, Canada and Caribbean Community and Common Market (CARICOM). Similarly, a growing number of export processing zones (EPZs) is established by countries such as USA, India, Ireland, China, Philippines, and Indonesia with the primary objective of attracting foreign direct investments. Inevitably, the FTAs and EPZs create more avenues of sourcing duty-free raw materials to global manufacturing companies. Though this may potentially mitigate the impact of duty drawback laws, the amount of savings that manufacturers can derive from duty refunds remains significant. This is possible mainly because many existing facilities are still located and new manufacturing facilities constructed in places with no duty-free access to foreign merchandise. The amount of drawback savings that these facilities can garner annually remains substantial. For example, Cerny (2002) estimates US$2 billion worth of drawbacks available to the US companies annually, out of which almost US$1.5 billion goes unclaimed. In another recent work, Wheatley (2002) quoted that the U.S. companies failed to claim as much as US$10 billion worth of duty drawbacks in 2001. These estimates aptly illustrate the potential and significance of drawback savings despite the proliferation of FTAs and EPZs. The hefty sum of unclaimed duty drawback also demonstrates the extent to which companies are neglecting drawbacks in their material procurement and product distribution strategies.

In a recent report (Zee et al., 2002), duty drawback has been recommended more favorably than EPZ by the International Monetary Fund (IMF) as one of the indirect tax incentives that developing nations should employ to attract foreign direct investments. This is certainly a testimony to the effectiveness of duty drawback as a pro-business policy. Clearly, the importance and significance of duty drawback to the global manufacturing community are unlikely to diminish in the years to come.

3.2.3 Drawback Regulations

Essentially, there are two drawback systems (Rhee, 1994) for computation of refundable duties, namely the fixed drawback system (FDS) and the individual drawback system (IDS). We now describe the essence of these two refund systems in the following two sections.

3.2.3.1 Fixed Drawback System (FDS)

In this system, computing MD is simple and straightforward. It simply depends on the amount or value of the export. The FDS simplifies the administration of duty refund by offering refund to all exporters, irrespective of whether their exports use imported feed materials or not. It sets refund rates based on the estimated duties that contribute to the cost of production of exports in a preset schedule. In order to ensure that their drawback systems do not allow an impermissible export subsidy under the WTO Agreement on Subsidies and Countervailing Measures, a country using FDS must set its refund rates such that the total duty refund does not exceed the total import duty collected.

However, it is clear that the FDS does not provide a fair mechanism for MD, especially to the manufacturers with extensive amounts of imports. To cater to the needs of such manufacturers, countries such as Taiwan and India that use FDS to manage their duty refunds also provide IDS as an alternative refund mechanism so that companies can opt for the most favorable system, subject to the conditions stipulated by relevant drawback regulations.

The fixed amount (specific duty) and fixed percentage (ad valorem duty) criteria that Taiwan employs are good examples of the FDS. The former refunds a predetermined amount per unit (weight or quantity) of the export, while the latter refunds a predetermined percentage of its free-on-board (FOB) value.

3.2.3.2 Individual Drawback System (IDS)

The IDS offers a more accurate methodology for assessing MD, because it considers the actual amount of imported materials utilized in manufacturing an export. Typically, a manufacturer must abide by the registration requirements of the relevant drawback regulations, before it can claim MD for a manufacturing process. This essentially entails (1) submitting a bill of materials (BOM) that stipulates the quantitative relationship between the inputs and outputs (including recoverable and irrecoverable wastes) of the manufacturing process and (2) providing evidence to substantiate the numbers in the proposed BOM. Examples of countries using the IDS include Australia, USA, EU nations, etc.

The IDS offers duty refund strictly based on the amount of imported materials that a manufacturer utilizes in manufacturing an export. In this system, a manufacturer qualifies for MD if it fulfills two key conditions. First, it must have used imported raw materials in its manufacturing process and must have paid the applicable import duties. The manufacturer could either import the raw materials directly or buy the same from domestic distributors. Second, it must export the finished products of its manufacturing process to countries that are eligible for drawback according to the pertinent drawback regulations. The regulations may also stipulate a secondary condition that the exports must be explicitly manufactured using the imported materials. In other words, product substitution is not permissible (refer to Table 3.1 for the key requirement for production substitution). The drawback laws of USA and EU nations do waive this secondary stipulation, subject to pertinent terms and conditions.

Overall, it is obvious that IDS requires a more complex methodology for computing MD and more resources for managing the drawback administration as compared to FDS. Nevertheless, many countries still adopt IDS, because it ensures that (1) only the deserving exporters receive duty refunds and (2) the domestic producers with extensive imports and exports receive the maximum possible benefit from the drawback regulations, which would help them compete in the global market. We now discuss our MD is computed in a IDS in the following section.

3.2.4 Computation of Manufacturing Drawback

Consider a general, multi-product chemical manufacturing facility *f* that procures raw materials from its suppliers (both domestic and international) strictly for production purposes. It pays import duty on the raw materials from its international suppliers and can claim drawback refund on the same. To this end, it has registered its manufacturing process with the customs authority and has an approved BOM given by,

$$\sum_{i \in \boldsymbol{IM}_f} \sigma_{if} m_i = \sum_{i \in \boldsymbol{OM}_f} \sigma_{if} m_i \tag{3.1}$$

where, m_i denotes material i that facility f consumes or produces, $\boldsymbol{IM}_f$ denotes the set of raw materials m_i ($i \in \boldsymbol{IM}_f$) consumed by f, $\boldsymbol{OM}_f$ denotes the set of finished products m_i ($i \in \boldsymbol{OM}_f$) produced by f, and σ_{if} is analogous to the stoichiometric coefficient of a species *i* in a reaction except that eq (3.1) is in terms of mass or units rather than moles. Note that σ_{if} is positive even for outputs, in contrast to the standard stoichiometric coefficient in a reaction. Furthermore, $\boldsymbol{OM}_f$ includes waste products as well as unreacted raw materials that are irrecoverably wasted. Although we explained eq (3.1) in terms of materials, we can also use the same for discrete parts. If two pieces of part 1 and four pieces of part 2 produce one piece of product 3, then $\sigma_1 = 2$, $\sigma_2 = 4$, and $\sigma_3 = 1$.

A BOM approved by the customs authority provides the basis for computing MD. A manufacturer must fulfill two primary conditions for claiming a MD for such a BOM. First, it must procure duty-paid raw materials by either importing them directly or through local supplier/s. The quantity of such a raw material and the amount of duty paid together impose an upper bound on the MD that the manufacturer can claim. Second, the manufacturer must export at least one of its finished products in the BOM. In a multiproduct manufacturing process, one or more raw materials may produce multiple finished products concurrently. It would be unfair if a manufacturer can claim the refund of all duties on a raw material simply by exporting a tiny amount of one of its final products. Thus, the amount of export that the manufacturer produces also has a bearing on the claimable MD. Clearly, a fair refund mechanism must apportion the paid duties to all the finished products according to the amounts and values of these products.

As per their respective drawback regulations (Code of Federal Regulations and Community Customs Code), both USA and EU nations employ relative values of finished products to apportion the paid import duty of each raw material among the finished products of a multi-product manufacturing process in the computation of MD. These relative values are based on the market prices (or other values approved by the customs authorities) at the *time of their manufacture*. Using the aforementioned notation for a facility f, the relative value RV_{jft} of a finished product m_j ($j \in \boldsymbol{OM_f}$) produced in an arbitrary period t is defined as,

$$RV_{jft} = \frac{\sigma_{jf} MP_{jt}}{\sum_{j' \in \boldsymbol{OM}_f} \sigma_{j'f} MP_{j't}} \tag{3.2}$$

where, MP_{jt} denotes the market price of m_j at t. Finished products m_j ($j \in \boldsymbol{OM_f}$) with no value or those irrecoverably wasted in a manufacturing process have $MP_{jt} = 0$.

Let us consider a case where f procures Q_{ift} ($i \in \boldsymbol{IM_f}$) amounts of raw materials, uses them in its registered process, produces Q_{jft} ($j \in \boldsymbol{OM_f}$) amounts of final products, and sells them, all during period t. f has two suppliers for its raw materials, one domestic and the other foreign. We also assume that f has zero inventories of raw materials and finished products at the beginning of period t. Let γ_{ift} be the fraction of material m_i ($i \in \boldsymbol{IM_f}$) that f imports from the foreign supplier during period t and CIF_{ift} denote the cost, insurance, and freight (\$/mass) that f pays for its import. If the import duty rate is ID_{ift} (\$/\$ of costs, insurance, & freight), then f must pay a total duty of $\gamma_{ift}ID_{ift}CIF_{ift}Q_{ift}$. If the duty refund rate is DR_{if} (\$/\$ of paid duty) as per the local regulations, then one upper limit for the claim amount MD_f for facility f during period t is,

$$MD_f \leq \sum_{i \in \mathrm{IM}_f} \gamma_{ift} ID_{ift} CIF_{ift} Q_{ift} DR_{if} \tag{3.3a}$$

In IDS, the values and amounts of the export products do affect a MD claim. To illustrate this, consider that f produces Q_{jft} amounts of final product m_j during period t. If f exports only a fraction γ_{jft} of this product during t, then the amount of raw material m_i required to produce exported product m_j is $\gamma_{jft}Q_{jft}\sigma_{if}/\sigma_{jf}$. The corresponding import and refundable duty amounts are $\gamma_{jft}ID_{ift}CIF_{ift}Q_{jft}\sigma_{if}/\sigma_{jf}$ and $\gamma_{j}ID_{ift}CIF_{ift}DR_{if}Q_{jft}\sigma_{if}/\sigma_{jf}$. Since this raw material also contributed to the production of other final products concurrently, we multiply the refund amount by RV_{jft} to identify the claim for the pair of materials m_i-m_j. Thus, an upper limit on the MD claim for import m_i with reference to export m_j is $\gamma_{jft}ID_{ift}CIF_{ift}DR_{itf}RV_{jft}Q_{jft}\sigma_{if}/\sigma_{jf}$. Summing over all exports m_j and then all imports m_i, we get,

$$MD_f \le \sum_{i \in \boldsymbol{IM}_f} \sum_{j \in \boldsymbol{OM}_f} \gamma_{jft} ID_{ift} CIF_{ift} Q_{jft} \frac{\sigma_{if}}{\sigma_{jf}} DR_{if} RV_{jft} \tag{3.3b}$$

From eqs. 3.3a and 3.3b, we get,

$$MD_f = \sum_{i \in \boldsymbol{IM}_f} ID_{ift} CIF_{ift} DR_{if} \min\left[\gamma_{ift} Q_{ift}, \sum_{j \in \boldsymbol{OM}_f} \gamma_{jft} Q_{jft} \frac{\sigma_{if}}{\sigma_{jf}} RV_{jft} \right] \tag{3.4}$$

From the above discussion, it is obvious that for computing MD in a multiproduct manufacturing process, we must consider all pairs of duty-paid raw materials and exported products. We now explain how this basic requirement changes in the presence of two additional factors.

3.2.4.1 Multiple International Suppliers

In practice, a manufacturer may source its raw materials from multiple international suppliers, instead of just one as in the example above. This further complicates the computation of MD, as the claim will now depend on the origins of imports, which affect the duty rates directly. The manufacturer must track the duty-paid raw materials from each international supplier and the exports that arise from these specific imports.

3.2.4.2 Multi-Period Planning Horizon

In production planning, it is often necessary to employ a multiperiod planning model to capture the variations in demands, market prices, costs, insurance, freight, etc. In a multi-period planning model with multiple international suppliers, MD computation becomes more involved due to the need to track three pieces of information in addition to the supplier identity, quantities of duty-paid raw materials, and quantities of exported products. These are:

1. The import times of raw materials: This is because the duty paid by a facility (which in turn affects its MD claim) depends on the time-dependent CIF values of materials.
2. The times of consumption of raw materials: This is because the manufacturing time determines the relative values of the finished products (as in the Code of Federal Regulations).
3. The export times of finished products: This is because the drawback regulations stipulate limits on the duration within which an imported raw material must be consumed to produce export products.

The computation of MD for multiproduct manufacturing processes poses significant modeling challenges in a global multiperiod planning model. We now address this complexity in our new model for DPDP-R.

3.3 Problem Description

A MNC owns a set $\boldsymbol{IF}$ of processing facilities ($f \in \boldsymbol{IF}$) in several countries. We call these as internal facilities. Each facility houses a manufacturing process that uses raw materials to manufacture some products. In addition to receiving/supplying materials from/to each other, an internal facility ($f \in \boldsymbol{IF}$) may also interact with some external facilities that do not belong to the MNC. These could be raw material suppliers, customers, and facilities to which internal facilities could outsource their production. We define $\boldsymbol{EF}$ as the set of all external facilities ($g \in \boldsymbol{EF}$) that could possibly interact with the internal facilities. Lastly, we define $\boldsymbol{F} = \boldsymbol{IF} \cup \boldsymbol{EF}$ and assume that the location and the incoming and outgoing materials for each $f \in \boldsymbol{F}$ (whether internal or external) are prefixed and known.

For each $f \in \boldsymbol{F}$, we group its associated materials (raw materials and products) into two sets as done in the previous section on MD computation. $\boldsymbol{IM}_f$ denotes the set of incoming materials m_i ($i \in \boldsymbol{IM}_f$) consumed by f, and $\boldsymbol{OM}_f$ denotes the set of outgoing materials m_j ($j \in \boldsymbol{OM}_f$) produced by f. Note that for an external facility $g \in \boldsymbol{EF}$, we include only the materials that are relevant to the MNC. For instance, suppose that an external facility g produces C and D from A and B. However, the MNC neither supplies currently or ponders supplying at any time A or B to g nor needs currently or ponders needing at any time D from g at any of its internal facilities. Then, $\boldsymbol{IM}_f = \varnothing$ and $\boldsymbol{OM}_f = \{C\}$. For each internal facility f ($f \in \boldsymbol{IF}$), we designate one material $\pi(f)$ as a primary material, and define the production capacity (X_{ft}^{U}) of f as the rate at which f uses or produces $\pi(f)$ during a period t. Thus, $\pi(f)$ can be either an incoming or an outgoing material of f.

Every internal facility f ($f \in \boldsymbol{IF}$) has three options of fulfilling an order placed by a customer c ($c \in \boldsymbol{EF}$) for a product i ($i \in \boldsymbol{OM}_f \cap \boldsymbol{IM}_c$). First, it may manufacture i in-house. Second, it may source i partially or fully from another internal facility g ($i \in \boldsymbol{OM}_g$, $g \neq f$) which will in turn produce and arrange i to be delivered to c. Third, it may outsource the production to external facilities g ($i \in \boldsymbol{OM}_g$) that will manufacture i and send it to c. In the last two options, the internal facility f bears the costs of getting the outsourcing facilities to produce and deliver i to customer c. On the front end of the supply chain, each internal facility f has two ways of getting its raw materials ($i \in \boldsymbol{IM}_f$). It can procure directly from other internal facilities g ($i \in \boldsymbol{OM}_g$) or external suppliers s ($s \in \boldsymbol{EF}$, $i \in \boldsymbol{OM}_s$).

Considering a global problem, we let the facilities be located in N different nations ($n = 1, 2, \ldots, N$) or countries, and define $\boldsymbol{F}_n$ as the set of facilities situated in nation n ($f \in \boldsymbol{F}_n$, $\boldsymbol{F}_1 \cup \boldsymbol{F}_2 \cup \ldots \cup \boldsymbol{F}_N = \boldsymbol{F}$, and $\boldsymbol{F}_n \cap \boldsymbol{F}_{n'} = \varnothing$ for $n \neq n'$). The legislation of a host country n normally imposes several restrictions on the ownership, imports, exports, accounts, earnings, etc. of the facilities located in its jurisdiction ($f \in \boldsymbol{F}_n$).

Based on the forecasted and confirmed orders from the sales division, the MNC wishes to develop an optimum production-distribution plan over the next fiscal year. We divide this tactically into T equally spaced time periods ($t = 1, 2, \ldots, T$) to form the time basis of planning for the MNC. The production-distribution plan comprises (1) production rate, (2) raw material sourcing scheme, and (3) finished product distribution strategy for every $f \in \boldsymbol{IF}$ during each period t. The objective of the production-distribution plan is to maximize the total after tax-profit (ATP) of the MNC over the planning horizon.

We make the following assumptions for the above DPDP.

1. All business intelligence data crucial for generating a reliable production-distribution plan are available. These include the sale orders, raw material requirements, raw material prices, product prices, transportation costs, operating costs, import duties, and corporate taxes of all internal facilities and the capacities of all internal and external supplier facilities over the T periods.
2. The business intelligence data are adjusted to account for the fluctuations in exchange rates of currencies involved in N nations over the T periods. Hence, we express all expenditures and returns in terms of a numeraire currency.
3. Although several regulatory factors affect the operation and earnings of the MNC, duty drawbacks, import duties, and corporate taxes are the only dominant regulatory factors. Others have negligible impact on the profit of MNC.
4. The internal facilities of each country n ($f \in \boldsymbol{IF} \cap \boldsymbol{F}_n$) pay corporate and other taxes collectively to the country's revenue authorities at the end of each fiscal year.
5. Every internal facility f pays the duties on all its imports from facilities (internal or external) that are outside its own country. All import duties are based on the CIF costs of imports at f. This refers to the total value of goods including the purchase, insurance, and freight costs incurred in bringing them to the delivery facility.
6. The incoterm (Karimi at al., 2002) governing all international sales contracts is the EX works (EXW). In EXW, the buyer or customer bears all costs and risks involved in taking the goods from the seller's premises.

7. MD is the only type of drawback relevant to the MNC. The rules governing the MD computations in all nations are similar to the Code of Federal Regulations (Title 19, Part 191). These countries and internal facilities have efficient drawback administrations to manage their duty refund mechanisms.
8. Every internal facility *f* needs to satisfy a time limit stipulated in its local drawback laws in order to claim MD. This time limit, represented by TL_f, defines the upper bound on the facility's holding duration of each manufactured product prior to its exportation. Thus, if *f* consumes its raw material for production at τ and exports it finished product at θ ($\theta \geq \tau$), then it can claim for MD only if $(\theta - \tau) \leq TL_f$.
9. The MNC has an established infrastructure that enables its facilities to claim drawbacks within the same fiscal year of the export of finished products.
10. The authorized BOM that forms the basis of MD computation for each internal facility *f* is given by,

$$\sum_{i \in \boldsymbol{IM}_f} \sigma_{if} m_i = \sum_{i \in \boldsymbol{OM}_f} \sigma_{if} m_i \qquad f \in \boldsymbol{IF} \qquad (3.5)$$

    where, the notation is similar to that previously described.
11. Each internal facility *f* has constant lower and upper limits on its production rate (denoted by X_f^L and X_f^U respectively, as measured in terms of the primary material) over the entire planning horizon. It must operate within these limits, and cannot shut down.
12. The length of each period (t = 1, 2, …, T) is adequately small so that the inventory levels of products at period ends provide sufficient granularity to compute the inventory costs and to track the fluctuation in product market prices and CIF values.

13. The depreciation charge incurred by each internal facility f due to its previous capital investments is constant over the planning horizon. Furthermore, there are no upcoming capacity expansion projects during the planning horizon.
14. Each local supplier s of an internal facility f ($f \in \boldsymbol{IF} \cap \boldsymbol{F}_n$, $s \in \boldsymbol{F}_n$, $f \neq s$) in nation n makes its products ($i \in \boldsymbol{IM}_f \cap \boldsymbol{OM}_s$) using only domestic raw materials. Thus, the material sourced from such appliers cannot save any MD for the internal facilities.

In the formulation presented below for the above stated DPDP-R, unless stated otherwise, the indexes (f, t, i, etc.) assume their full ranges of values.

3.4 Model Formulation

To model the incoming and outgoing flows of materials at the facilities, we let $F_{isct} \geq 0$ ($i \in \boldsymbol{OM}_s \cap \boldsymbol{IM}_c$, $c \neq s$) denote the quantity of material i that a facility $s \in$ F sells directly to a facility $c \in$ F during period t. If x_{ift} and X_{ft} respectively denote the actual consumption/ production levels of materials m_i and $\pi(f)$ at an internal facility f during t, then we must have,

$$\sigma_{\pi(f)f}\, x_{ift} = \sigma_{if}\, X_{ft} \qquad i \in \boldsymbol{OM}_f \cup \boldsymbol{IM}_f \qquad (3.6)$$

We also let G_{ifgct} denote the quantity of material i that an internal facility f outsources to another facility $g \in \boldsymbol{F}$ to fulfill orders from a facility $c \in \boldsymbol{F}$ partially or fully during period t, where $i \in \boldsymbol{OM}_f \cap \boldsymbol{OM}_g \cap \boldsymbol{IM}_c$, $f \neq c$, $f \neq g$, and $g \neq c$. Therefore, the inventory level (I_{ift}) of a material i associated with an internal facility f at the end of a period t is,

$$I_{ift} = I_{if(t-1)} - X_{ft}\left(\sigma_{if} \big/ \sigma_{\pi(f)f}\right) + \sum_{s \ni i \in \boldsymbol{OM}_s} F_{isft} \qquad f \in \boldsymbol{IF},\ i \in \boldsymbol{IM}_f \tag{3.7a}$$

$$I_{ift} = I_{if(t-1)} + X_{ft}\left(\sigma_{if} \big/ \sigma_{\pi(f)f}\right) - \sum_{g \in \boldsymbol{IF} \ni i \in \boldsymbol{OM}_g} \sum_{c \ni i \in \boldsymbol{IM}_c} G_{igfct} - \sum_{c \ni i \in \boldsymbol{IM}_c} F_{ifct} \quad f \in \boldsymbol{IF},\ i \in \boldsymbol{OM}_f \tag{3.7b}$$

Note that I_{if0} denotes the inventory level of i at f at time zero.

For each external facility $c \in \boldsymbol{EF}$, we define D_{ict} ($i \in \boldsymbol{IM}_c$) as the minimum quantity of i, which c has ordered and the MNC must supply during t. We also define S_{ist} ($i \in \boldsymbol{OM}_s$) as the maximum amount of i, which an external facility s ($s \in \boldsymbol{EF}$) can supply to the MNC during t as a direct supplier of raw material or as an outsourcing facility. To ensure that delivery equals order and supply does not exceed available capacity, we use,

$$\sum_{f \in \boldsymbol{IF}} \left(F_{ifct} + \sum_{h \in \boldsymbol{F} \ni i \in \boldsymbol{OM}_h} G_{ifhct} \right) = D_{ict} \qquad c \in \boldsymbol{EF},\ i \in \boldsymbol{IM}_c \cap \boldsymbol{OM}_f \tag{3.8}$$

$$\sum_{f \in \boldsymbol{IF} \ni i \in \boldsymbol{IM}_f} F_{isft} + \sum_{f \in \boldsymbol{IF} \ni i \in \boldsymbol{OM}_f} \sum_{c \in \boldsymbol{EF} \ni i \in \boldsymbol{IM}_c} G_{ifsct} \le S_{ist} \quad s \in \boldsymbol{EF},\ i \in \boldsymbol{OM}_s \tag{3.9}$$

MD computation requires that we track the materials from import all the way to export and consider each pair of imported and exported materials separately. Thus, let us consider that an internal facility ($f \in \boldsymbol{IF}$) imports a material i from a supplier s ($i \in \boldsymbol{OM}_s$) during a period t. It uses some or all of this i to make a material j ($j \in \boldsymbol{OM}_f$) during period $\tau \ge t$, which it exports to a customer c ($j \in \boldsymbol{IM}_c$) during a period θ ($T \ge \theta \ge \tau$). Note that this sort of tracking is possible and routine in a batch plant such as a pharmaceutical plant. However, this is neither possible nor does it normally occur in a continuous plant. Thus, for a continuous plant, it merely represents an artificial distribution of materials to compute MD rather than actual physical tracking of the materials. For computing MD for this scenario, we define three variables:

1. $q_{sfijt\tau}$: The amount of i imported from s during t on which f can claim MD due to its subsequent consumption in τ to make export j. If s is a local supplier, then $q_{sfijt\tau} = 0$.
2. $q_{sfij0\tau}$: The amount of i imported from s prior to the start of the planning horizon on which f can claim MD due to its subsequent consumption in τ to make export j. This is to account for i that exists in the inventory at the beginning of the planning horizon and it is eligible for MD. For simplicity, we assume that each $q_{sfij0\tau}$ has a single corresponding import duty rate and CIF value to compute the eligible MD.
3. $r_{fcj\tau\theta}$: The amount of j that f makes during τ, subsequently exports to c during θ, and on which it can claim MD. If c is a local customer or it is in a nation for which MD is not claimable, then $r_{fcj\tau\theta} = 0$.

Since the total amount of i that f imports from s during t and consumes over periods t to T cannot exceed the quantity of i that f receives from s during t, we have,

$$\sum_{\tau=t}^{T} q_{sfijt\tau} \le F_{isft} \qquad f \in \boldsymbol{IF} \cap \boldsymbol{F}_n,\, s \in \boldsymbol{F}'_n,\, i \in \boldsymbol{IM}_f \cap \boldsymbol{OM}_s,\, j \in \boldsymbol{OM}_f \tag{3.10a}$$

Note that $\boldsymbol{F}'_n = \boldsymbol{F} - \boldsymbol{F}_n$. Similarly, the total amount of i that f imports from s prior to the start of the horizon for consumption over the planning horizon cannot exceed the quantity of i that is present in the inventory at the start of the horizon, i.e.,

$$\sum_{\tau=1}^{T} q_{sfij0\tau} \le \alpha_{isf} I_{if0} \qquad f \in \boldsymbol{IF} \cap \boldsymbol{F}_n,\, s \in \boldsymbol{F}'_n,\, i \in \boldsymbol{IM}_f \cap \boldsymbol{OM}_s,\, j \in \boldsymbol{OM}_f \qquad (3.10b)$$

where, α_{isf} is the fraction (known) of i in the inventory of f at the start of the horizon that f procured from s. Note that

$$\sum_{s \in \boldsymbol{F} \ni i \in \boldsymbol{OM}_s} \alpha_{isf} = 1 \qquad f \in \boldsymbol{IF},\, i \in \boldsymbol{IM}_f,\, s \in \boldsymbol{F} \qquad (3.11)$$

Likewise, the total amount of j that f makes until period θ, exports to c during θ, and on which it can claim MD, cannot exceed the amount of j that f delivers to c during θ. Therefore,

$$\sum_{\tau=\max[1,\theta-TL_f]}^{\theta} r_{fcj\tau\theta} \le F_{jfc\theta} + \sum_{g \in \boldsymbol{IF} \ni j \in \boldsymbol{OM}_g} G_{jgfc\theta} \qquad f \in \boldsymbol{IF} \cap \boldsymbol{F}_n,\, c \in \boldsymbol{F}'_n,\, j \in \boldsymbol{OM}_f \cap \boldsymbol{IM}_c \qquad (3.12)$$

where, TL_f is previously defined as the duration within which f must export a material after its manufacture to be able to claim MD. Considering the fact that every f would try to claim maximum MD each fiscal year, we assume that f has negligible inventory of finished product ($j \in \boldsymbol{OM}_f$) that is manufactured prior to the start of planning horizon and that entitles f to MD upon exportation.

Whether we compute MD based on the amount of imported material i or on the amount of exported material j, we must get the same MD. In other words, these two computational bases must be consistent with each other, or

$$\sigma_{jf} \sum_{s \in \boldsymbol{F}_n' \ni j \in \boldsymbol{OM}_s} \sum_{t=0}^{\tau} q_{sfijt\tau} = \sigma_{if} \sum_{c \in \boldsymbol{F}_n' \ni j \in \boldsymbol{IM}_c} \sum_{\theta=\tau}^{\min[\tau+TL_f, T]} r_{fcj\tau\theta} \qquad f \in \boldsymbol{IF} \cap \boldsymbol{F}_n, i \in \boldsymbol{IM}_f, j \in \boldsymbol{OM}_f \quad (3.13)$$

Lastly, the total amount of *i* that *f* imports from *s* before *τ* and on which *f* can claim MD cannot exceed the amount of *i* used to produce *j* during *τ*, therefore,

$$\sigma_{\pi(f)f} \sum_{s \in \boldsymbol{F}_n' \ni i \in \boldsymbol{OM}_s} \sum_{t=0}^{\tau} q_{sfijt\tau} \le \sigma_{if} X_{f\tau} \qquad f \in \boldsymbol{IF} \cap \boldsymbol{F}_n, i \in \boldsymbol{IM}_f, j \in \boldsymbol{OM}_f \quad (3.14)$$

Note that eqs. 3.13 and 3.14 ensure that the total amount of *j* that *f* makes during *τ*, exports later, and on which it can claim MD does not exceed the amount of *j* that *f* makes during *τ*.

Based on the Code of Federal Regulations, we now require a duty refund rate DR_{if} (\$/\$ of duty paid) on *i* for *f* and relative value $RV_{jf\tau}$ of *j* among all finished products of *f* during *τ*. Then, the MD claim for *f* over the planning horizon is,

$$MD_f = \sum_t \left[\sum_{i \in \boldsymbol{IM}_f} \sum_{s \ni i \in \boldsymbol{OM}_s} \sum_{j \in \boldsymbol{OM}_f} DR_{if} RV_{jft} CIF_{isf0} ID_{isf0} q_{sfij0t} + \sum_{i \in \boldsymbol{IM}_f} \sum_{s \ni i \in \boldsymbol{OM}_s} \sum_{j \in \boldsymbol{OM}_f} \sum_{\tau \ge t} DR_{if} RV_{jf\tau} CIF_{isft} ID_{isft} q_{sfijt\tau} \right] \quad (3.15)$$

Now, to compute the MNC's collective corporate taxes in a host nation *n*, we need the taxable incomes of its facilities in that nation. The taxable income is gross income minus depreciation and gross income is the sum of sales and duty drawback credits less operating expense. The operating expense is the sum of procurement, inventory, outsourcing, and manufacturing (or variable production) costs. To this end, let P_{isct}, CIF_{isct}, and ID_{isct} denote respectively the purchase price (\$/kg), CIF cost (\$/kg), and import duty (\$/\$ of CIF cost) of material i ($i \in \boldsymbol{OM}_s \cap \boldsymbol{IM}_c$) sold by $s \in \boldsymbol{F}$ to $c \in \boldsymbol{F}$ during t. Note that P_{isct} refers to the inter-company transfer price of the MNC when both s and c ($c \neq s$) are internal facilities. Let IC_{ift} denote the inventory cost (\$/kg per period) of material m_i at f during t, and OC_{ifhct} denote the cost (\$/kg) incurred by f for every unit of i ($i \in \boldsymbol{OM}_f$) that it outsources to facility h ($h \in \boldsymbol{F}$, $i \in \boldsymbol{OM}_h$) to meet an order of customer c ($c \in \boldsymbol{EF}$, $i \in \boldsymbol{IM}_c$) during t, where $f \neq c$, $f \neq g$, and $g \neq c$. Then, the gross income GI_f of $f \in \boldsymbol{IF}$ over the planning horizon is,

$$
\begin{aligned}
GI_f = \sum_t \Bigg[& \sum_{i \in \boldsymbol{OM}_f} \sum_{c \ni i \in \boldsymbol{IM}_c} P_{ifct} F_{ifct} + \sum_{g \in \boldsymbol{IF} \ni i \in \boldsymbol{OM}_g} \sum_{c \ni i \in \boldsymbol{IM}_c} P_{ifgt} G_{igfct} + \sum_{h \in \mathrm{F} \ni i \in \boldsymbol{OM}_h} \sum_{c \ni i \in \boldsymbol{IM}_c} P_{ifct} G_{ifhct} + \\
& \sum_{i \in \boldsymbol{IM}_f} \sum_{s \ni i \in \boldsymbol{OM}_s} \sum_{j \in \boldsymbol{OM}_f} DR_{if} RV_{jft} CIF_{isf0} ID_{isf0} q_{sfij0t} + \\
& \sum_{i \in \boldsymbol{IM}_f} \sum_{s \ni i \in \boldsymbol{OM}_s} \sum_{j \in \boldsymbol{OM}_f} \sum_{\tau \geq t} DR_{if} RV_{jf\tau} CIF_{isft} ID_{isft} q_{sfijt\tau} - \sum_{h \in \boldsymbol{F} \ni i \in \boldsymbol{OM}_h} \sum_{c \ni i \in \boldsymbol{IM}_c} OC_{ifhct} G_{ifhct} - \\
& MC_{ft} X_{ft} - \sum_{i \in \boldsymbol{IM}_f} \sum_{s \ni i \in \boldsymbol{OM}_s} (1 + ID_{isft}) CIF_{isft} F_{isft} - \sum_{i \in \boldsymbol{IM}_f \cup \boldsymbol{OM}_f} 0.5 IC_{ift} (I_{if(t-1)} + I_{ift}) \Bigg]
\end{aligned}
\qquad (3.16)
$$

where, MC_{ft} is the manufacturing cost [\$/kg of $\pi(f)$] of f during t. Note that we use CIF_{isf0}, and ID_{isf0} to denote the corresponding CIF values and import duties for i that exists in the inventory of f at time zero and was imported from s prior to the start of the planning horizon. The first three summation terms on the right side of eq 3.16 represent the following three sales components respectively.

(1) direct sales of products by f to customers

(2) sales for internal facilities that have outsourced their production to f

(3) sales of products that f has outsourced to other facilities

The fourth and fifth summation terms denote the MD savings of *f* over the planning horizon, while the remaining terms represent *f*'s outsourcing costs, manufacturing costs, CIF and import duty expenses, and inventory costs respectively.

Thus, the taxable income TI_n of the MNC in nation *n* over the planning horizon becomes as follows.

$$\begin{aligned} TI_n \geq \sum_{f\in \boldsymbol{IF}\cap \boldsymbol{F}_n} \sum_t \Bigg[& \sum_{i\in \boldsymbol{OM}_f} \sum_{c\ni i\in \boldsymbol{IM}_c} P_{ifct}F_{ifct} + \sum_{g\in \boldsymbol{IF}\ni i\in \boldsymbol{OM}_g} \sum_{c\ni i\in \boldsymbol{IM}_c} P_{ifgt}G_{igfct} + \sum_{h\in \boldsymbol{F}\ni i\in \boldsymbol{OM}_h} \sum_{c\ni i\in \boldsymbol{IM}_c} P_{ifct}G_{ifhct} + \\ & \sum_{i\in \boldsymbol{IM}_f} \sum_{s\ni i\in \boldsymbol{OM}_s} \sum_{j\in \boldsymbol{OM}_f} DR_{if} RV_{jft} CIF_{isf0} ID_{isf0} q_{sfij0t} + \\ & \sum_{i\in \boldsymbol{IM}_f} \sum_{s\ni i\in \boldsymbol{OM}_s} \sum_{j\in \boldsymbol{OM}_f} \sum_{\tau\geq t} DR_{if} RV_{jf\tau} CIF_{isft} ID_{isft} q_{sfijt\tau} - \\ & \sum_{h\in \boldsymbol{F}\ni i\in \boldsymbol{OM}_h} \sum_{c\ni i\in \boldsymbol{IM}_c} OC_{ifhct}G_{ifhct} - \sum_{i\in \boldsymbol{IM}_f \cup \boldsymbol{OM}_f} 0.5IC_{ift}(I_{if(t-1)} + I_{ift}) - \\ & \sum_{i\in \boldsymbol{IM}_f} \sum_{s\ni i\in \boldsymbol{OM}_s} (1+ID_{isft})CIF_{isft}F_{isft} - MC_{ft}X_{ft} \Bigg] - DC_f \end{aligned} \tag{3.17}$$

Note that TI_n is a nonnegative variable, while DC_f refers to the constant depreciation charge that MNC incurs at *f* over the planning horizon. If the tax rate ($/$ of taxable income) is TR_n (non-negative) for nation *n*, then the corporate tax for the MNC during *t* is TR_nTI_n. With this, ATP for the MNC for the planning horizon is,

$$\begin{aligned} \text{ATP} = & \sum_{f\in \boldsymbol{IF}} \sum_t \sum_{i\in \boldsymbol{OM}_f} \sum_{c\ni i\in \boldsymbol{IM}_c} P_{ifct}F_{ifct} + \sum_{f\in \boldsymbol{IF}} \sum_t \sum_{g\in \boldsymbol{IF}\ni i\in \boldsymbol{OM}_g} \sum_{c\ni i\in \boldsymbol{IM}_c} P_{ifgt}G_{igfct} + \\ & \sum_{f\in \boldsymbol{IF}} \sum_t \sum_{h\in \boldsymbol{F}\ni i\in \boldsymbol{OM}_h} \sum_{c\ni i\in \boldsymbol{IM}_c} P_{ifct}G_{ifhct} + \sum_{f\in \boldsymbol{IF}} \sum_t \sum_{i\in \boldsymbol{IM}_f} \sum_{s\ni i\in \boldsymbol{OM}_s} \sum_{j\in \boldsymbol{OM}_f} DR_{if} RV_{jft} CIF_{isf0} ID_{isf0} q_{sfij0t} + \\ & \sum_{f\in \boldsymbol{IF}} \sum_t \sum_{i\in \boldsymbol{IM}_f} \sum_{s\ni i\in \boldsymbol{OM}_s} \sum_{j\in \boldsymbol{OM}_f} \sum_{\tau\geq t} DR_{if} RV_{jf\tau} CIF_{isft} ID_{isft} q_{sfijt\tau} - \\ & \sum_{f\in \boldsymbol{IF}} \sum_t \sum_{h\in \boldsymbol{F}\ni i\in \boldsymbol{OM}_h} \sum_{c\ni i\in \boldsymbol{IM}_c} OC_{ifhct}G_{ifhct} - \sum_{f\in \boldsymbol{IF}} \sum_t \sum_{i\in \boldsymbol{IM}_f} \sum_{s\ni i\in \boldsymbol{OM}_s} (1+ID_{isft})CIF_{isft}F_{isft} - \end{aligned}$$

$$\sum_{f \in \boldsymbol{IF}} \sum_{t} \sum_{i \in \boldsymbol{IM}_f \cup \boldsymbol{OM}_f} 0.5 IC_{ift} (I_{if(t-1)} + I_{ift}) - \sum_{f \in \boldsymbol{IF}} \sum_{t} MC_{ft} X_{ft} -$$

$$\sum_{f \in \boldsymbol{IF}} DC_f - \sum_{n} TR_n TI_n \qquad (3.18)$$

Finally, the variables in our formulation should satisfy certain bounds. For instance, due to the limited storage space availability and the requirement to maintain a minimum stock level for each material, we have,

$$I_{if}^{L} \le I_{ift} \le I_{if}^{U} \qquad f \in \boldsymbol{IF},\ i \in \boldsymbol{OM}_f \cup \boldsymbol{IM}_f \qquad (3.19)$$

where, I_{if}^{L} and I_{if}^{U} respectively are the lower and upper limits on the inventory level of *i* at *f* over the planning horizon.

Similarly, the production rate of each *f* has some lower and upper limits,

$$X_{f}^{L} \le X_{ft} \le X_{f}^{U} \qquad f \in \boldsymbol{IF} \qquad (3.20)$$

where, X_{f}^{L} and X_{f}^{U} are the lower and upper production limits of *f* over the horizon respectively. Recall that X_{ft} is the actual consumption/production level of $\pi(f)$ at *f* during *t*.

This completes our formulation for the PDP in the presence of corporate taxes, import duties, and duty drawbacks as the regulatory factors. It comprises maximizing ATP (eq 3.18) subject to eqs 3.7−3.10, 3.12-3.14, 3.16, 3.17, 3.19, and 3.20. We now illustrate our model with a realistic example and demonstrate the significant impact of regulatory factors in production-distribution planning.

3.5 Case Study

An MNC owns twelve facilities (***IF*** = {F1-F12}) that are classified into two main categories, namely the primary and secondary plants. The primary plants are the upstream processing facilities that supply raw materials to the downstream secondary plants. In this study, the MNC needs a tactical biweekly production-distribution plan for the next fiscal year. In other words, the planning horizon has 26 equal time periods ($t = 1, 2, \ldots, T = 26$). The key external business partners that deal extensively with the MNC are ten customers (C1-C10), eight suppliers (S1-S8), and eight outsourcing facilities (O1-O8). This means ***EF*** = {C1-C10, S1-S8, O1-O8}. The internal facilities of the MNC sell their products to these customers, procure raw materials from the suppliers, and outsource their production to the outsourcing facilities. The twelve internal facilities (***IF*** = {F1-F12}) and the twenty-six external facilities (customers, suppliers, and outsourcing facilities) are geographically spread in ten nations (n = N1-N10) around the globe as illustrated in Figure 3.1.

Figure 3.1: Geographical spread of the nations hosting the facilities in the case study

Due to the sheer size of entire case study data (e. g., operating costs, limits, prices, locations, demands, BOMs, details of regulatory factors, etc.), we are unable to present them all fully in tabular formats. The readers may obtain the full data for our case study by contacting the author's thesis supervisor.

Based on the aforementioned problem data, we solved our model for two scenarios. In scenario 1, we included the three regulatory factors (corporate taxes, import duties, and duty drawbacks). Scenario 2 is similar to scenario 1 except that we ignore duty drawbacks. Hence, in scenario 2, we omitted eqs. 3.10a, 3.10b, 3.12-3.14 and 3.17, all $q_{sfij t\tau}$ variables, and set $DR_{if} = 0$. The resulting model determines X_{ft}, F_{ifct}, and G_{ifgct} values that maximize the MNC's ATP without accounting for duty drawbacks. In order to have a meaningful comparison of the solutions in these two scenarios, we computed the corresponding ATP of the MNC after considering duty drawbacks in an after-the-fact manner for the solution in scenario 2. To do so, we used X_{ft}, F_{ifct}, and G_{ifgct} from scenario 2 to compute the corresponding $q_{sfij t\tau}$, $r_{fcj\tau\theta}$, and hence the MDs, TI_{nt} and ATP by solving an LP model. This LP model is similar to the model for scenario 1 except that eqs. 3.7-3.9, 3.19, and 3.20 are omitted and X_{ft}, F_{ifct}, G_{ifgct} are constant model parameters.

We used CPLEX 9.0 solver within GAMS (distribution 21.4) running on a Windows XP workstation with a Pentium 4 Xeon (2.8 GHz, 2 GB RAM) processor. Scenario 1 involved 209,920 continuous variables, 16,453 constraints, and 703,316 nonzeros, while scenario 2 involved 52,347 continuous variables, 4,272 constraints, and 217,337 nonzeros. CPLEX solved scenario 1 in 34.5 s and gave the maximum ATP of \$279.0 million. It solved scenario 2 in 5.1 s and gave a maximum ATP (without accounting duty drawbacks) of \$218.6 million. After accounting for the duty drawbacks, the corresponding ATP rose to \$260.9 million for the MNC in scenario 2.

Note that this required solving another LP model with 155,788 continuous variables, 12,189 constraints, and 453,911 nonzeros, for which CPLEX took 4.5 s to solve.

The omission of the duty drawbacks in scenario 2 resulted in a very different production-distribution plan from scenario 1. The differences include the raw material sourcing strategies, production allocation among internal facilities, outsourcing strategies, and allocation of customer demands among the MNC's internal facilities (see Oh and Karimi, 2006 for details). Instead of discussing in detail how the omission of duty drawbacks in scenario 2 contributes to all these differences in the optimal production-distribution plans, we focus on two key differences to explain the effect of duty drawbacks and to illustrate the importance of modeling duty drawbacks in PDP problems.

First, the import and export profiles of the internal facilities change in the presence or absence of duty drawbacks. Although there is only a small difference (1%) in the total export sales by the internal facilities in the two scenarios (see Table 3.1), material sourcing strategies of these facilities differ significantly. As shown in Table 3.2, the consumption of imported raw materials by each internal facility in scenario 1 is greater or equal to that in scenario 2. This is primarily because imported materials are generally more expensive than domestic materials based on their CIF values and import duties. Therefore, it is not surprising that the optimal solution in scenario 2 sources as much of the cheaper domestic products as possible. Conversely, the accounting of duty drawbacks in scenario 1 means that the material sourcing strategy in an optimal PDP is no longer dependent only on the materials' CIF values and import duties. Now, an optimal solution also entails a coordination of import and export activities of the internal facilities so that the MNC can harness drawback savings, which may help lower the costs of imported materials. In only cases where these drawback savings make the imported materials more competitive relative to the domestic goods, it would make financial sense for an internal facility to consume more imported materials as illustrated in this case study.

Table 3.1: Export sales (M$) of internal facilities

f	Scenario 1	Scenario 2	Difference[a] (%)
F1	217,502	228,890	-5.2
F2	216,754	180,201	16.9
F3	112,762	133,176	-18.1
F4	340,231	365,228	-7.3
F5	328,041	305,647	6.8
F6	119,014	109,965	7.6
F7	164,854	179,608	-8.9
F8	370,726	366,187	1.2
F9	158,111	132,535	16.2
F10	170,267	173,164	-1.7
F11	540,093	523,190	3.1
F12	273,946	285,593	-4.3
Total	3,012,301	2,983,384	1.0

[a]The differences are percents of the sales in scenario 1.

Table 3.2: Sourcing strategies of the internal facilities in the case study

f	Material	Duty-payable sources (%)	
	m_i (i)	Scenario 1	Scenario 2
F1	1	61.6	46.5
F2	1	65.4	28.6
F3	1	0	Same
F4	2	36.4	8.4
F5	2	57.7	7.4
F6	2	100	Same
F7	3	100	Same
F8	3	22.5	5.1
F9	3	100	Same
F10	4	100	Same
F11	4	100	Same
F12	4	6.3	1.4

The percentage is computed based on the total material flow over the entire planning horizon.

The second key difference in the optimal solutions of the two scenarios lies in the MNC's earnings. Essentially, the omission of duty drawbacks has an adverse impact on the ATP of the MNC. In scenario 1, the optimal PDP enables the MNC to earn an ATP of $279 million. This is $28 million more than that in scenario 2 when duty drawbacks are accounted accordingly based on its optimal PDP (see Table 3.3). In effect, the omission of duty drawbacks in scenario 2 slashes the MNC's ATP by 6.5%. Also, note that the duty drawbacks eligible to the MNC in scenarios 1 and 2 amount to $94.6 million and $45.8 million respectively. These correspond to about 60% and 44% of the import duties that MNC has to pay over the horizon in scenarios 1 and 2 respectively. Clearly, the substantial drawback savings in these scenarios demonstrates the substantial financial benefit that companies can reap if they operate in an environment similar to the one in this case study.

Table 3.3: The MNC's ATPs and percent differences in the case study

Component	Scenario 1 (M$)	Scenario 2 (M$)	Difference (M$)	Difference[a] (%)
Sales	4,515	4,512	2,249	0.0
Manufacturing drawback	95	46	49	51.6
Outsourcing costs	1,481	1,483	-2	-0.1
CIF costs	2,225	2,240	-15	-0.7
Import duties	156	105	52	33.0
Production costs	322	323	-1	-0.4
Depreciation costs	13	13	0	0.0
Inventory costs	102	104	-2	-1.6
Corporate taxes	32	31	1	3.3
ATP	279	261	18	6.5

[a]The differences are percents of the component in scenario 1.

3.6 Discussion

At this stage, it is worthwhile to highlight four distinguishing features of our model relative to the only other existing model of Arntzen et al. (1995) that incorporates duty drawbacks.

First, it is the first PDP model that (1) incorporates the effects of three key regulatory factors (corporate taxes, import duties, and duty drawbacks) and (2) computes duty drawbacks for multi-product manufacturing processes that abound in the chemical industry. As mentioned previously, the model of Arntzen et al. (1995) computes duty drawbacks for single-product manufacturing operations only. In addition, Arntzen et al. (1995) conspicuously omitted corporate taxes in their formulation, even though corporate taxes usually constitute a significant portion of a company's annual expenditure. For example, in countries such as Croatia, Peru, Belgium, Italy, and Singapore, companies must set aside 20% to 40% of their before tax profits for corporate taxes.

Second, in contrast to the model of Arntzen et al. (1995), the solution of our model offers direct traceability from imported materials to exported products. Such traceability (based on the values of $q_{sfijt\tau}$ and $r_{fci\tau\theta}$) is necessary for computing MD accurately in a multi-product manufacturing environment, especially when the market and CIF values of products are functions of time over the given planning horizon. It also offers information that is necessary for allocating drawbacks among products or effectively managing inventory so that all eligible MDs are duly claimed as per the drawback regulations. For instance, if product substitution (see Table 3.1) is not permitted by the relevant duty drawback regulations, then the production-distribution plan needs to have details of the utilization path of every batch of imported material in order to ensure that all eligible MDs are duly claimed. These details include the origins, batch identities, delivery times, and utilization or consumption times of imported materials and the export times of merchandise made from them. In our model, $q_{sfijt\tau}$ offers such details, as it reflects the amount of i imported from s to f at t and used to produce j at τ.

Thirdly, even though our model is developed primarily for production-distribution planning in multi-product manufacturing environment, it works equally well for the single-product manufacturing operations.

Lastly and most importantly, our model can also handle uncertainty in problem parameters with only a few straightforward modifications. For example, if a given PDP has uncertain market prices, demands, CIF values, etc., and one can represent the uncertainties by a set of probabilistic scenarios with known probabilities of occurrence, then one can easily use our model in such a scenario-based approach that can mimic those described by Tsiakis et al. (2001) and Oh and Karimi (2004). For this, the main modifications in our model will be as follows:

(1) Add one additional index to each decision variable to signify its scenario,

(2) Replicate all constraints for each scenario with specific realizations of uncertain parameters,

(3) Maximize the expected ATP over all scenarios instead of one single deterministic ATP.

We would like to point out that the LP nature of our formulation is a great advantage, when extending it to the above scenario-based approach. Of course, the scenario-based approach will increase the model size significantly; but that poses no problem for the state-of-the-art LP algorithms. However, we must point out that the 5-index and 6-index variables ($r_{fci\tau\theta}$ and $q_{sfij t\tau}$ respectively) in our deterministic model does pose a problem, when one uses a commercial algebraic modeling software such as GAMS. GAMS required considerable RAM resources to generate our model. For scenario 1 of our case study, GAMS needed more than 1.7 Gb RAM and real time of about eleven minutes to generate our model before it took only another 34.5 s to solve the LP. However, we should point that this problem is specific to GAMS. It is not mandatory to use GAMS for model generation; we can write special-purpose programs that are more efficient. In addition to the parameter uncertainty, several possible extensions of our model include the accounting of non-linear relationship between raw material consumption and merchandise production or economies of scale in freight expenses, etc. These extensions are clearly relevant to the manufacturing world as they reflect real operational constraints and modeling/solution challenges. Therefore, improving the formulation and model generation methodology constitute significant future research opportunities for this problem. This would be an essential goal for increasing our model's applicability in the real, uncertain, industrial environment.

4. Deterministic Capacity Expansion Problem with Variable Expansion Duration

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Essentially, this chapter is an extension of chapter 2 where the former addresses a major shortcoming of existing capacity expansion planning research. To the best of the authors' knowledge, majority of existing capacity-expansion planning models are developed with the assumption that the expansion duration is independent of expansion volume. This assumption is particularly inappropriate in the chemical industry where there is usually a significant lead or construction duration before new capacity becomes available for production and this duration generally increases with the volume of new capacity. Inevitably, the assumption of fixed expansion duration limits the application of existing capacity expansion planning models in the industry, especially in the current economic era where the intensely competitive business environment makes the turnaround time needed for new capacity availability a crucial factor for consideration in capacity-expansion planning. This is particularly true among manufacturers of short value cycle products like consumer electronics. These products can become obsolete rapidly in time scale of months due to intense competition, and phenomenal rate of technology development. As such their manufacturers have limited horizon over which it remains profitable to add new capacities.

This chapter aims to fill the research gap attributed to the above shortcoming in two major ways. First, it presents novel mixed-integer nonlinear programming (MINLP) model to represent a capacity expansion problem (CEP) with unprecedented account of four key regulatory factors (i.e. import tariff, corporate tax, duty drawback, loss carry-forward) and piecewise linear relationships between capacity expansion duration with expansion volume. It also describes how the aforementioned MINLP model can be transformed into a mixed-integer linear programming (MILP) model through variable substitutions and constraint additions. Finally, this chapter shows how this MILP model can be applied to address a CEP of industrial scale through a simple case study.

4.1. Previous Work

Instead of duplicating the literature review that is already presented in chapter 2, this section only discusses areas which have not been covered previously. Despite the relatively long history of research on CEPs and the progress that has been accomplished over the years in terms of model and solution methodology development, an improvement opportunity remains available in this research area. Essentially, this opportunity arises due to an underlying assumption of most existing capacity expansion planning models that clearly does not reflect the reality of the industry. Typically, there is a lead time or construction duration before new capacity becomes available for production. In expansion projects that entail wide range of expansion volume or size, this duration generally increases with the volume of new capacity. Moreover, the time at which a new capacity is available for production also affects the annual appreciation charge of a manufacturer which in turn has a direct impact on the bottom line of the corporate organization.

However, it is astounding to note that majority of existing capacity-expansion planning models in the literature have been formulated based on the assumption of a fixed expansion duration which is independent of expansion volume. Though the CEP model of Sahinidis et al. (1989) was formulated in a manner that the availability of newly installed production capacity can be function of new capacity volume, it did not account for the impact of depreciation charges of newly installed capacity on the net present value of the corporate organization involved. Inevitably, the aforementioned assumption has limited the application potential of existing expansion planning models in the industry. This is particularly true in the increasingly competitive business conditions where the turnaround time for new capacity availability is a crucial factor for consideration in capacity-expansion planning. For example, manufacturers of short value cycle products like consumer electronics have limited horizon over which it remains profitable to add new capacities. As such, they tend to avoid expansion projects that have such a long duration that it may no longer be profitable to raise the manufacturing level when the new production capacity becomes available due to significant drop in market values of their products.

With a good overview of latest research status on CEPs and a key research opportunity, we now describe a CEP with features that have glaringly been overlooked by researchers even though their omission can adversely affect the quality of the expansion planning decisions.

4.2 Problem Description

We consider a deterministic CEP which shares the basic features as those described in Oh and Karimi (2004) or chapter 2. As such, we use the same notation that has been employed in chapter 2 to describe the problem in this chapter. Instead of duplicating the problem description which is already presented in section 2.2, we focus in this section only on the differences between the problem to be addressed in this chapter and that in chapter 2. Essentially, all assumptions described in section 2.2 with exceptions of assumptions 4 to 6 remain valid in this chapter. Thus, we adopt the same convention for the mass balance of each internal facility f where it is given by,

$$\sum_{i \in \boldsymbol{IM}_f} \sigma_{if} m_i = \sum_{i \in \boldsymbol{OM}_f} \sigma_{if} m_i \qquad f \in \boldsymbol{IF} \qquad (4.1)$$

Recall that m_i denotes material i that f consumes or produces, and σ_{if} is analogous to the stoichiometric coefficient of a species i in a reaction except that the above balance is in terms of mass (ton) rather than moles.

Though the CEP in this chapter is similar to that of Oh and Karimi (2004) or chapter 2, there is one fundamental difference between them. The latter problem permits expansion construction activity to commence at any time period of the planning horizon. This is different from the CEP in this chapter where we assume all expansion construction activities are to commence at the beginning of planning horizon. Clearly, our CEP offers better fit of the problems faced by the decision makers if the latter do not recognize the practical need of planning for future investment decisions due to the underlying uncertainty of future business environment. Due to the dynamic nature of business world, it is impractical to plan a capacity expansion project which only commences say three or more years later since the optimal expansion plan is likely to change as business conditions evolve between start of planning horizon to commencement date of expansion activities. As such, we only consider expansion activities which commence at the start of planning horizon in this chapter. In addition, the CEP in this chapter also incorporates two industrially relevant problem features which distinguish it from other CEPs in existing literature. We now describe these two features in the following two sections respectively.

4.2.1 Comprehensive Account of Key Regulatory Factors

The importance of accounting for regulatory factors in supply chain planning has been elaborated extensively in chapter 1. In this chapter, our CEP distinguishes itself from others in existing literature by accounting for simultaneously four key regulatory factors which have significant impact on the bottom-line of the MNC. These regulatory factors are corporate tax, import tariff, duty drawback, and carry-forward loss. Essentially, carry-forward loss is a tax incentive offered by authority to alleviate corporate tax liabilities of companies which have just recovered from losses incurred in previous years. In a survey of 23 countries performed by Eldor and Zilcha (2002), all these countries offer loss carry-forward option to corporate organizations. To illustrate the concept of carry-forward losses, let us consider a simple example where a company in a country is allowed to carry its loss in a year forward to the next five years. This means that if this company incurs a loss in a particular year say Y, then it may deduct part or whole of this loss in any of the next five years (i.e. Y+1, Y+2, …, Y+5) whenever its taxable income is positive. Evidently, the account of this loss carry-forward feature in capacity expansion planning projects allows companies to assess their corporate taxes payable and net profits more accurately. This is especially relevant to capital-intensive chemical manufacturing companies which may incur losses during the initial start-up years of their new manufacturing facilities or during unfavorable business conditions.

4.2.2 Realistic Representation of Project Cost and Project Duration Profiles

We assume that the project cost and project duration profiles of our CEP to be piecewise linear functions of the expansion volumes. Figures 4.1 and 4.2 illustrate these profiles respectively for a facility *f* of the MNC where parameters used in these profiles are distinguished by superscripts *C* and *D* respectively. In Figure 4.1 (4.2), x-axis of the profile has total of K_f^C (K_f^D) segments. Each of these segments has a value range of $0 \le \Delta q_{fk}^{C} \le \Delta \overline{q}_{fk}^{C}$ ($0 \le \Delta q_{fk}^{D} \le \Delta \overline{q}_{fk}^{D}$). We denote Q_f^L as the lower limit of any capacity expansion at *f*. Therefore, the volume of capacity-expansion at *f* is $Q_f^L + \sum_{k=1}^{K_f^C} \Delta q_{fk}^{C}$ or $Q_f^L + \sum_{k=1}^{K_f^D} \Delta q_{fk}^{D}$. In Figure 4.1, we use R_{fk}^{C} ($1 \le k \le K_f^C$) to represent the slope of linear segment *k* in the profile and g_{fk}^{C} to denote the quantum change in capital expenditure when Δq_{fk}^{C} exceeds zero. This is to reflect the significant change in project cost at discrete points of the expansion size scale. The profile in Figure 4.2 only differs from that of Figure 4.1 by the zero slopes of its linear segments. Essentially, the zero slopes reflect the insensitivity of project duration over change in expansion volume within specific range. In practice, there is usually no significant change in project duration when the expansion volume varies over a pre-defined range. In addition, projected expansion duration is typically expressed in discrete number terms like weeks, months or quarters in major strategic capacity-expansion projects. To conform to this industrial practice, we define g_{fk}^{D} as a multiple of the smallest interval, *d* in which the project duration is measured and *d* has unit of week, month or quarter. Clearly, such representation of project cost and duration profiles have more industry realism than those in existing capacity expansion planning models like Oh and Karimi (2004) where the project duration is assumed to be independent of expansion volume and project cost profile of each facility is a simple linear function of expansion volume with $K_f^C = 1$.

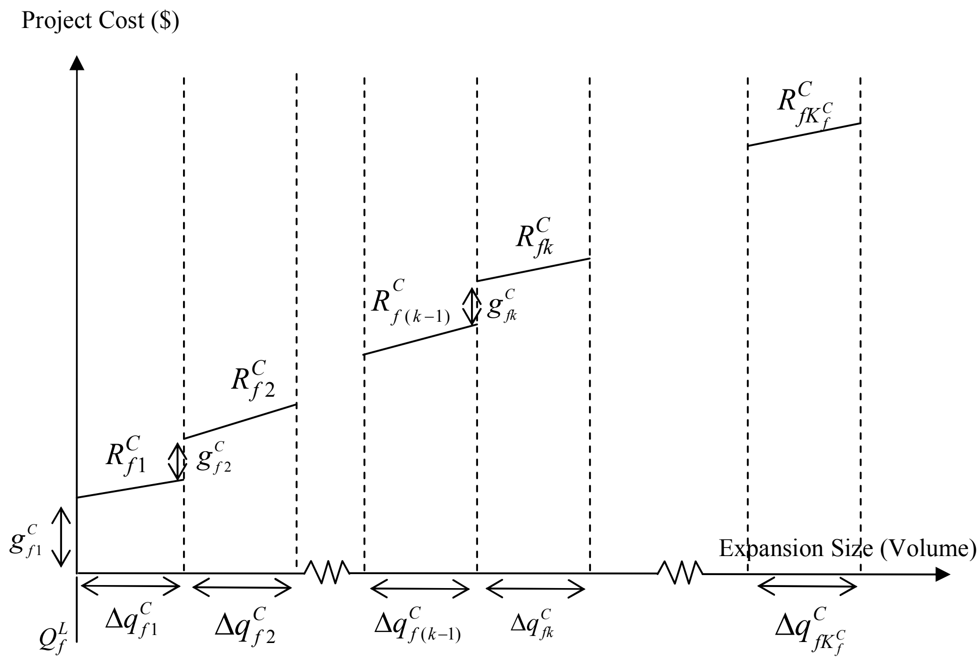


Figure 4.1: Project cost versus expansion volume profile

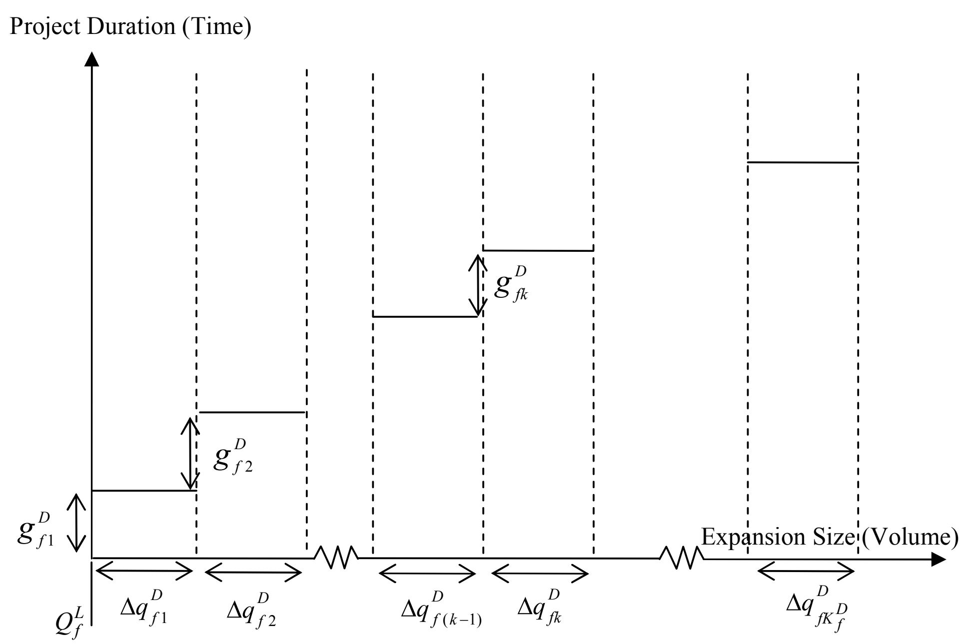


Figure 4.2: Project duration versus expansion volume profile

4.3 Model formulation

Using the notation which is similar to that described in Oh and Karimi (2004), we now present the model formulation of the aforementioned CEP. Due to the comprehensive account of regulatory factors and piecewise linear representation of project cost and duration, the number of variables and constraints required to model this problem is relatively large. To facilitate reading and understanding of our formulation, we divide our model description into four main sections. Systematically, these four sections describe the variables and constraints needed to represent (i) project cost and duration, (ii) production, distribution and outsourcing, (iii) duty drawbacks, (iv) carry-forward loss and taxable incomes respectively. Unless stated otherwise, the indexes (*f*, *t*, *i*, *k*, etc.) assume their full ranges of values in the rest of this section.

4.3.1 Project Duration and Cost

The strategic decisions of our CEP basically entail determination of the locations and amounts of capacity expansion of each internal facility. To model these decisions, we use the binary variable y_f to represent whether or not facility $f \in \boldsymbol{IF}$ expands. Therefore, the amount (q_f) capacity expansion in facility $f \in \boldsymbol{IF}$ based on expansion volume variables used in project cost profile (see Figure 4.1) is,

$$q_f = Q_f^L y_f + \sum_{k=1}^{K_f^C} \Delta q_{fk}^C \qquad f \in \boldsymbol{IF} \tag{4.2}$$

If MNC does not expand $f \in \boldsymbol{IF}$ at all over the planning horizon, its expansion volume must be zero. Thus, we get,

$$\sum_{k=1}^{K_f^C} \Delta q_{fk}^C \le y_f (Q_f^U - Q_{f0} - Q_f^L) \quad f \in \boldsymbol{IF} \tag{4.3}$$

Recall that Q_{f0} is the initial capacity of existing facility f at the beginning of horizon (thus Q_{f0} = 0 for $f \in$ ***FIF***), Q_f^U is the maximum allowable capacity at f, and Q_f^L is minimum incremental expansion allowed at existing facility $f \in$ ***EIF*** or the minimum capacity of a new construction at facility $f \in \boldsymbol{FIF}$. Note that Q_f^U is the maximum allowable capacity of f and $Q_f^U = Q_{f0} + Q_f^L + \sum_{k=1}^{K_f^C} \Delta \overline{q}_{fk}^C$ or $Q_f^U = Q_{f0} + Q_f^L + \sum_{k=1}^{K_f^D} \Delta \overline{q}_{fk}^D$.

To determine the total project cost of capacity expansion at $f \in$ ***IF*** based on the profile shown in Figure 4.1, we need to introduce the following binary variable.

$$h_{fk}^C = \begin{cases} 1 & \text{if } \Delta q_{fk}^C > 0 \\ 0 & \text{otherwise} \end{cases} \qquad f \in \boldsymbol{IF},\ 2 \le k \le K_f^C$$

Thus, the total project cost (PC_f) of capacity expansion at $f \in$ ***IF*** is

$$PC_f = g_{f1}^C y_f + R_{f1}^C \Delta q_{f1}^C + \sum_{k=2}^{K_f^C} \left(g_{fk}^C h_{fk}^C + R_{fk}^C \Delta q_{fk}^C \right) \qquad f \in \boldsymbol{IF} \tag{4.4}$$

Note that the above cost is expressed in terms of the native currency of f.

Since Δq_{fk}^C ($2 \le k \le K_f^C$) can be greater than zero only when h_{fk}^C is one, we have,

$$\Delta q_{fk}^C \le \Delta \overline{q}_{fk}^C h_{fk}^C \quad f \in \boldsymbol{IF},\ 2 \le k \le K_f^C \tag{4.5}$$

Similarly, Δq_{f1}^{C} can be greater than zero only when go-ahead decision is made on the expansion or construction of $f \in \boldsymbol{IF}$. Thus, we also have,

$$\Delta q_{f1}^{C} \leq \Delta \overline{q}_{f1}^{C} y_f \qquad f \in \boldsymbol{IF} \tag{4.6}$$

In order to maintain the mathematical legitimacy of equation (4.3), two additional sets of constraints have to be imposed. The first set arises because h_{fk}^{C} ($3 \leq k \leq K_f^C$) can be greater than zero only when h_{fk-1}^{C} is one. Therefore,

$$h_{fk}^{C} \leq h_{fk-1}^{C} \qquad f \in \boldsymbol{IF},\ 3 \leq k \leq K_f^C \tag{4.7}$$

Moreover, h_{f2}^{C} can be greater than zero only when y_f equals to one. Thus, we also have,

$$h_{f2}^{C} \leq y_f \qquad f \in \boldsymbol{IF} \tag{4.8}$$

Similarly, if h_{fk}^{C} ($2 \leq k \leq K_f^C$) is one, then the expansion quantum in the previous segment (k-1) must have reached its upper limit.

$$\Delta q_{f(k-1)}^{C} \geq \Delta \overline{q}_{f(k-1)}^{C} h_{fk}^{C} \qquad f \in \boldsymbol{IF},\ 2 \leq k \leq K_f^C \tag{4.9}$$

Whether it is an expansion or new construction, the MNC will need incur capital expenses. We define *CB* as the MNC's allotted capital budget for capacity expansion and new construction based on a numeraire currency. Therefore, we use,

$$\sum_{f \in \boldsymbol{IF}} PC_f e_{f0} \le CB \tag{4.10}$$

where, e_{ft} denotes currency exchange rate which is in units of a numeraire currency per unit of currency of internal facility f at t while e_{f0} is the exchange rate at start of planning horizon.

Using the same logic as above, we can write down the following to determine the duration of capacity expansion at $f \in \boldsymbol{IF}$ based on the profile shown in Figure 4.2.

$$h_{fk}^D = \begin{cases} 1 & \text{if } \Delta q_{fk}^D > 0 \\ 0 & \text{otherwise} \end{cases} \quad f \in \boldsymbol{IF},\ 2 \le k \le K_f^D$$

$$PD_f = g_{f1}^D y_f + \sum_{k=2}^{K_f^D} g_{fk}^D h_{fk}^D \qquad f \in \boldsymbol{IF} \tag{4.11}$$

$$\Delta q_{fk}^D \le \Delta \overline{q}_{fk}^D h_{fk}^D \qquad f \in \boldsymbol{IF}, 2 \le k \le K_f^D \tag{4.12}$$

$$\Delta q_{f1}^D \le \Delta \overline{q}_{f1}^D y_f \qquad f \in \boldsymbol{IF} \tag{4.13}$$

$$h_{fk}^D \le h_{fk-1}^D \qquad f \in \boldsymbol{IF},\ 3 \le k \le K_f^D \tag{4.14}$$

$$h_{f2}^D \le y_f \qquad f \in \boldsymbol{IF} \tag{4.15}$$

$$\Delta q^D_{f(k-1)} \geq \Delta \overline{q}^D_{f(k-1)} h^D_{fk} \quad f \in \boldsymbol{IF}\,,\ 2 \leq k \leq K^D_f \tag{4.16}$$

where, PD_f is the project duration for expansion at $f \in \boldsymbol{IF}$.

Note that the capacity expansion volume of each facility $f \in \boldsymbol{IF}$ can be computed using either Δq^C_{fk} or Δq^D_{fk} in our problem. To ensure consistency in the expansion volume values regardless of variable types used in the computation, we have,

$$\sum_{k=1}^{K^D_f} \Delta q^D_{fk} = \sum_{k=1}^{K^C_f} \Delta q^C_{fk} \qquad f \in \boldsymbol{IF} \tag{4.17}$$

4.3.2 Production, Distribution and Outsourcing

A facility $f \in \boldsymbol{IF}$ cannot process more than its available capacity at time period t. The available capacity of a facility $f \in \boldsymbol{IF}$ basically depends on both the volume and project duration of capacity expansion or new construction if f is identified as a plant for possible expansion or new construction. To account for this, we introduce a new index η where $1 \leq \eta \leq M$ to denote the sub-division of each period $t \in T$ where M represents the total number of sub-divisions in t and each of these sub-divisions shares the same dimension as d. In addition, we also introduce new binary variable $\Delta PD_{ft\eta}$ so that the project duration of capacity expansion or new construction at $f \in \boldsymbol{IF}$ can be alternatively expressed as follows.

$$g^D_{f1} y_f + \sum_{k=2}^{K^D_f} g^D_{fk} h^D_{fk} = \sum_{t=1}^{T} \sum_{\eta=1}^{M} \Delta PD_{ft\eta} \qquad f \in \boldsymbol{IF} \tag{4.18}$$

To ensure mathematical legitimacy of equation (4.18), we need to impose the following two constraints.

$$\Delta PD_{ft1} \le \Delta PD_{f(t-1)M} \qquad f \in \boldsymbol{IF},\ 2 \le t \le T \tag{4.19}$$

$$\Delta PD_{ft\eta} \le \Delta PD_{ft(\eta-1)} \qquad f \in \boldsymbol{IF},\ 2 \le \eta \le M \tag{4.20}$$

The above two equations allows $\Delta PD_{ft\eta}$ to be greater than zero only when $\Delta PD_{f11} = \Delta PD_{f12} = \ldots = \Delta PD_{f1M} = \Delta PD_{f21} = \ldots = \Delta PD_{ft1} = \ldots = \Delta PD_{ft(\eta-2)} = \Delta PD_{ft(\eta-1)}$ = 1. With these binary variables, the available capacity of $f \in \boldsymbol{IF}$ ($Q_{ft\eta}$) for production at η of t is

$$Q_{ft\eta} = [Q_{f0} + (1-\Delta PD_{ft\eta})q_f]/M \tag{4.21}$$

Now, if X_{ft} denotes the actual consumption/production levels (units/year) of $\pi(f)$ at an internal facility $f \in \boldsymbol{IF}$ during t, we can express the constraint on the production capacity of $f \in \boldsymbol{IF}$ at t as follows,

$$X_{ft} \le \sum_{\eta=1}^{M} \left(\frac{(Q_{f0} + q_f) - \Delta PD_{ft\eta} q_f}{M} \right) \qquad f \in \boldsymbol{IF} \tag{4.22}$$

To model the incoming and outgoing flows of materials for the facilities, we let F_{ifct} denote the quantity of material i that facility $s \in \boldsymbol{F}$ sells to facility $c \in \boldsymbol{F}$ during period t, where $s \neq c$. Note that F_{isct} is a non-negative variable that exists only for $i \in$

$\boldsymbol{OM}_s \cap \boldsymbol{IM}_c$. Since inventory does not carry over from one period to the next, the material amounts consumed (produced) by a facility ($f \in \boldsymbol{IF}$) must match its incoming (outgoing) material flows. Therefore, we must have,

$$\sigma_{if} X_{ft} = \sigma_{\pi(f)f} \left(\sum_{c \ni i \in \boldsymbol{IM}_c} F_{ifct} + \sum_{s \ni i \in \boldsymbol{OM}_s} F_{isft} \right) \qquad f \in \boldsymbol{IF},\ i \in \boldsymbol{OM}_f \cup \boldsymbol{IM}_f \qquad (4.23)$$

To ensure that delivery does not exceed demand, and supply does not exceed capacity, we write the following equation.

$$\sum_{f \in \boldsymbol{IF} \ni i \in \boldsymbol{OM}_f} (F_{ifgt} + G_{ifgt}) + \sum_{f \in \boldsymbol{IF} \ni i \in \boldsymbol{IM}_f} F_{igft} \le D_{igt} + S_{igt} \qquad g \in \boldsymbol{EF},\ i \in \boldsymbol{OM}_g \cup \boldsymbol{IM}_g \qquad (4.24)$$

where, G_{ifgt} denote the production quantity of i ($i \in \boldsymbol{OM}_f$) that f outsources during period t to meet the demand of customer g, D_{igt} is the demand of customer g during period t, and S_{igt} is the maximum amount of i, which g can supply during t. Note that $G_{ifgt} = 0$ for $i \in \boldsymbol{IM}_f$. Since there is an upper limit on how much production can be outsourced by each existing facility $f \in \boldsymbol{EIF}$, we write,

$$\sum_{g \in \boldsymbol{EF} \ni i \in \boldsymbol{IM}_g} G_{ifgt} \le G^U_{ift} \qquad f \in \boldsymbol{EIF},\ i \in \boldsymbol{OM}_f \qquad (4.25)$$

For each internal facility $f \in \boldsymbol{FIF}$ which is available for production only after the start of planning horizon, it also has an upper limit (G^U_{ift}) on how much of its production can be outsourced. We assume that this limit has to be pro-rated accordingly if the new construction is not available for production for entire period t. To account for this, we have,

$$\sum_{g \in \boldsymbol{EF} \ni i \in \boldsymbol{IM}_g} G_{ifgt} \le G_{ift}^U (M - \sum_{\eta=1}^{M} \Delta PD_{ft\eta}) / M \qquad f \in \boldsymbol{FIF},\ i \in \boldsymbol{OM}_f \qquad (4.26)$$

Moreover, there should be no outsourcing by internal facility $f \in \boldsymbol{FIF}$ if there is no plan to construct it at the start of the planning horizon. Thus, we also write,

$$\sum_{g \in \boldsymbol{EF} \ni i \in \boldsymbol{IM}_g} G_{ifgt} \le G_{ift}^U y_f \quad f \in \boldsymbol{FIF},\ i \in \boldsymbol{OM}_f \qquad (4.27)$$

4.3.3 Duty Drawbacks

As highlighted previously, we assume that nations where all the existing and potential future facilities in our problem are located adopt the manufacturing drawback schemes which are similar to those in US. Moreover, the turnover rates of materials involved in these facilities are so fast that (1) all time limits pertinent to drawback claims can be satisfied, and (2) there is no carryover of inventory from any period t to the next. We define W_{ijsft} as units of i that are eligible for manufacturing drawback (MD) claim by f due to its import from s (i.e. f and s are located in different countries) during t, and subsequent manufacture of j for export. Clearly, W_{ijsft} has an upper bound which is determined by the amount of i imported by f from s, i.e.

$$W_{ijsft} \le F_{isft} \qquad f \in \boldsymbol{IF} \cap \boldsymbol{F}_n, s \in \boldsymbol{F}_n^{'}, i \in \boldsymbol{OM}_s \cup \boldsymbol{IM}_f, j \in \boldsymbol{OM}_f \qquad (4.28)$$

Note that $\boldsymbol{F}'_n = \boldsymbol{F} - \boldsymbol{F}_n$. Similarly, W_{ijsft} also has an upper bound which is based on the amount of *j* that has been exported out of *f*, i.e.

$$\sum_{s \in \boldsymbol{F}'_n \ni i \in \boldsymbol{OM}_s} W_{ijsft} \leq \frac{\sigma_{if}}{\sigma_{jf}} \sum_{c \in \boldsymbol{F}'_n \ni j \in \boldsymbol{IM}_c} F_{jfct} \quad f \in \boldsymbol{IF} \cap \boldsymbol{F}_n, i \in \boldsymbol{OM}_s \cup \boldsymbol{IM}_f, j \in \boldsymbol{OM}_f \tag{4.29}$$

Thus, the MD claim for *f* at *t* is,

$$MD_{ft} = \sum_{i \in \boldsymbol{IM}_f} \sum_{j \in \boldsymbol{OM}_f} \sum_{s \in \boldsymbol{F}'_n \ni i \in \boldsymbol{OM}_s} W_{ijsft} CIF_{isft} ID_{isft} RV_{jft} DR_{if} \quad f \in \boldsymbol{IF} \tag{4.30}$$

where, DR_{if} (\$/\$ of paid duty) is the duty refund rate as per the local regulations while CIF_{isct} and ID_{isct} denote respectively cost, insurance and freight (CIF) cost (\$/unit), and import duty (\$/\$ of CIF cost) of material m_i ($i \in \boldsymbol{OM}_s \cap \boldsymbol{IM}_c$) sold by $s \in \boldsymbol{F}$ to $c \in \boldsymbol{F}$ during *t*. RV_{jft} represents the relative value of product m_j ($j \in \boldsymbol{OM}_f$) which is based on the market prices (or other values approved by the customs authorities) of all finished products at the *time of their manufacture*. Thus, the parameter RV_{jft} of a finished product m_j ($j \in \boldsymbol{OM}_f$) produced in an arbitrary period *t* is defined as,

$$RV_{jft} = \frac{\sigma_{jf} MP_{jt}}{\sum_{j' \in \mathbf{OM}_f} \sigma_{j'f} MP_{j't}} \tag{4.31}$$

where, MP_{jt} denotes the market price of m_j at t. Note that finished products m_j ($j \in$ $\boldsymbol{OM}_f$) with no value or those irrecoverably wasted in a manufacturing process have $MP_{jt} = 0$.

4.3.4 Carry-Forward Loss and Taxable Incomes

To compute the MNC's corporate tax during each t in each host nation n, we need the taxable income of the MNC's facility in that nation n. The taxable income is gross income minus depreciation, and gross income is sales minus operating expense. The operating expense is the sum of procurement and manufacturing (or variable production) costs. To this end, let P_{isct}, the purchase price (\$/unit) of material m_i ($i \in$ $\boldsymbol{OM}_s \cap \boldsymbol{IM}_c$) sold by $s \in \boldsymbol{F}$ to $c \in \boldsymbol{F}$ during t. We also define CO_{ifct} as the unit cost (\$/unit) that f incurs during t for outsourcing the production of product i and its delivery to customer c. Then, the gross income GI_{ft} of $f \in \boldsymbol{IF}$ during t is,

$$GI_{ft} = -MC_{ft}X_{ft} + \sum_{i \in \boldsymbol{OM}_f} \sum_{c \ni i \in \boldsymbol{IM}_c} [P_{ifct}(F_{ifct} + G_{ifct})] - \sum_{i \in \boldsymbol{IM}_f} \sum_{s \ni i \in \boldsymbol{OM}_s} (1 + ID_{isft})CIF_{isft}F_{isft} +$$

$$\sum_{i \in \boldsymbol{IM}_f} \sum_{j \in \boldsymbol{OM}_f} \sum_{s \in \boldsymbol{F}_n^{'} \ni i \in \boldsymbol{OM}_s} W_{ijsft}CIF_{sfit}ID_{sfi}RV_{ijft}DR_{if} - \sum_{i \in \boldsymbol{OM}_f} \sum_{c \ni i \in \boldsymbol{IM}_c} G_{ifct}CO_{ifct} \tag{4.32}$$

where, MC_{ft} is the manufacturing cost [\$/unit of $\pi(f)$] of $f \in \boldsymbol{IF}$ during t.

For computation of depreciation, we use the straight-line method which is the same as the one used in Oh and Karimi (2004). There two depreciation charges to consider where one arises from the (old) investments before $t = 0$, and the other arises due to capacity expansion or new construction. Let the former charge be ODC_{ft}, while for the latter, we define $NDC_{ft\eta}$ as the depreciation charge during η of t for the capital investment at $f \in \boldsymbol{IF}$ at start of planning horizon. Then, we obtain,

$$NDC_{ft\eta} = (1\text{-}\Delta PD_{ft\eta})\, PC_f/L_f \tag{4.33}$$

where, L_f is the project life of the new capacity at f and it shares the same dimension with $\Delta PD_{ft\eta}$.

We assume all facilities owned by the MNC in a country n report their combined earnings and pay corporate tax as a single corporate entity. We also let PE_{nt} and NE_{nt} denote respectively the pre-tax profit and pre-tax loss of the MNC in nation n during t. Then, we can write,

$$\begin{aligned} PE_{nt} - NE_{nt} = \sum_{f \in \boldsymbol{IF} \cap \boldsymbol{F}_n} \Bigg[& \sum_{i \in \boldsymbol{OM}_f} \sum_{c \ni i \in \boldsymbol{IM}_c} P_{ifct}(F_{ifct} + G_{ifct}) - \sum_{i \in \boldsymbol{IM}_f} \sum_{s \ni i \in \boldsymbol{OM}_s} (1 + ID_{isft}) CIF_{isft} F_{isft} + \\ & \sum_{i \in \boldsymbol{IM}_f} \sum_{j \in \boldsymbol{OM}_f} \sum_{s \in \boldsymbol{F}_n \ni i \in \boldsymbol{OM}_s} W_{ijsft} CIF_{isft} ID_{isft} RV_{jft} DR_{if} - \sum_{i \in \boldsymbol{OM}_f} \sum_{c \ni i \in \boldsymbol{IM}_c} G_{ifct} CO_{ifct} - \\ & MC_{ft} X_{ft} - ODC_{ft} - \sum_{\eta=1}^{M} (1 - \Delta PD_{ft\eta}) PC_f \big/ L_f \Bigg] \end{aligned} \tag{4.34}$$

To ensure mathematical legitimacy of equation (4.34), both PE_{nt} and NE_{nt} which are non-negative, cannot be not greater than zero simultaneously. This means that if the right hand side of equation (4.34) is positive (negative), then only PE_{nt} (NE_{nt}) is positive while NE_{nt} (PE_{nt}) is zero. Such condition can be achieved by introduction of the following binary variable and the three constraints in the formulation.

$$YP_{nt} = \begin{cases} 1 & \text{if } PE_{nt} - NE_{nt} \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

$$PE_{nt} \leq YP_{nt}\overline{P}_{nt} \tag{4.35}$$

$$NE_{nt} \leq (1 - YP_{nt})\overline{N}_{nt} \tag{4.36}$$

where $\overline{P}_{nt}$ and $\overline{N}_{nt}$ are the upper bounds of profit and loss respectively of the MNC in *n* during *t*.

Now, we define $CFL_{ntt'}$ as the nonnegative loss amount incurred by MNC in *n* for period *t* and that is available for tax rebate at the beginning of *t'*. If ω_n is the number of years that corporate losses can be carried forward based on the loss carry-forward policy of *n*, then we obtain,

$$NE_{nt} \geq \sum_{t'=t+1}^{t+\omega_n} CFL_{ntt'} \tag{4.37}$$

Note that $CFL_{ntt'} = 0$ for $(t + \omega_n) < t' \leq T$ and $t' \leq t$. Therefore, taxable income payable (TIP_{nt}) by MNC in *n* at the end of *t* is,

$$TIP_{nt} \geq PE_{nt} - \sum_{t'<t} CFL_{nt't} \tag{4.38}$$

where, TIP_{nt} is nonnegative.

If the tax rate ($/$ of taxable income) is TR_{nt} (non-negative) for nation n during t, then the corporate tax for the MNC during t is $TR_{nt}TIP_{nt}$. Note that all prices (P_{ifct}), cost elements (MC_{ft}, CIF_{isft}, CO_{ifct}) are expressed in the currency of the internal facility f involved while TIP_{nt} is expressed in terms of the currency of the nation n involved. With this, the NPV of the net cash flow for the MNC is,

$$
\begin{aligned}
\text{NPV} = & \sum_{f\in \boldsymbol{IF}}\sum_{t}\frac{\sum_{i\in \boldsymbol{OM}_f}\sum_{c\ni i\in \boldsymbol{IM}_c} e_{ft}P_{ifct}(F_{ifct}+G_{ifct})-e_{ft}MC_{ft}X_{ft}}{(1+r)^t} - \\
& \sum_{f\in \boldsymbol{IF}}\sum_{t}\frac{\sum_{i\in \boldsymbol{IM}_f}\sum_{s\ni i\in \boldsymbol{OM}_s} e_{ft}(1+ID_{isft})CIF_{isft}F_{isft} - \sum_{i\in \boldsymbol{OM}_f}\sum_{c\ni i\in \boldsymbol{IM}_c} e_{ft}G_{ifct}CO_{ifct}}{(1+r)^t} + \\
& \sum_{f\in \boldsymbol{IF}}\sum_{t}\frac{\sum_{i\in \boldsymbol{IM}_f}\sum_{j\in \boldsymbol{OM}_f}\sum_{s\ni i\in \boldsymbol{OM}_s} e_{ft}W_{ijsft}CIF_{isft}ID_{isft}RV_{jft}DR_{if}}{(1+r)^t} - \\
& \left.\sum_{n}\sum_{t}\frac{\varepsilon_{nt}TIP_{nt}TR_{nt}}{(1+r)^t}\right] - \sum_{f\in \boldsymbol{IF}} PC_f e_{f0}
\end{aligned}
\tag{4.39}
$$

where, r is the annual interest rate (fraction), ε_{nt} is currency exchange rate which is in units of a numeraire currency per unit of currency of nation n during t.

This completes our formulation for our CEP with account of corporate taxes, import duties, duty drawbacks, and loss carry-forward. We name this model CEPM and it comprises maximizing NPV (4.39) subject to eqs. (4.2)-(4.20), (4.22)-(4.29), (4.34)-(4.38).

4.4 Linearization

Essentially, CEPM is a MINLP model due to the presence of two sets of bilinear terms (i.e. $\Delta PD_{ft\eta}q_f$ and $\Delta PD_{ft\eta}PC_f$) in (4.22) and (4.34). To eliminate this nonlinearity, we apply the approach developed by Petersen (1971) and extended by Glover (1975). This approach entails application of two key steps on each set of bilinear terms. First, we perform variable substitution where we let nonnegative $A_{ft\eta} = \Delta PD_{ft\eta}q_f/M$. Then, we also impose the following two linear equations to the mathematical legitimacy among the values of variables $\Delta PD_{ft\eta}$, q_f and $A_{ft\eta}$.

$$q_f/M - V_f(1 - \Delta PD_{ft\eta}) \le A_{ft\eta} \le q_f/M \qquad f \in \boldsymbol{IF} \tag{4.40}$$

$$A_{ft\eta} \le V_f \Delta PD_{ft\eta} \qquad f \in \boldsymbol{IF} \tag{4.41}$$

where, $V_f = (Q_f^L + \sum_{k=1}^{K_f^C} \Delta\overline{q}_{fk}^C)/M$ or $V_f = (Q_f^L + \sum_{k=1}^{K_f^D} \Delta\overline{q}_{fk}^D)/M$

Thus, in the presence of equations (4.40) and (4.41), the original product terms of $\Delta PD_{ft\eta}q_f/M$ in CEPM in (4.22) can be substituted by $A_{ft\eta}$. As a result, the nonlinearity of CEPM attributed to bilinear terms of $\Delta PD_{ft\eta}q_f$ is eliminated.

Using the same approach, we apply the above two linearization steps on the second set of bilinear terms ($\Delta PD_{ft\eta}PC_f$). We first let nonnegative $B_{ft\eta} = \Delta PD_{ft\eta}PC_f/L_f$. Then, we also add the following two linear equations to ensure mathematical legitimacy among the values of variables $\Delta PD_{ft\eta}$, PC_f and $B_{ft\eta}$.

$$PC_f/L_f - U_f(1 - \Delta PD_{ft\eta}) \le B_{ft\eta} \le PC_f/L_f \tag{4.42}$$

$B_{ft\eta} \leq U_f \Delta PD_{ft\eta}$ (4.43)

where, $U_f = \sum_{k=1}^{K_f^C} \left(g_{fk}^C + R_{fk}^C \Delta \overline{q}_{fk}^C \right) / L_f$

To this end, it is clear that the substitutions of $\Delta PD_{ft\eta} q_f / M$ and $\Delta PD_{ft\eta} PC_f / L_f$ by nonnegative variables $A_{ft\eta}$ and $B_{ft\eta}$ respectively, and the addition of constraints represented by linear equations (4.40)-(4.43) elegantly transforms CEPM from a MINLP model into a MILP model. For reference purpose, we denote the linearized CEPM as CEPM-L. Essentially, the latter has objective NPV maximization subject to eqs. (4.2)-(4.20), (4.22)-(4.29), (4.34)-(4.38), (4.40)-(4.43) with $\Delta PD_{ft\eta} q_f / M$ and $\Delta PD_{ft\eta} PC_f / L_f$ replaced by nonnegative variables $A_{ft\eta}$ and $B_{ft\eta}$ respectively.

4.5 Case Study

To illustrate the application potential of CEPM-L as a decision-support model for capacity expansion planning, we apply it to address a realistic CEP of industrial scale. In this problem, an MNC owns a set of four internal facilities (***EIF***={F1,F2,F3,F4}). At the start of planning horizon, the MNC has allocated a budget of \$500 million (in numeraire currency) for all expansion-related activities (CB = 500 M\$). A special task force has been formed to evaluate the possibility of expanding F1 and/or constructing two other new facilities (***FIF***={F5,F6}) to meet the growth forecasts in the global demands of its products over the next five fiscal years (i.e. T=5). The MNC classifies its internal facilities as primary (F2, F3, F4) or secondary (F1, F5, F6). The primary upstream processing facilities may supply raw materials to the secondary downstream facilities (see Figure 4.3 for the material flows among these facilities). Alternatively, the secondary facilities may also purchase its raw materials from external facilities.

Table 4.1 lists the initial capacity (Q_{f0}), capacity limits (Q_f^L, Q_f^U), primary materials [$\pi(f)$], mass balance equations, depreciation charges (ODC_{ft}), values of K_f^C and K_f^D for each facility f ($f \in \boldsymbol{IF}$). The values of parameters which are used to represent the project cost and duration profiles of facilities eligible for expansion or new construction are tabulated in Tables 4.2 and 4.3 respectively. Note that in this case study, we let M =12 to represent the twelve sub-divisions (i.e. months) of each fiscal year t.

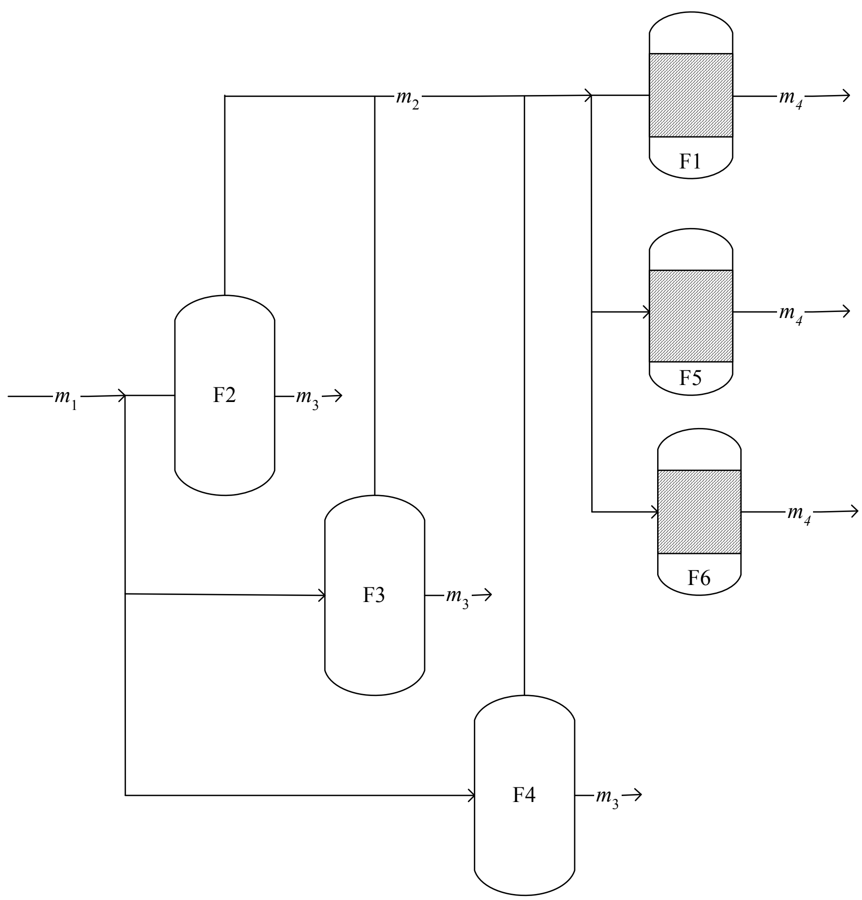


Figure 4.3: Material flow among MNC's internal facilities

Table 4.1: Types, initial capacities (kton/year), capacity limits (kton/year), mass balances, primary materials, annual interest rates, depreciation charges (k$) of MNC's facilities in case study

Facility (f)	Initial Cap. (Q_{f0})	Max Cap. (Q_f^U)	Min Exp. (Q_f^L)	K_f^C	K_f^D	Depreciation Charges (ODC_{ft})
F1	40	50	12	2	3	360.7
F2	50	-	-	-	-	303.2
F3	45	-	-	-	-	403.4
F4	35	-	-	-	-	122.2
F5	0	85	20	3	6	0.0
F6	0	70	15	3	5	0.0

Process mass balances:
F2, F3 and F4: $m_1 = 0.5m_2 + 0.4m_3 + 0.1m_{11}$
F1, F5 and F6: $m_2 = 0.9m_4 + 0.1m_{21}$

F2, F3 and F4 are primary facilities, while all others are secondary. The first product on the right hand side of the mass balance equation represents the primary material $\pi(f)$ of the facility concerned. The annual interest rate (r) is constant at 6% for all facilities. All old depreciation charges (ODC_{ft}) are constant over the entire planning horizon and are expressed in native currency of f.

Table 4.2: Parameters used the project cost profiles where all dollars are in native currency of internal facilities

Parameters	**Facility (*f*)**	***k***		
		1	2	3
$\Delta\bar{q}_{fk}^C$ (kton/year)	F1	20	18	N.A.
	F5	25	25	15
	F6	20	20	15
g_{fk}^C ($)	F1	3,979,859	4,178,316	N.A.
	F5	3,651,445	2,627,763	2,678,574
	F6	1,752,621	4,118,139	2,230,923
R_{fk}^C ($/ton/year)	F1	3522.3	4756.1	N.A.
	F5	3325.1	4535.7	3096.8
	F6	4065.1	4561.4	3131.6

Table 4.3: Parameters used in the project duration profiles

Parameters	**Facility (*f*)**	***k***					
		1	2	3	4	5	6
$\Delta\overline{q}^{D}_{fk}$ (kton/year)	F1	18	12	8	-	-	-
	F5	15	10	10	10	10	10
	F6	15	10	10	10	10	-
g^{D}_{fk} (month)	F1	9	6	4	-	-	-
	F5	8	10	6	6	5	5
	F6	10	10	8	6	6	-

The projected manufacturing costs (MC_{ft}) and the projected upper production outsourcing limits (G^{U}_{ift}) of each internal facility f ($f \in \boldsymbol{IF}$) over next five fiscal years are tabulated in Tables 4.4 and 4.5 respectively. Similarly, the projected exchange rates (ε_{nt}) of the native currency of internal facility f ($f \in \boldsymbol{IF}$) with reference to numeraire currency over the planning horizon are shown in Table 4.6. Based on the duty drawback schemes of country where each internal facility f ($f \in \boldsymbol{IF}$) is located, the values of DR_{if} ($/$ of paid duty) are fixed as shown in Table 4.7. The key external business partners that deal extensively with the MNC are twelve customers (*g*=C1, C2, …, C12) and nine suppliers (*g*=S1, S2, …, S9). Essentially, the internal facilities of the MNC and their key external partners are geographically spread in ten nations (n = N1-N10) around the world as shown in Table 4.8. The corporate tax rates of (TR_{nt}) of the nations where the internal facilities are located and their respective ω_n values are also tabulated in Table 4.8. Lastly, the projected product demands (D_{igt}) of the twelve customers and the capacities (S_{igt}) of the nine suppliers over the planning horizon are shown in Tables 4.9 and 4.10 respectively. Due to the sheer size of other data sets like CIF_{isct}, ID_{isct} P_{isct}, and CO_{ifct}, we are unable to present them all fully in tabular formats. Readers may obtain the full data for this problem by contacting the thesis advisor of the author.

Table 4.4: Manufacturing cost (MC_{ft}) of internal facility *f* in \$/kg of $\pi(f)$ over planning horizon based on native currency of *f*

f	*t*				
	1	2	3	4	5
F1	0.733	0.755	0.778	0.801	0.826
F2	0.687	0.708	0.729	0.751	0.773
F3	1.222	1.259	1.296	1.335	1.375
F4	0.720	0.742	0.764	0.787	0.81
F5	0.58	0.597	0.615	0.634	0.653
F6	0.685	0.706	0.727	0.749	0.771

Table 4.5: Upper limit of outsourcing (G^U_{ift}) of *i* by *f* in kton/year over planning horizon

f	*i*	*t*				
		1	2	3	4	5
F1	m_4	28.0	15.3	14.8	24.7	19.8
F2	m_2	18.4	23.7	18.2	24.7	17.7
F2	m_3	12.4	21.7	19.6	10.0	22.5
F3	m_2	18.5	16.0	10.4	18.9	17.8
F3	m_3	9.9	16.4	19.6	9.5	11.7
F4	m_2	17.2	14.6	17.0	15.0	10.3
F4	m_3	10.8	10.2	13.7	7.2	15.8
F5	m_4	25.5	23.0	34.7	40.5	36.6
F6	m_4	25.7	30.6	25.0	21.4	26.7

Table 4.6: Currency exchange rates (ε_{nt}) which are in units of a numeraire currency per unit of currency of nation *n* respectively over planning horizon

n	*t*					
	0	1	2	3	4	5
N3	1.605	1.671	1.659	1.952	2.061	2.244
N5	1.582	1.630	1.704	1.584	1.782	1.939
N6	1.807	1.780	1.624	1.607	1.408	1.567
N7	1.415	1.375	0.813	0.482	0.565	0.42
N9	0.988	0.963	0.907	0.734	0.595	0.582
N10	1.004	1.008	0.888	0.904	0.764	0.745

Table 4.7: Values of DR_{if} ($/$ of paid duty) based duty drawback schemes of country where f is located

f	i	
	m_1	m_2
F1	-	1.0
F2	0.30	-
F3	0.10	-
F4	0.95	-
F5	-	0.20
F6	-	0.45

Table 4.8: Locations of internal (MNC's own facilities) and external facilities (other suppliers and customers), relevant corporate tax rates and values of ω_n in case study

Nation	**Facilities**			**Corporate Tax Rates**	ω_n
(n)	**Customer**	**Supplier**	**MNC's**	**100*** TR_{nt}	
N1	C1	-	-	-	-
N2	C2	S1	-	-	-
N3	C3	S2	F1	18%	3
N4	C4	S3	-	-	-
N5	C5	S4	F2	40%	3
N6	C6,C11	S5	F5	30%	3
N7	C7	S6	F3	24%	3
N8	C8	S7	-	-	-
N9	C9,C12	S8	F6	26%	3
N10	C10	S9	F4	15%	3

Note: The corporate tax rates are assumed to be constant over the planning horizon.

Table 4.9: Projected product demands (D_{igt}) in kton/year of customer g over planning horizon

i	*t*	*g*											
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
m_2	1	10.3	10.9	10.4	10.1	10.2	10.0	9.8	10.2	10.1	10.2	10.1	10.9
	2	10.3	11.0	10.0	10.3	10.2	10.0	9.6	10.2	10.2	10.3	10.1	10.9
	3	10.2	10.7	10.4	10.3	10.3	10.0	9.7	9.7	10.4	10.5	10.2	10.7
	4	10.4	11.0	10.2	10.0	10.0	9.9	9.9	10.1	10.4	10.3	10.3	10.7
	5	10.1	10.7	10.4	10.3	10.4	9.7	9.8	9.9	10.3	10.4	9.9	10.8
m_3	1	9.7	10.3	9.8	10.1	9.6	10.2	11.2	10.1	10.3	10.2	10.7	10.5
	2	10.0	10.0	9.9	10.1	9.6	10.1	11.1	10.4	10.5	10.2	10.8	10.5
	3	10.0	10.2	10.1	10.0	9.6	10.1	11.1	10.0	10.5	10.2	10.7	10.4
	4	10.1	10.3	10.0	10.1	9.5	10.4	11.1	10.3	10.3	10.0	10.7	10.4
	5	10.1	10.2	10.0	10.2	9.5	10.4	11.1	10.4	10.6	10.0	10.6	10.5
m_4	1	9.5	10.3	10.6	10.0	9.7	11.0	10.8	10.8	10.6	10.9	10.4	10.9
	2	9.5	10.1	10.6	10.2	10.0	10.9	10.8	10.9	10.5	11.1	10.4	10.9
	3	9.5	10.0	10.6	10.3	10.2	10.8	10.9	10.7	10.6	10.7	10.5	11.1
	4	9.5	10.0	10.9	10.4	10.0	11.1	10.7	10.6	10.5	10.6	10.5	11.0
	5	9.3	10.1	10.8	10.0	10.0	11.0	10.9	10.8	10.6	11.1	10.5	11.0

Table 4.10: Production capacities (S_{gt}) in kton/year of supplier g over planning horizon

i	*g*	*t*				
		1	2	3	4	5
m_1	S1	56.0	51.2	55.9	57.8	59.4
	S2	57.9	55.4	50.2	49.3	52.3
	S3	70.0	70.1	68.8	73.3	79.2
	S5	59.2	56.4	58.8	61.7	60.6
	S6	22.0	23.4	23.0	22.8	22.3
	S7	30.1	31.8	31.0	31.8	29.0
	S9	50.4	46.8	45.4	43.2	39.1
m_2	S1	47.0	45.8	44.7	46.2	50.4
	S3	53.5	58.1	59.7	62.1	65.2
	S4	67.3	71.9	73.6	79.0	72.0
	S5	68.5	62.4	61.5	56.1	54.5
	S6	42.8	44.6	47.5	50.0	54.4
	S7	35.5	35.5	32.1	31.8	33.5
	S8	72.0	78.1	71.8	78.0	70.4

We used CPLEX 10.1 within GAMS (Distribution 22.3) running on a Windows XP workstation with a Pentium 4 Xeon (2.8 GHz, 2 GB RAM) processor to solve CEPM-L of the illustrative problem with $\overline{P}_{nt}$ and $\overline{N}_{nt}$ set at 5x10^8, L_f =120 months. The MILP model consists of 3,765 continuous variables, 245 binary variables, 3,632 constraints, and 15,624 nonzeros. CPLEX solved the model in 2.546s and gave a maximum NPV of $4.93 billion. The optimal capacity expansion plan requires a total capital expenditure of $294.5 million (in numeraire currency) and its details are tabulated in Table 4.11. The new annual depreciation charges (ODC_{ft}) of these expanded facilities are listed in Table 4.12. Note that the account of variable expansion duration in CEPM-L has allowed these new depreciation charges to be pro-rated accordingly if the new or added capacity is not available in a full fiscal year. Inevitably, this has enabled the MNC to determine an optimal capacity expansion plan with better accuracy of NPV computation compared to existing models which assumed fixed expansion duration.

Table 4.11: Optimal capacity expansion plan of case study

Facility (*f*)	Expansion volume (kton/year)	Expansion duration (months)	Expansion cost (M$)
F1	30	9	108.1
F5	45	18	156.8
F6	21.9	10	29.5

Table 4.12: New depreciation charges (ODC_{ft}) of expanded facilities in their respective native currencies

Facility	*t*				
(*f*)	1	2	3	4	5
F1	1,684,531	6,738,126	6,738,126	6,738,126	6,738,126
F5	-	4,338,947	8,677,895	8,677,895	8,677,895
F6	497,757	2,986,541	2,986,541	2,986,541	2,986,541

Based on the optimal solution of CEPM-L which also includes the production-distribution plan, three major highlights of the results are observed.

(1) The sales and pre-tax profit of the MNC are projected to increase by more than 89% and 168% respectively over the five-year planning horizon (see Figure 4.4).

(2) Though the MNC pays a total of \$585.2 million of import duties over the horizon, it is able to claim 78% of this expense from the revenue authorities due to the duty drawback schemes which are available to its internal facilities. See Table 4.13 for the fraction of import duties that each internal facility can claim in each fiscal

(3) F3 suffers a net loss of \$38,135 (in currency of N7) at the end of its third year (see Figure 4.5). The optimal solution of CEPM-L proposes this loss to be carried forward to the following year and then deducted accordingly from the pre-tax profit of that year for computation of net tax payable by the facility.

From the above discussion, it is evident that the explicit account of duty drawback and loss carry-forward in CEPM-L has enabled the MNC to harness savings which would otherwise be overlooked if these regulatory factors are accounted adequately in formulation of optimal capacity expansion plan.

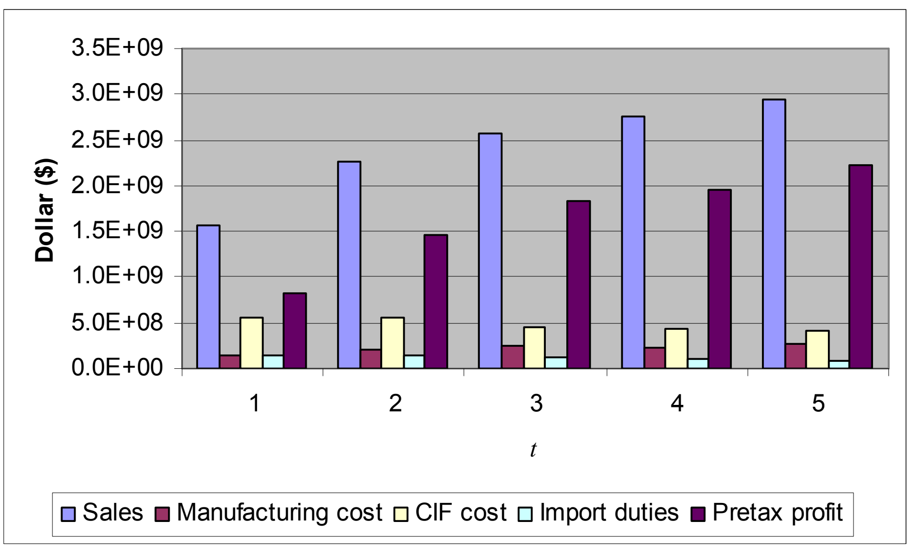


Figure 4.4: Projected annual financial performance of MNC based on optimal solution of case study

Table 4.13: Fraction of import duties claimable by internal facilities due to available duty drawback schemes

Facility	*t*				
(*f*)	1	2	3	4	5
F1	1.0	1.0	1.0	0.07	1.0
F2	0.30	0.30	0.30	0.30	0.30
F3	-	-	-	-	-
F4	0.95	0.95	0.95	0.95	0.95
F5	-	-	-	-	-
F6	-	-	0.45	-	-

Note: "-" indicates no duty is refundable due to null purchase of raw materials from overseas. In the case of F5, there is no import of raw material in the first year because the facility is available for production only in the second half of second year (see Table 4.11)

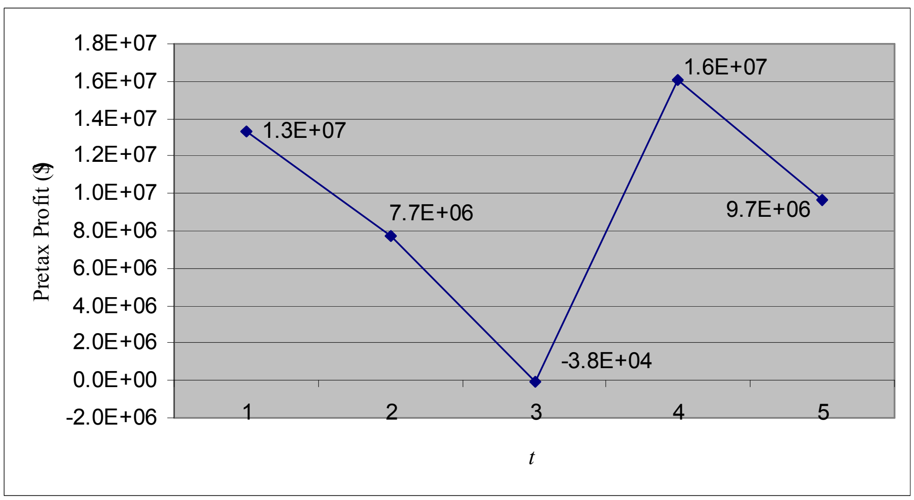


Figure 4.5: Projected pre-tax profit of F3 in its native currency

4.6 Discussion

In this chapter, we presented a novel MINLP model for deterministic capacity expansion planning with account of (1) piecewise linear relationship between expansion duration and expansion volume, and (2) four regulatory factors namely corporate tax, import tariff, duty drawback and loss carry-forward. We also explained how the nonlinearity of the above model can be eliminated through variable substitutions and constraint additions. Given its realistic representation of CEPs faced by companies in the manufacturing industry, the linearized model is clearly an improvement over existing works. It is also extremely relevant in the modern economic era due to the increasingly global nature of manufacturing companies. In addition, our case study of industrial scale has also demonstrated the application potential of our new model as a decision-support tool for capacity expansion planning in the industry.

Despite the contributions of this chapter in the area of capacity expansion planning, ample research opportunities remain available. For example, it is important to note that a deterministic capacity expansion planning approach may not be acceptable to industry practitioners if they wish to account for demand uncertainty. When such uncertainty arises, it warrants the need to evaluate the effect of uncertainty on the tradeoff between excess capacity and unfulfilled customer demand, or between profitability and unfulfilled customer demand. In cases where the variability of a company's financial performance which arises due to uncertainty is of concern to the decision-makers, the latter may also wish to impose financial risk constraints in accordance to their risk appetite. To date, majority of existing models that have been developed to address stochastic CEPs incorporate risk constraints that can correlate quantitatively to the risk-appetite of decision-makers. Inevitably, this has limited the application potential of existing solution methodologies that have been developed to address stochastic CEPs.

In following chapter, we show how our unprecedented deterministic capacity expansion planning model presented in this chapter can be extended to accommodate uncertainty and financial risk constraints that can correlate quantitatively to the risk-appetite of decision-makers. Moreover, we also introduce a novel solution methodology that can solve the extended model of industrial scale.

5. Stochastic Capacity Expansion Problem

Essentially, there are two approaches of addressing a capacity expansion problem (CEP). First, the decision-makers assume all problem parameters which include product demands, prices, freight rates, etc to be fixed and known, and such capacity expansion problem is commonly terms as deterministic. Second, the decision-makers account for the uncertainty in one or more problem parameters in their decision making processes. This uncertainty arises mainly due to inherent dynamic nature of business or market conditions where there are usually product price fluctuations, demand uncertainties, foreign currency exchange variability, etc.

In the literature, there are two main ways of representing the uncertain parameters in stochastic CEP (SCEP). First, an uncertain parameter can be represented by discrete probability density function. Such representation is also known as scenario-based approach and it requires (1) forecasting all possible future outcomes or scenarios of the uncertain parameter, and (2) assignment of occurrence probability to each of these scenarios. Second, an uncertain parameter can also be represented by continuous probability density function. Essentially, all these two uncertainty representations require collation and analysis of market intelligence information as well as business acumen and experience of individuals. Nevertheless, it must be highlighted that each uncertainty representation has its limitations. For example, a SCEP which uses scenario-based approach to represent its uncertainty suffers from "curse of dimensionality" since the number of possible scenarios increases exponentially with the number of uncertain parameters. As such, it may be computationally prohibitive to solve a SCEP of industrial scale where there are a significant number of uncertain parameters. On the other hand, representation of uncertain parameter by continuous probability density function introduces non-linearity to the model formulation. This again makes SCEPs of industrial scale computationally prohibitive to solve.

When uncertainty is represented by discrete or continuous probability density functions, one of the most widely used solution approaches developed for SCEP is two-stage stochastic programming method. In this approach, the decision variables are partitioned into two sets. The first-stage variables correspond to the design or "here-and-now" decisions (i.e. location and size of capacity expansion) that need to be made prior to the realization of uncertain parameters. In contrast, the second-stage variables which are also known as "wait-and-see" or "recourse" decisions are typically made based on the first-stage decisions and upon realization of the uncertain parameters. In capacity expansion planning context, the second-stage variables consist of the operational level decisions like production and distribution planning decisions that have to be made with account of all relevant operational constraints. Clearly, the objective function value of the second-stage problem is stochastic in nature due to presence of uncertainty. As such, the objective function value of the overall problem usually consists of the sum of the first-stage function value and the expected second-stage function value (as commonly known as recourse function). In cases where the variability of the second-stage function value is of concern to the decision-makers, additional risk-related metrics such as the variance of the second-stage function value may also be appended to the overall problem's objective function so as to avoid solutions with large variability of the second-stage function value. To date, the risk-related metrics that have been employed in the literature to limit the variability of the second-stage function value cannot correlate quantitatively to the risk-appetite of decision-makers. Inevitably, this has limited the application potential of existing solution methodologies that have been developed to address SCEPs.

Despite the relatively long history of research in the domain of CEP, there is surprisingly lack of deterministic and stochastic capacity expansion planning models with comprehensive account regulatory factors and realistic representation of relationship between capacity expansion duration and expansion volume. Moreover, there is also lack of risk-control constraints in stochastic capacity expansion planning models that correlate quantitatively to the risk-appetite of decision makers. This chapter aims to fill this research gap in two main ways. First it presents a new model to represent a stochastic capacity expansion problem with comprehensive account of regulatory factors, realistic representation of relationship between capacity expansion duration and expansion volume, and risk-control measures that correlate quantitatively with risk appetite of decision makers. Second, this chapter also introduces a novel solution methodology that can address the new model of industrial size.

5.1 Previous Work

Since the 1960s, SCEPs have attracted extensive interests from researchers. Several solution approaches have evolved over the years to address capacity expansion planning with uncertainty. One solution approach that is widely employed since the early 1990s entails the applications of two-stage stochastic programming framework. Thus, we restrict our review in this section only on works that employ two-stage stochastic programming approach to address SCEPs.

Eppen et al. (1989) were among the earliest adopters of two-stage stochastic programming framework to address SCEP in the automotive industry. They introduce an equivalent MILP model which has discrete representation of demand uncertainty and has the objective of expected profit maximization. To meet stochastic capacity expansion planning needs in semiconductor industry, two-stage stochastic programming approach has also been employed by Karabuk and Wu (2003), and Barahona et al. (2005). The former authors introduce four decentralized planning schemes in their formulation to capture the dynamics of capacity planning process in the industry where manufacturing, marketing managers and senior management share different planning objectives. Their two-stage stochastic programming model allows the senior management to perform impact-analysis under different degree of divisional coordination. Barahona et al. (2005) present a MILP model that is based on two-stage programming framework for capacity planning of an IBM semiconductor manufacturing plant. They also introduce a heuristic based on cutting planes and limited enumeration to solve a two-stage stochastic mixed-integer program which has the objective of minimizing expected value of unmet demand. Recently, Poojari et al. (2008) address a general multi-echelon SCEP where an entire manufacturing supply chain (from material acquisition to delivery of finished products) is considered. The authors employ Benders' decomposition algorithm to solve their two-stage stochastic integer programming model.

Several models have also been developed to address SCEPs in the chemical industry. They include those of Ierapetritou & Pistikopoulos (1994), Liu & Sahinidis (1996), Bok et al. (1998), and Barbaro & Bagajewicz (2004) which primarily aim to address two-stage SCEPs with multiple continuous chemical manufacturing processes. Ierapetritou & Pistikopoulos (1994) introduce a solution methodology that uses Gaussian quadrature scheme to evaluate their expected profit function. In contrast, Liu & Sahinidis (1996), Bok et al. (1998) and Barbaro & Bagajewicz (2004) employ Benders-based decomposition solution approach to address their respective models. To suit the needs of companies with batch chemical manufacturing facilities, Petkov & Maranas (1998) and Maravelias & Grossmann (2001) also present two-stage stochastic programming models of their respective SCEPs. Petkov & Maranas (1998) introduce an equivalent mixed-integer nonlinear programming (MINLP) model for their batch plants which operate in single product campaign mode. The SCEP of Maravelias and Grossmann (2001) entails scheduling of regulatory tests for new products, production and capacity expansion planning of batch plants. The authors introduce an iterative heuristic based on the Lagrangean decomposition to solve their resulting large-scale MILP model. In a recent work, Oh & Karimi (2004) apply the scenario-based planning approach to formulate an equivalent MILP model which is similar to a two-stage stochastic programming framework for a SCEP of a generic petrochemical company. One distinguishing feature of their model is the inclusion of multiple regulatory factors in their formulation.

Among the papers that have been reviewed in this section, three have included risk-control measures in their formulations. Eppen et al. (1989) introduce the concept of expected downside risk which is basically the expected value of shortfall in actual profit from target profit set by the decision-maker (i.e. expected value of {target profit - actual profit}). In their work, the authors keep the downside risk of their capacity expansion plan in check by appending an upper limit constraint on the value of expected downside risk in their formulation. Using a similar approach, Barbaro & Bagajewicz (2004) manage the downside risk of their SCEP by (1) accounting of multiple profit targets, and (2) inclusion of multiple downside risk measures (each being assigned with appropriate weights) in the composite objective function. In contrast, Bok et al. (1998) manage the variability of recourse function by formulating a model with maximizing the following composite function: expected net present value

(ENPV) - the expected square of deviation of NPV – expected square of excess capacity. Now, when a decision-maker is able to state his/her risk appetite explicitly and quantitatively, none of the aforementioned three models can be used directly for capacity expansion decision-making. For example, the decision maker may express the desire to have an optimal capacity expansion plan where the probability of actual profit falling short of a target profit to be less than 0.01 given a probability density function of an uncertain business parameter. The model of Eppen et al. (1989) will not able to meet this requirement since the appropriate upper limit value of the expected downside risk that corresponds to the risk appetite of the decision maker is unknown. Similarly, the models of Bok et al. (1998) and Barbaro & Bagajewicz (2004) will also not able to serve the need of the decision-maker since their solution frameworks manage risk by incorporating risk measures into their respective composite objective functions.

With a good overview of papers that have applied two-stage stochastic programming framework to address SCEPs, it is timely to highlight three limitations of existing literature which inhibit their application for capacity expansion planning purpose by industry practitioners. First, there is apparent lack of stochastic models which comprehensively account for all key regulatory factors. To date, only one model (Oh & Karimi, 2004) has accounted for regulatory factors for capacity expansion planning under uncertainty. Moreover, only two regulatory factors (i.e. import tariff and corporate tax) are accounted for in this model and this somehow limits its application in business environment where other regulatory factors may have significant impact on optimal capacity expansion planning solutions. Second, majority of existing models that have been developed to address SCEPs assume a fixed capacity expansion duration that is independent of expansion volume. To the best of the author’s knowledge, most of these models do not realistically account for either the relationship between capacity expansion duration and expansion volume or impact of depreciation charges of newly installed capacities based on their respective availability on the bottom line performance of the corporate organizations involved. Inevitably, omission of this relationship again limits the application of existing models and methodologies in capacity planning. This is especially true in the chemical industry where there is significant expansion construction duration before new capacity becomes available for production and this duration generally increases with the volume of new capacity. Third, most of the existing models do not incorporate risk-control measures that can relate quantitatively with the risk appetite of decision-makers. Recall that uncertainty results in variability of the second-stage or recourse function in a two-stage stochastic programming framework. From a capacity expansion planning decision-maker's standpoint, it is prudent to impose restriction on this variability according to the amount of risk that a decision-maker is willing to stomach.

This completes our review of past work on the SCEPs. In the following section, we introduce a risk metric which is widely employed in the industry. Besides explaining the key underlying concepts of this metric, we also highlight its importance in risk management in capacity planning context.

5.2 What is Value-at-Risk?

Value-at-Risk (VAR) is a statistical measure of possible losses from a business venture or investment. According to Linsmeier & Pearson (2000), VAR is the loss that is expected to be exceeded with a probability of pre-specified x percent over a given planning horizon. For example, if x is 3% and the profit/loss (Z) distribution of a business investment project over a planning horizon of concern is as shown in Figure 5.1, then the VAR for this project is -$30M. It is also important to note that the choice of *x* value and/or planning horizon length has direct impact on the VAR value. Thus, there must be common bases in terms of *x* value and length of planning horizon before any comparison can be made between VAR values of different decisions in any capital investment project.

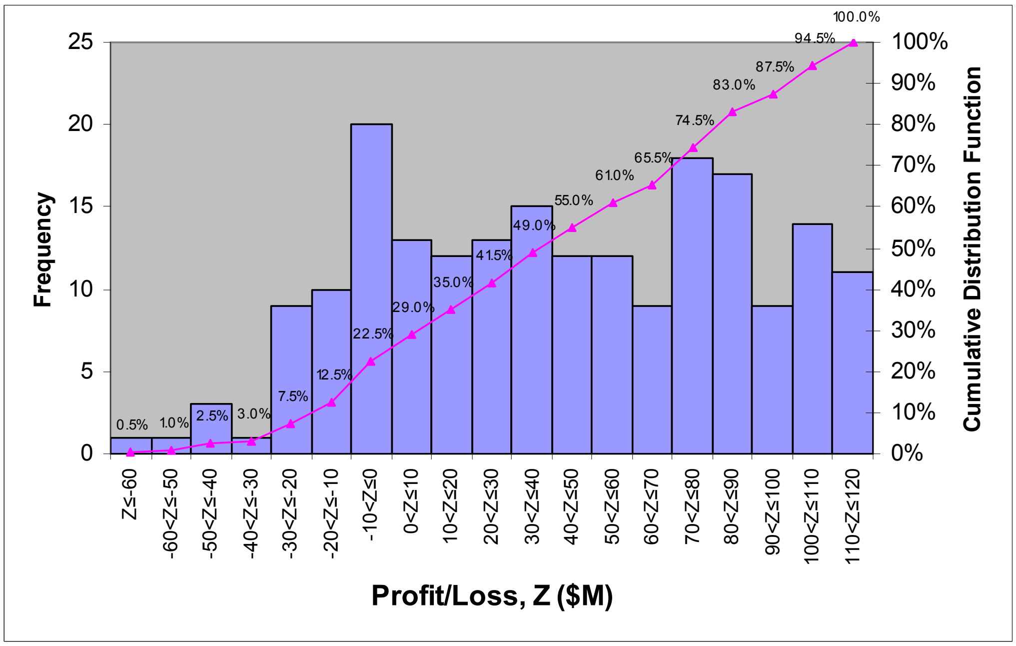


Figure 5.1: Profit/Loss distribution for VAR illustration

The concept and application of VAR is fairly new. It was only in the late 1980s that major financial firms began to employ VAR as a metric to measure the risks of their trading portfolios. Since then, the use of VAR has received widespread acceptance by financial institutions, nonfinancial corporations, institutional investors, and even regulatory agencies. These agencies include the Basle Committee on Banking Supervision and U.S. Securities and Exchange Commission. The former permits banks to calculate their capital requirements for market risk using their own proprietary VAR models. On the other hand, the U.S. Securities and Exchange

Commission requires the U.S. companies to disclose quantitative measures of market risks and it has listed VAR as one of three possible disclosure methods.

Undoubtedly, VAR has brought transparency to market risk. Its popularity in the industry arises mainly due to three main reasons. First, VAR is a simple and easy-to-compute metric that can correlate quantitatively to risk appetite of any decision-maker. Second, VAR is asymmetric measure that reflects the loss of an investment project that is to be exceeded at a given confidence level (i.e. x percent). It is independent of the project yield performance at confidence level above x. This clearly suits the risk-control needs of decision-makers who are concerned about managing the downside risk of their investments. Third, incorporation of VAR measure in an optimization framework does not contribute to non-linearity to the overall formulation. This is an attractive attribute from programming standpoint as it prevents the resulting model from becoming too computationally prohibitive to solve. Despite of its strengths as a risk-control measure, VAR does have its weaknesses. For example, VAR does not indicate the expected size of losses if the yield of an investment does fall below VAR. In addition, VAR lacks the sub-activity property such that VAR of a portfolio with two instruments may not be the sum of individual VARs of these two instruments. Nevertheless, VAR remains a popular risk metric in the industry as the benefits of VAR as a risk measure far exceed the computational inconvenience caused by its undesirable properties. In an optimization framework, VAR can be used in two ways. The decision-maker may append a constraint on the VAR in the overall formulation which aims to maximize the expected return. Alternatively, the decision-maker may employ a formulation which aims to maximize VAR while a lower limit is imposed on the expected return.

5.3. Problem Description

In this chapter, we consider a SCEP which is fundamentally similar to the CEP that is addressed in the preceding chapter. Instead of duplicating the problem description that is already available in the latter chapter, we discuss only in this section the two features that distinguish our SCEP from the earlier CEP.

5.3.1 Problem Uncertainty

The SCEP to be addressed in this chapter is basically a stochastic version of the earlier CEP. Every uncertain parameter (e.g. demand, price, etc) of our SCEP is represented by a discrete probability density function that has *NS* (discrete) number of scenarios and each of these scenarios χ ($1 \leq \chi \leq NS$) has a known probability of occurrence (ψ_{χ}). The objective of our SCEP entails maximization of the expected NPV (ENPV) of the company's net cash flows over the planning horizon over all possible scenarios (χ = 1, 2, …, *NS*) of the stochastic parameters.

5.3.2 Risk-Control Measures

To cope with variability of the problem's objective function attributed to problem uncertainty, the decision-makers involved in our SCEP impose risk-control constraints based on underlying concepts of VAR in accordance to industry practice. They aim to determine a capacity expansion plan that not only maximizes the ENPV of the company's net cash flows over the planning horizon. They have a target NPV of the company's net cash flows over the planning horizon (denoted by v) and they want a capacity expansion plan where the probability of profit falling below or equal to v be kept less than or equal to κ.

5.4 Model Formulation

With a good overview of the SCEP to be addressed in this chapter and an understanding of its similarity with the earlier CEP addressed in the preceding chapter, it is clear that the variables and equations needed to formulate our SCEP will also be similar to those employed in model formulation of earlier CEP (i.e. CEPM-L). As such, variables and equations of SCEP which are equal or similar to those employed in CEPM-L would not be introduced and derived again to avoid duplication. Instead, we would only cite these variables and equations in this section. In contrast, variables and equations which are only necessary for formulation of our SCEP but not in CEPM-L would be discussed in greater details. Unless stated otherwise, the notation used in this chapter is same as those in the preceding chapter, and the indexes (*f*, *t*, *i*, *k*, etc.) assume their full ranges of values.

5.4.1 Extension of CEPM-L

Essentially, all variables and equations that employed in CEPM-L are required in the formulation of our SCEP. However, there are two types of decision variables in our SCEP. First, there are decision variables that need to fixed (i.e. assigned with values) prior to the realization of uncertain parameters. These decision variables are also commonly known as first-stage decision variables. Second, there are decision variables whose optimal values are dependent only on the scenarios of uncertain parameters after first-stage decision variables are known. The first-stage decision variables of our SCEP consist of capacity expansion related decisions and they include q_f, y_f, Δq^{C}_{fk}, Δq^{D}_{fk}, PC_f, h^{C}_{fk}, h^{D}_{fk}, $\Delta PD_{ft\eta}$, $A_{ft\eta}$, $B_{ft\eta}$ while the rest of the variables in CEPM-L are scenario-dependent decision variables. Since the optimal values of scenario-dependent decision variables of our SCEP can be determined simultaneously after the first-stage decision variables are fixed, the former variables are also known as second-stage variables. To distinguish their differences in values in different scenarios, we assign superscript χ to all second-stage decision variables in the formulation of SCEP and they consist of X^{χ}_{ft}, F^{χ}_{ifct}, F^{χ}_{isft}, G^{χ}_{ifgt}, W^{χ}_{ijsft}, PE^{χ}_{nt}, NE^{χ}_{nt}, YP^{χ}_{nt}, $CFL^{\chi}_{ntt'}$, TIP^{χ}_{nt} (see the nomenclature to recall the definitions of these variables). Thus, we have the following objective function, first-stage and second-stage equations which are based on formulation of CEPM-L to model our SCEP.

a) Objective function

$$\max \text{ENPV} = \sum_{\chi \le NS} \psi_{\chi} \left[\sum_{f \in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i \in \boldsymbol{OM}_f} \sum_{c \ni i \in \boldsymbol{IM}_c} e^{\chi}_{ft} P^{\chi}_{ifct} (F^{\chi}_{ifct} + G^{\chi}_{ifct}) - e^{\chi}_{ft} MC_{ft} X^{\chi}_{ft}}{(1+r)^t} - \right.$$

$$\sum_{f \in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i \in \boldsymbol{IM}_f} \sum_{s \ni i \in \boldsymbol{OM}_s} e^{\chi}_{ft} (1 + ID_{isft}) CIF^{\chi}_{isft} F^{\chi}_{isft} - \sum_{i \in \boldsymbol{OM}_f} \sum_{c \ni i \in \boldsymbol{IM}_c} e^{\chi}_{ft} G^{\chi}_{ifct} CO^{\chi}_{ifct}}{(1+r)^t} +$$

$$\sum_{f \in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i \in \boldsymbol{IM}_f} \sum_{j \in \boldsymbol{OM}_f} \sum_{s \ni i \in \boldsymbol{OM}_s} e^{\chi}_{ft} W^{\chi}_{ijsft} CIF^{\chi}_{isft} ID_{isft} RV^{\chi}_{jft} DR_{if}}{(1+r)^t} -$$

$$\left. \sum_{n} \sum_{t} \frac{\varepsilon^{\chi}_{nt} TIP^{\chi}_{nt} TR_{nt}}{(1+r)^t} \right] - \sum_{f \in \boldsymbol{IF}} e_{f0} PC_f \tag{5.1}$$

b) First-stage equations

$$q_f = Q^L_f y_f + \sum_{k=1}^{K^C_f} \Delta q^C_{fk} \qquad f \in \boldsymbol{IF} \tag{5.2}$$

$$\sum_{k=1}^{K_f^C} \Delta q_{fk}^C \le y_f (Q_f^U - Q_{f0} - Q_f^L) \quad f \in \boldsymbol{IF} \tag{5.3}$$

$$PC_f = g_{f1}^C y_f + R_{f1}^C \Delta q_{f1}^C + \sum_{k=2}^{K_f^C} \left(g_{fk}^C h_{fk}^C + R_{fk}^C \Delta q_{fk}^C \right) \qquad f \in \boldsymbol{IF} \tag{5.4}$$

$$\Delta q_{fk}^C \le \Delta \overline{q}_{fk}^C h_{fk}^C \quad f \in \boldsymbol{IF},\ 2 \le k \le K_f^C \tag{5.5}$$

$$\Delta q_{f1}^C \le \Delta \overline{q}_{f1}^C y_f \qquad f \in \boldsymbol{IF} \tag{5.6}$$

$$h_{fk}^C \le h_{fk-1}^C \qquad f \in \boldsymbol{IF},\ 3 \le k \le K_f^C \tag{5.7}$$

$$h_{f2}^C \le y_f \qquad f \in \boldsymbol{IF} \tag{5.8}$$

$$\Delta q_{f(k-1)}^C \ge \Delta \overline{q}_{f(k-1)}^C h_{fk}^C \qquad f \in \boldsymbol{IF},\ 2 \le k \le K_f^C \tag{5.9}$$

$$\sum_{f \in \boldsymbol{IF}} PC_f e_{f0} \le CB \tag{5.10}$$

$$\Delta q_{fk}^D \le \Delta \overline{q}_{fk}^D h_{fk}^D \qquad f \in \boldsymbol{IF}, 2 \le k \le K_f^D \tag{5.11}$$

$$\Delta q_{f1}^D \le \Delta \overline{q}_{f1}^D y_f \qquad f \in \boldsymbol{IF} \tag{5.12}$$

$$h_{fk}^D \le h_{fk-1}^D \qquad f \in \boldsymbol{IF},\ 3 \le k \le K_f^D \tag{5.13}$$

$$h^D_{f2} \le y_f \qquad f \in \boldsymbol{IF} \tag{5.14}$$

$$\Delta q^D_{f(k-1)} \ge \Delta \bar{q}^D_{f(k-1)} h^D_{fk} \quad f \in \boldsymbol{IF},\ 2 \le k \le K^D_f \tag{5.15}$$

$$\sum_{k=1}^{K^D_f} \Delta q^D_{fk} = \sum_{k=1}^{K^C_f} \Delta q^C_{fk} \qquad f \in \boldsymbol{IF} \tag{5.16}$$

$$g^D_{f1} y_f + \sum_{k=2}^{K^D_f} g^D_{fk} h^D_{fk} = \sum_{t=1}^{T} \sum_{\eta=1}^{M} \Delta PD_{ft\eta} \qquad f \in \boldsymbol{IF} \tag{5.17}$$

$$\Delta PD_{ft1} \le \Delta PD_{f(t-1)M} \qquad f \in \boldsymbol{IF},\ 2 \le t \le T \tag{5.18}$$

$$\Delta PD_{ft\eta} \le \Delta PD_{ft(\eta-1)} \qquad f \in \boldsymbol{IF},\ 2 \le \eta \le M \tag{5.19}$$

$$q_f/M - V_f(1 - \Delta PD_{ft\eta}) \le A_{ft\eta} \le q_f/M \qquad f \in \boldsymbol{IF} \tag{5.20}$$

$$A_{ft\eta} \le V_f \Delta PD_{ft\eta} \qquad f \in \boldsymbol{IF} \tag{5.21}$$

$$PC_f/L_f - U_f(1 - \Delta PD_{ft\eta}) \le B_{ft\eta} \le PC_f/L_f \tag{5.22}$$

$$B_{ft\eta} \le U_f \Delta PD_{ft\eta} \tag{5.23}$$

c) Second-stage equations

$$X_{ft}^{\chi} \le \sum_{\eta=1}^{M} \left(\frac{(Q_{f0} + q_f)}{M} - A_{ft\eta} \right) \qquad f \in \boldsymbol{IF} \qquad (5.24)$$

$$\sigma_{if} X_{ft}^{\chi} = \sigma_{\pi(f)f} \left(\sum_{c \ni i \in \boldsymbol{IM}_c} F_{ifct}^{\chi} + \sum_{s \ni i \in \boldsymbol{OM}_s} F_{isft}^{\chi} \right) \qquad f \in \boldsymbol{IF},\, i \in \boldsymbol{OM}_f \cup \boldsymbol{IM}_f \qquad (5.25)$$

$$\sum_{f \in \boldsymbol{IF} \ni i \in \boldsymbol{OM}_f} (F_{ifgt}^{\chi} + G_{ifgt}^{\chi}) + \sum_{f \in \boldsymbol{IF} \ni i \in \boldsymbol{IM}_f} F_{igft}^{\chi} \le D_{igt}^{\chi} + S_{igt} \qquad g \in \boldsymbol{EF},\, i \in \boldsymbol{OM}_g \cup \boldsymbol{IM}_g \qquad (5.26)$$

$$\sum_{g \in \boldsymbol{EF} \ni i \in \boldsymbol{IM}_g} G_{ifgt}^{\chi} \le G_{ift}^{U} \qquad f \in \boldsymbol{EIF},\, i \in \boldsymbol{OM}_f \qquad (5.27)$$

$$\sum_{g \in \boldsymbol{EF} \ni i \in \boldsymbol{IM}_g} G_{ifgt}^{\chi} \le G_{ift}^{U} (M - \sum_{\eta=1}^{M} \Delta PD_{ft\eta}) / M \qquad f \in \boldsymbol{FIF},\, i \in \boldsymbol{OM}_f \qquad (5.28)$$

$$\sum_{g \in \boldsymbol{EF} \ni i \in \boldsymbol{IM}_g} G_{ifgt}^{\chi} \le G_{ift}^{U} y_f \qquad f \in \boldsymbol{FIF},\, i \in \boldsymbol{OM}_f \qquad (5.29)$$

$$W_{ijsft}^{\chi} \le F_{isft}^{\chi} \qquad f \in \boldsymbol{IF} \cap \boldsymbol{F}_n, s \in \boldsymbol{F}_n^{'}, i \in \boldsymbol{OM}_s \cup \boldsymbol{IM}_f, j \in \boldsymbol{OM}_f \qquad (5.30)$$

$$\sum_{s \in \boldsymbol{F}_n' \ni i \in \boldsymbol{OM}_s} W_{ijsft}^{\chi} \le \frac{\sigma_{if}}{\sigma_{jf}} \sum_{c \in \boldsymbol{F}_n' \ni j \in \boldsymbol{IM}_c} F_{jfct}^{\chi} \qquad f \in \boldsymbol{IF} \cap \boldsymbol{F}_n, i \in \boldsymbol{OM}_s \cup \boldsymbol{IM}_f, j \in \boldsymbol{OM}_f \qquad (5.31)$$

$$PE_{nt}^{\chi} - NE_{nt}^{\chi} = \sum_{f \in \boldsymbol{IF} \cap \boldsymbol{F}_n} \left[\sum_{i \in \boldsymbol{OM}_f} \sum_{c \ni i \in \boldsymbol{IM}_c} P_{ifct}^{\chi} (F_{ifct}^{\chi} + G_{ifct}^{\chi}) - \sum_{i \in \boldsymbol{IM}_f} \sum_{s \ni i \in \boldsymbol{OM}_s} (1 + ID_{isft}) CIF_{isft}^{\chi} F_{isft}^{\chi} + \right.$$

$$\sum_{i\in \boldsymbol{IM}_f}\sum_{j\in \boldsymbol{OM}_f}\sum_{s\in \boldsymbol{F}_n^{'} \ni i\in \boldsymbol{OM}_s} W_{ijsft}^{\chi} CIF_{isft}^{\chi} ID_{isft} RV_{jft}^{\chi} DR_{if} - \sum_{i\in \boldsymbol{OM}_f}\sum_{c\ni i\in \boldsymbol{IM}_c} G_{ifct}^{\chi} CO_{ifct}^{\chi} -$$

$$\left. MC_{ft} X_{ft}^{\chi} - ODC_{ft} - \sum_{\eta=1}^{M} (PC_f / L_f - B_{ft\eta}) \right] \tag{5.32}$$

$$PE_{nt}^{\chi} \le YP_{nt}^{\chi} \overline{P}_{nt} \tag{5.33}$$

$$NE_{nt}^{\chi} \le (1 - YP_{nt}^{\chi}) \overline{N}_{nt} \tag{5.34}$$

$$NE_{nt}^{\chi} \ge \sum_{t'=t+1}^{t+\omega_n} CFL_{ntt'}^{\chi} \tag{5.35}$$

$$TIP_{nt}^{\chi} \ge PE_{nt}^{\chi} - \sum_{t'<t} CFL_{nt't}^{\chi} \tag{5.36}$$

5.4.2 Other Variables and Equations

In addition to the above equations which are based on equations of CEPM-L, we need other variables and equations to model the risk-control constraints imposed by the MNC as described in section 5.3.2. To do so, we introduce the following binary variable.

$$Z^{\chi} = \begin{cases} 1 & \text{if NPV of MNC in } \chi \le \upsilon \\ 0 & \text{otherwise} \end{cases}$$

If ρ denotes the maximum possible return that the MNC can earn over the planning horizon, then the definition of binary variable Z^{χ} can be enforced by the following two equations.

$$\left(\sum_{f\in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i\in \boldsymbol{OM}_f} \sum_{c\ni i\in \boldsymbol{IM}_c} e^{\chi}_{ft} P^{\chi}_{ifct} (F^{\chi}_{ifct} + G^{\chi}_{ifct}) - e^{\chi}_{ft} MC_{ft} X^{\chi}_{ft}}{(1+r)^t} - \right.$$

$$\sum_{f\in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i\in \boldsymbol{IM}_f} \sum_{s\ni i\in \boldsymbol{OM}_s} e^{\chi}_{ft} (1+ID_{isft}) CIF^{\chi}_{isft} F^{\chi}_{isft} - \sum_{i\in \boldsymbol{OM}_f} \sum_{c\ni i\in \boldsymbol{IM}_c} e^{\chi}_{ft} G^{\chi}_{ifct} CO^{\chi}_{ifct}}{(1+r)^t} +$$

$$\sum_{f\in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i\in \boldsymbol{IM}_f} \sum_{j\in \boldsymbol{OM}_f} \sum_{s\ni i\in \boldsymbol{OM}_s} e^{\chi}_{ft} W^{\chi}_{ijsft} CIF^{\chi}_{isft} ID_{isft} RV^{\chi}_{jft} DR_{if}}{(1+r)^t} -$$

$$\left. \left. \sum_{n} \sum_{t} \frac{\varepsilon^{\chi}_{nt} TIP^{\chi}_{nt} TR_{nt}}{(1+r)^t} \right] - \sum_{f\in \boldsymbol{IF}} e_{f0} PC_f \right) - \upsilon \le \rho (1 - Z^{\chi}) \qquad (5.37)$$

$$\upsilon - \left(\sum_{f\in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i\in \boldsymbol{OM}_f} \sum_{c\ni i\in \boldsymbol{IM}_c} e^{\chi}_{ft} P^{\chi}_{ifct} (F^{\chi}_{ifct} + G^{\chi}_{ifct}) - e^{\chi}_{ft} MC_{ft} X^{\chi}_{ft}}{(1+r)^t} - \right.$$

$$\sum_{f\in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i\in \boldsymbol{IM}_f} \sum_{s\ni i\in \boldsymbol{OM}_s} e^{\chi}_{ft} (1+ID_{isft}) CIF^{\chi}_{isft} F^{\chi}_{isft} - \sum_{i\in \boldsymbol{OM}_f} \sum_{c\ni i\in \boldsymbol{IM}_c} e^{\chi}_{ft} G^{\chi}_{ifct} CO^{\chi}_{ifct}}{(1+r)^t} +$$

$$\sum_{f\in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i\in \boldsymbol{IM}_f} \sum_{j\in \boldsymbol{OM}_f} \sum_{s\ni i\in \boldsymbol{OM}_s} e^{\chi}_{ft} W^{\chi}_{ijsft} CIF^{\chi}_{isft} ID_{isft} RV^{\chi}_{jft} DR_{if}}{(1+r)^t} -$$

$$\left. \left. \sum_{n} \sum_{t} \frac{\varepsilon^{\chi}_{nt} TIP^{\chi}_{nt} TR_{nt}}{(1+r)^t} \right] - \sum_{f\in \boldsymbol{IF}} e_{f0} PC_f \right) \le \rho Z^{\chi} \qquad (5.38)$$

Essentially, risk-control constraints are required to impose an upper limit on the total number of scenarios with NPV of the MNC falling below or equal to v and this upper limit equals $\kappa^* NS$. Thus, we have,

$$\sum_{\chi \le NS} Z^{\chi} \le \kappa^* NS \qquad (5.39)$$

This completes our formulation for the SCEP with account of corporate tax, import tariff, duty drawback, loss carry-forward, and risk-control constraints. We name this model SCEPM and it comprises maximizing expected NPV (5.1) subject to eqs. (5.2)-(5.39). In two-stage programming framework, the first-stage problem of our SCEP entails q_f, y_f, Δq_{fk}^{C} , Δq_{fk}^{D} , PC_f, h_{fk}^{C} , h_{fk}^{D} , $\Delta PD_{ft\eta}$, $A_{ft\eta}$, $B_{ft\eta}$ as variables and equations (5.2)-(5.23) as constraints. The second-stage variables consist of $X_{ft}^{\chi}, F_{ifct}^{\chi}, F_{isft}^{\chi}, G_{ifgt}^{\chi}, W_{ijsft}^{\chi}, PE_{nt}^{\chi}, NE_{nt}^{\chi}, YP_{nt}^{\chi}, CFL_{ntt'}^{\chi}$, $TIP_{nt}^{\chi}, Z^{\chi}$ while the corresponding second-stage constraints are (5.24)-(5.39).

5.5 Problem Complexity

Specifically, SCEPM is a two-stage stochastic mixed-integer programming (2SSMIP) problem where both first and second-stage decision variables are mixed integer. 2SSMIP model is complex and difficult to solve. This is primarily due to the presence of binary variables in the second-stage problems which make the second-stage value functions to be lower semicontinuous with respect to the first-stage variables. As such, each of the objective expressions of second-stage problems is a non-convex function of the first-stage variables. For many years, there is dearth of solution methodologies that can address 2SSMIP models efficiently. It is only over the last decade that researchers begin to involve more actively in this domain. As such, there are only a few papers in the literature that address 2SSMIP models. Both Carøe and Schultz (1999), and Sherali and Zhu (2006) introduce solution approaches that both involve scenario-based decomposition and a branch and bound framework. Recently, Till et al. (2007) present a heuristic that iterates between evolutionary algorithmic search of the first-stage variables and solving of second-stage MIP problems by a standard solver (CPLEX).

However, it is not feasible to apply any of the aforementioned solution methodologies to solve our SCEPM in this project. This is primarily attributed to the presence of risk-control constraints as represented by equations (5.37) to (5.39) in SCEPM. Essentially, these risk-control constraints impose restriction on solutions of second-stage problems in all scenarios through its limit on the total number of scenarios where the NPV of MNC can fall below or equal to v. As such, the second-stage problems cannot be decomposed based on scenarios as in the solution frameworks of both Carøe & Schultz (1999) and Sherali & Zhu (2006). Moreover, the solution approach of Till et al. (2007) is also not practical to solve our SCEPM since it requires solving of all second-stage problems in all scenarios to optimality for every set of first-stage decisions derived by evolutionary search. As such, the feasibility of any first-stage decisions can only be known after solutions of all second-stage problems in all scenarios are available. This is undesirable because it requires excessive computational resources to search for feasible first-stage decisions that can abide the risk-control constraints, especially when the number of scenarios involved is large and/or risk-control constraints are tight. Unless cuts can be systematically generated to eliminate the infeasible solution space of first-stage problem, it is not computationally efficient to apply the heuristic of Till et al. (2007) to address our SCEPM.

5.6 Illustrative Example

To illustrate the enormous computational memory requirement to solve SCEPM as an equivalent MILP, we address a realistic SCEP using CPLEX. Essentially, this problem is similar to the case study described in the preceding chapter in terms of problem details and parameters. The key difference between these two problems lies in the presence of demand uncertainty of the former problem. The forecasting department of the MNC has projected 700 possible scenarios (i.e. *NS*=700) of product demands (D_{igt}^{χ}) over the given planning horizon. The management of the expansion project team has set the v and κ values to be \$2x10^9 (in numeraire currency) and 0.01 respectively. The readers may refer to the problem parameters presented in the case study of preceding chapter for an overview on the scale of problem involved in this chapter. Alternatively, they may obtain the full data of this problem by contacting the thesis advisor of the author.

We used CPLEX 10.1 within GAMS (Distribution 22.3) running on a Windows XP workstation with a Pentium 4 Xeon (2.8 GHz, 2 GB RAM) processor to solve the equivalent large scale MILP model of the illustrative problem. The equivalent MILP model consists of 1,971,450 continuous variables, 21,915 binary variables, 704,033 constraints, and 9,329,670 nonzeros. Unfortunately, CPLEX terminated its algorithmic search process prior to the start of iteration log due to out of memory. From this simple illustrative example, it is clear that enormous computational memory to solve SCEPM of industrial scale as an equivalent MILP model. The result also highlights the practical need to develop an alternative solution approach that can solve SCEPM efficiently without exhausting excessive computational memory resources.

5.7 Novel Solution Procedure

Solving SCEPM as an equivalent MILP model is a viable option only if (1) there is a small number of dominant scenarios in the problem and (2) solving an equivalent MILP model with account of only these dominant scenarios yields a solution which is similar to the case when all scenarios are accounted for. It is based this underlying principle that we develop a novel and efficient solution methodology that can address our SCEPM of industrial scale. Basically, this new methodology entails selection of *characteristic* scenarios, identification of *critical lower tail-end* scenarios, and solving of an equivalent MILP with account of only the aforementioned scenarios. We now define the features of characteristic and critical lower tail-end scenarios before we present in details the algorithmic procedure involved.

5.7.1 Characteristic Scenarios

Without the risk-control constraints represented by equations (5.37) to (5.39), the problem structure of SCEPM is a classic 2SSMIP model that has been addressed by Carøe & Schultz (1999), Sherali & Zhu (2006) and Till et al. (2007) where there is no restriction on solutions of second-stage problems in all scenarios. We denote this scaled-down version of SCEPM as SCEPM-SD. In this chapter, characteristic scenarios are defined as dominant scenarios that have significantly more influence on the optimal solution of a SCEPM-SD than other scenarios so that solving an equivalent MILP model of SCEPM-SD with account of only characteristic scenarios yields optimal decision variables which are equal or similar to that of an equivalent MILP model of SCEPM-SD which is solved with account of all scenarios. We label these two equivalent MILP models with selected characteristic scenarios and all scenarios as EMIP-S and EMIP-A respectively. Note that objective function of EMIP-S is similar to equation (5.1) except that former has summation over characteristic scenarios (instead of all scenarios) and these characteristic scenarios assumes equal probability of occurrence. Thus, if ***C*** denotes the set of characteristic scenarios, then the objective function of EMIP-S is as follows.

$$\text{ENPV} = \sum_{\chi\in \boldsymbol{C}} \frac{1}{|\boldsymbol{C}|}\left[\sum_{f\in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i\in \boldsymbol{OM}_f} \sum_{c\ni i\in \boldsymbol{IM}_c} e_{ft}^{\chi} P_{ifct}^{\chi} (F_{ifct}^{\chi} + G_{ifct}^{\chi}) - e_{ft}^{\chi} MC_{ft} X_{ft}^{\chi}}{(1+r)^t} - \right.$$

$$\sum_{f\in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i\in \boldsymbol{IM}_f} \sum_{s\ni i\in \boldsymbol{OM}_s} e_{ft}^{\chi} (1+ID_{isft}) CIF_{isft}^{\chi} F_{isft}^{\chi} - \sum_{i\in \boldsymbol{OM}_f} \sum_{c\ni i\in \boldsymbol{IM}_c} e_{ft}^{\chi} G_{ifct}^{\chi} CO_{ifct}^{\chi}}{(1+r)^t} +$$

$$\sum_{f\in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i\in IM_f} \sum_{j\in OM_f} \sum_{s\ni i\in OM_s} e_{ft}^{\chi} W_{ijsft}^{\chi} CIF_{isft}^{\chi} ID_{isft} RV_{jft}^{\chi} DR_{if}}{(1+r)^t} -$$

$$\left. \sum_{n} \sum_{t} \frac{\varepsilon_{nt}^{\chi} TIP_{nt}^{\chi} TR_{nt}}{(1+r)^t} \right] - \sum_{f\in \boldsymbol{IF}} e_{f0} PC_f \qquad (5.40)$$

Moreover, the constraints represented by eqs. (5.24)-(5.36) which are defined over all possible scenarios in SCEPM and EMIP-A are valid only over $\chi \in \boldsymbol{C}$ in EMIP-S.

Essentially, the collection of characteristic scenarios should constitute only a small subset of all possible scenarios in the original problem so that the memory requirement of solving EMIP-S is significantly lesser than that of EMIP-A. Later in this chapter, we introduce a model that can be employed for selection of characteristic scenarios. We also show through our case studies that a good linear correlation ($Z_A = f(Z_S)$) can be established between the optimal objective values of EMIP-S and EMIP-A which we denote as Z_S and Z_A respectively. Basically, this linear co-relationship permits projection of actual objective function value (i.e. Z_A) based the solution of EMIP-S.

5.7.2 Critical Lower Tail-End Scenarios

In financial risk assessments that use VAR, the probability *x* are typically assigned with values of 1, 2.5 and 5 percent (Linsmeier and Pearson, 2000). Correspondingly, κ are to be assigned as 0.01, 0.025 and 0.05 respectively. As such, one can establish the conformance of any first-stage solution to the risk-control constraints described by equations (5.37) to (5.39) via solving only second-stage problems in scenarios that contribute to the lower tail-end of a profit/loss distribution (such as the one shown in Figure 5.1). We define this collection of scenarios as critical lower tail-end (CLT) scenarios and their set is represented by ***S***. Basically, there are two groups of CLT scenarios in ***S***. First, there are CLT scenarios which consistently remain in the ***S*** regardless of the strategic investment decisions (i.e. first-stage decisions) that are made prior to the realization of uncertain parameters. This is because such scenarios are usually associated with unfavorable business circumstances which consistently yield poorer results compared to those of other scenarios. In capacity expansion planning context, these lower tail-end scenarios exhibit traits like poor demands, low end-product prices, high raw material costs, etc. Inevitably, these scenarios tend to contribute to the lower tail-end of the NPV distribution of a MNC no matter what expansion planning decisions are made. On the other hand, there are CLT scenarios whose memberships in ***S*** are dependent on first-stage solutions or strategic investment decisions. Such scenarios are usually marginally unfavorable business conditions which may yield good or bad returns, depending strongly on the strategic investment decisions made.

Clearly, in order to establish the conformance of any first-stage solution to the risk-control constraints, it is only necessary to account for the aforementioned two types of CLT scenarios instead of all scenarios in the formulation of SCEPM. Thus, if a systematic way of identifying the CLT scenarios can be established as shown later in this chapter, the risk-control constraints can be compactly expressed with significantly fewer equations. Specifically, the alternative formulation has equations (5.37) and (5.38) being valid only for $\chi \in \boldsymbol{S}$, and equation (5.39) is replaced by

$$\sum_{\chi \in \boldsymbol{S}} (1 - Z^{\chi}) \leq \kappa * NS \tag{5.41}$$

5.7.3 Algorithmic Procedure

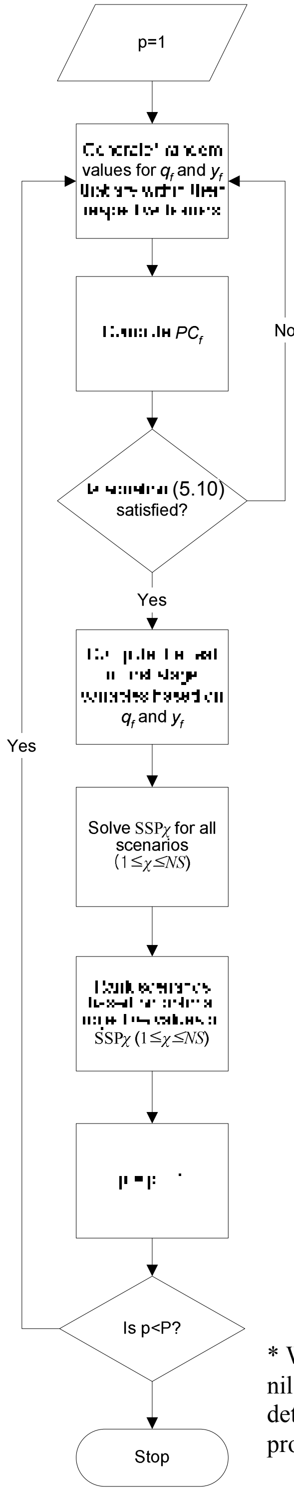
With a clear understanding of characteristic scenarios and CLT scenarios, we now introduce a new algorithm that is designed to solve SCEPM efficiently. Essentially, this algorithm entails identification of both characteristic scenarios and CLT scenarios before an equivalent MILP is solved with account of only these scenarios instead of all possible scenarios. Since this algorithm results in drastic reduction in the number of scenarios used in the MILP formulation, a phenomenon which is similar to the sharp volume reduction in gas to liquid condensation process, we name our new algorithm scenario-condensation approach (SCA). Basically, SCA consists of five key steps and we now describe of each of these steps in details as follows.

5.7.3.1 Initialization

Basically, this step iteratively and randomly generates feasible first-stage solutions that satisfy all first-stage constraints of SCEPM defined by eqns (5.1)-(5.23) before the second-stage problems *without* the risk-control constraints are partitioned based on scenarios and each of them is then solved to optimality with objective of maximizing NPV in each corresponding scenario χ ($1 \le \chi \le NS$). The constraints of a second-stage problem of scenario χ are represented by eqns (5.24)-(5.36) and its objective function is defined as follows.

$$
\begin{aligned}
\text{NPV} = & \sum_{f \in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i \in \boldsymbol{OM}_f} \sum_{c \ni i \in \boldsymbol{IM}_c} e_{ft}^{\chi} P_{ifct}^{\chi} (F_{ifct}^{\chi} + G_{ifct}^{\chi}) - e_{ft}^{\chi} MC_{ft} X_{ft}^{\chi}}{(1+r)^t} \\
& \sum_{f \in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i \in \boldsymbol{IM}_f} \sum_{s \ni i \in \boldsymbol{OM}_s} e_{ft}^{\chi} (1 + ID_{isft}) CIF_{isft}^{\chi} F_{isft}^{\chi} - \sum_{i \in \boldsymbol{OM}_f} \sum_{c \ni i \in \boldsymbol{IM}_c} e_{ft}^{\chi} G_{ifct}^{\chi} CO_{ifct}^{\chi}}{(1+r)^t} + \\
& \sum_{f \in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i \in IM_f} \sum_{j \in OM_f} \sum_{s \ni i \in OM_s} e_{ft}^{\chi} W_{ijsft}^{\chi} CIF_{isft}^{\chi} ID_{isft} RV_{jft}^{\chi} DR_{if}}{(1+r)^t} - \\
& \sum_{n} \sum_{t} \frac{\varepsilon_{nt}^{\chi} TIP_{nt}^{\chi} TR_{nt}}{(1+r)^t} - \sum_{f \in \boldsymbol{IF}} e_{f0} PC_f
\end{aligned}
\qquad (5.42)
$$

We define this second-stage problem of scenario χ as SSPχ. Refer to Figure 5.2 for an overview of algorithmic procedure of this step and Appendix A for details on how feasible first-stage solutions are randomly generated. This initialization step terminates when P sets of feasible first-stage solutions are generated and their corresponding second-stage problems (i.e. SSPχ) in all scenarios ($1 \le \chi \le NS$) are solved.



* When p=1, all facilities ($f \in \boldsymbol{IF}$) have nil expansion. See Appendix E for details of the random number generation procedure.

Figure 5.2: Process flow in the initialization step

5.7.3.2 Identification of Characteristic Scenarios

Once the initialization step terminates, the scenarios ($1 \leq \chi \leq NS$) are then ranked accordingly based on optimal objective values of SSPχ ($1 \leq \chi \leq NS$) for every set of randomly generated feasible first-stage solutions. This means that once P sets of feasible first-stage solutions are generated, their corresponding second-stage problems SSPχ ($1 \leq \chi \leq NS$) are solved to optimality, and the aforementioned ranking exercise is completed, an incidence matrix that indicates the number of appearances in each rank by every scenario ($1 \leq \chi \leq NS$) can be generated. Note that the scenarios are ranked in descending order based on the objective values of SSPχ ($1 \leq \chi \leq NS$) for every set of feasible first-stage solutions. As an illustration, a SCEPM-SD with 5 scenarios (i.e. NS=5) and P=100 may have an incidence matrix as shown in Table 5.1. In an incidence matrix, each number essentially represents the number of times a scenario has been ordered at a rank. For instance, scenario 1 in Table 5.1 has been ranked one and two in the fifty times each. Therefore, if $I_{\chi l}$ denotes the number of times a scenario χ has been ranked l where $1 \leq \chi \leq NS$ and $1 \leq l \leq NS$, then $I_{11}=I_{12}=50$ while $I_{13}=I_{14}=I_{15}=0$.

Table 5.1: An example of incidence matrix

Scenario (χ)	**Rank** (l) 1	2	3	4	5
1	50	50	0	0	0
2	20	30	50	0	0
3	20	20	30	30	0
4	10	0	20	40	30
5	0	0	0	30	70

Basically, characteristic scenarios represent the essence of a SCEPM-SD so that the latter can be equivalently formulated with account of only these scenarios instead of all scenarios. In order to keep the number of characteristic scenarios representing a SCEPM-SD small, the selected characteristic scenarios must possess distinctive problem traits with minimal similarity in business conditions. Intuitively, we postulate that the characteristic scenarios must satisfy the following two conditions which we will validate through results of our case studies later in this chapter. First, a characteristic scenario should have a dominant rank so that its probability of occurrence in the dominant rank is significantly higher compared to other ranks. This means that if the dominant rank of a characteristic scenario χ is d, then $I_{\chi d}$ is significantly higher than other $I_{\chi l}$ where $1 \le l \le NS$ and $l \neq d$. As such, a characteristic scenario should have relatively small spread of ranks (i.e. small range of l where $I_{\chi l} > 0$) in order to exhibit dominant rank traits. This requires ranks ($1 \le l \le NS$) over which a characteristic scenario χ has $I_{\chi l}$ greater than zero to be confined to a relatively small range. Second, the collection of characteristic scenarios must not share any common ranks in the incidence matrix. For example, a characteristic scenario c has $I_{cl} > 0$ ($1 \le l \le NS$) only when l =1,2,3. Then, the set of other characteristic scenarios ($\chi \neq c$) must not have $I_{\chi l} > 0$ at l =1,2,3.

Now, we proceed to introduce a new optimization model which can systematically identify the characteristic scenarios that satisfy the aforementioned two conditions. Basically, it is an integer programming (IP) model with the following binary variable.

$$y_{\chi} = \begin{cases} 1 & \text{if } \chi \text{ is chosen as a characteristic scenario} \\ 0 & \text{otherwise} \end{cases}$$

In addition, we introduce two new parameters which are based on the incidence matrix. The first one is the following binary parameter which is defined for every possible scenario χ.

$$L_{\chi l} = \begin{cases} 1 & \text{if MinRank}_{\chi} \le l \le \text{MaxRank}_{\chi} \\ 0 & \text{otherwise} \end{cases}$$

where, MinRank_χ and MaxRank_χ correspond to the minimum and maximum l ($1 \le l \le NS$) respectively with $I_{\chi l} > 0$. The second parameter is the maximum possible probability (MaxP_χ) of occurrence of χ based on a given incidence matrix. Therefore, if $\max_l \{I_{\chi l}\}$ denotes the maximum possible value of $I_{\chi l}$ over all possible values of rank l for a scenario χ, then MaxP_χ can be expressed as follows.

$$\text{MaxP}_\chi = \max_r \{I_{\chi r}\} / \text{P} \tag{5.43}$$

Since we have postulated that characteristic scenarios should have dominant ranks, our IP model is designed with the objective of maximizing the following function Z.

$$Z = \sum_{\chi \le NS} \text{MaxP}_\chi y_\chi \tag{5.44}$$

Recall our earlier postulation that each characteristic scenario should have relatively small spread of ranks and the collection of characteristic scenarios should not share any common rank in the incidence matrix. We enforce this condition by writing the following constraint.

$$\sum_{\chi \le NS} L_{\chi l} y_\chi \le 1 \qquad 1 \le l \le NS \tag{5.45}$$

If φ is a predetermined maximum number of characteristic scenarios to be chosen for a given problem, then we also have,

$$\sum_{\chi \le NS} y_{\chi} \le \varphi \tag{5.46}$$

To this end, we complete the description of the new IP model which entails maximizing Z subject to constraints defined by equations (5.45) and (5.46). Once the set ($\boldsymbol{C}$) of characteristic scenarios is selected, we proceed to establish the correlation that offers the best fit description on the linear relationship between the objective value of EMIP-S (i.e. Z_S) and that of EMIP-A (i.e. Z_A) based on the P sets of feasible first-stage solutions generated in initialization step as described in section 5.7.3.1. This task can be easily accomplished with the aid of trendline option in Microsoft Excel and we let this linear correlation be $Z_A = f(Z_S)$.

5.7.3.3 Identification of Critical Lower Tail-End Scenarios

This is a straightforward process which consists of two keys steps. The first step entails computation of the minimum number of scenarios (α) that needs to be accounted in the risk-control constraints. Basically, this number equals to $\lfloor x * NS/100 \rfloor$ or $\lfloor \kappa * NS \rfloor$ where $\lfloor n \rfloor$ is the largest integer equal or less than n. In another words, this number also represents the maximum number of scenarios that have objective function values of SSPχ ($1 \le \chi \le NS$) being less than or equal to v. Second, a screening of the incidence matrix is carried out where scenarios ($1 \le \chi \le NS$) with $I_{\chi l} > 0$ at any value of l which falls within the range of $NS\text{-}\alpha \le l \le NS$ are conservatively classified as CLT scenarios ($\chi \in \boldsymbol{S}$).

5.7.3.4 Solving the Equivalent MILP

This constitutes the penultimate step of our new solution methodology (SCA) developed to address SCEPM where the equivalent MILP formulation with account of only the characteristic and CLT scenarios is solved to optimality using a commercial solver like CPLEX. Essentially, formulation is similar to that described in SCEPM except (1) the risk-control constraints represented by equations (5.37) to (5.39) are defined only over CLT scenarios ($\chi \in \boldsymbol{S}$), (2) other constraints represented by equations (5.24)-(5.36) are valid only over both characteristic and CLT scenarios ($\chi \in \boldsymbol{C} \cup \boldsymbol{S}$), and (3) the objective function entails maximization of Z_A where, $Z_A = f(Z_S)$, and

$$
\begin{aligned}
Z_S = \sum_{\chi \in \boldsymbol{C}} \frac{1}{|\boldsymbol{C}|} \Bigg[& \sum_{f \in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i \in \boldsymbol{OM}_f} \sum_{c \ni i \in \boldsymbol{IM}_c} e_{ft}^{\chi} P_{ifct}^{\chi} (F_{ifct}^{\chi} + G_{ifct}^{\chi}) - e_{ft}^{\chi} MC_{ft} X_{ft}^{\chi}}{(1+r)^t} - \\
& \sum_{f \in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i \in \boldsymbol{IM}_f} \sum_{s \ni i \in \boldsymbol{OM}_s} e_{ft}^{\chi} (1 + ID_{isft}) CIF_{isft}^{\chi} F_{isft}^{\chi} - \sum_{i \in \boldsymbol{OM}_f} \sum_{c \ni i \in \boldsymbol{IM}_c} e_{ft}^{\chi} G_{ifct}^{\chi} CO_{ifct}^{\chi}}{(1+r)^t} + \\
& \sum_{f \in \boldsymbol{IF}} \sum_{t} \frac{\sum_{i \in IM_f} \sum_{j \in OM_f} \sum_{s \ni i \in OM_s} e_{ft}^{\chi} W_{ijsft}^{\chi} CIF_{isft}^{\chi} ID_{isft} RV_{jft}^{\chi} DR_{if}}{(1+r)^t} - \\
& \sum_{n} \sum_{t} \frac{\varepsilon_{nt}^{\chi} TIP_{nt}^{\chi} TR_{nt}}{(1+r)^t} \Bigg] - \sum_{f \in \boldsymbol{IF}} e_{f0} PC_f
\end{aligned}
\tag{5.47}
$$

If the equivalent MILP model is infeasible, the algorithmic procedure terminates with no feasible solution to the SCEPM that satisfies the risk constraints imposed by the decision maker. In contrast, if the model can be solved to optimality, then the algorithmic procedure proceeds to the following step.

5.7.3.5 Verification of Solution Feasibility

In the previous step, selected CLT scenarios ($\chi \in \boldsymbol{S}$) are employed in the corresponding equivalent MILP model to ensure conformance to the risk-control constraints. To verify that capacity expansion plan or first-stage decisions of any solution to this model does conform to the risk-control constraints when all scenarios are accounted for, the following two steps are performed. First, each SSPχ ($1 \leq \chi \leq NS$) is solved based on known first-stage solutions of equivalent MILP model (in previous step) to optimality with objective of maximizing its corresponding NPV as shown in equation (5.42). Given the optimal objective function values of the SSPχ ($1 \leq \chi \leq NS$), one can then proceed to assess if the risk-control constraints are satisfied. Now, if the given first-stage solutions satisfy the risk-control constraints, then the algorithmic procedure terminates with a feasible capacity expansion plan that satisfies the risk-control constraints imposed by the decision-makers. Otherwise, identify scenario(s) which (1) has the optimal objective function value of SSPχ falling below or equal to v, and (2) is not in the current set of CLT scenarios. Once such scenario(s) is (are) identified, add the scenario(s) to the set of CLT scenarios and return to the previous step. See Figure 5.3 for an overview of the process flow in the SCA procedure.

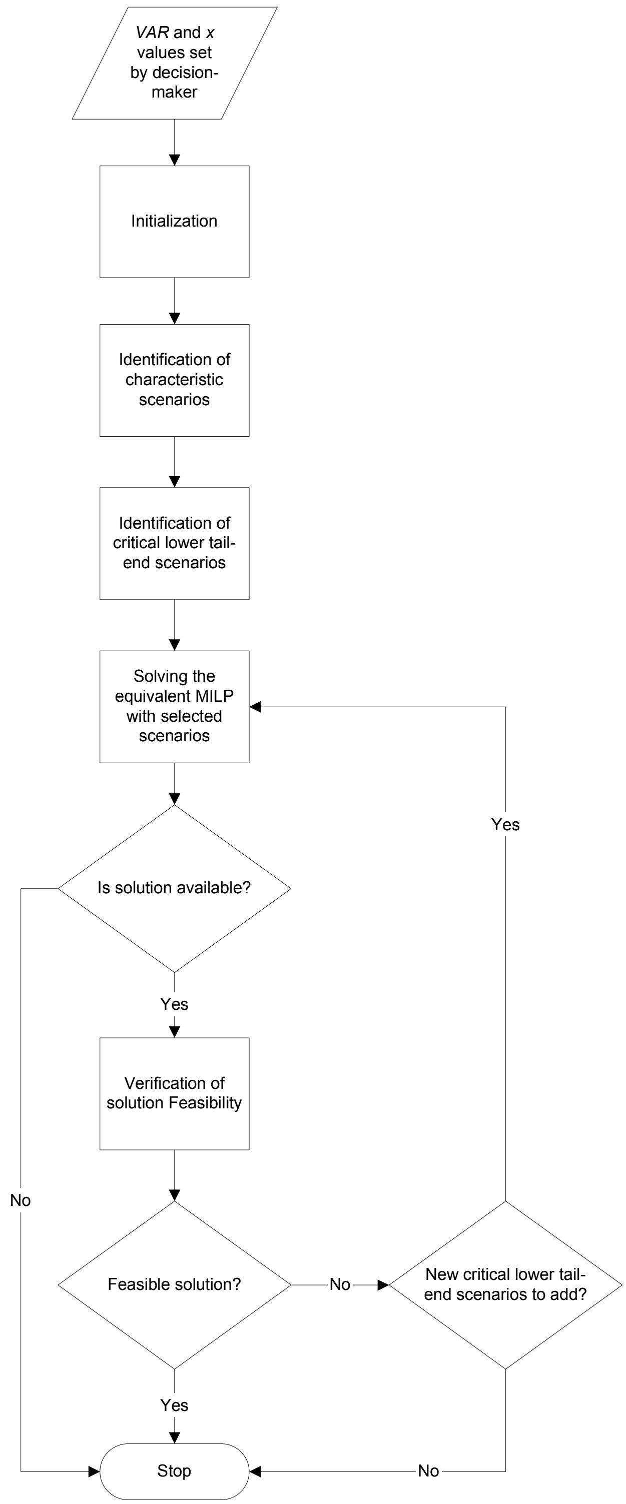


Figure 5.3: Process flow in SCA

5.8 Case Studies

To illustrate that the new proposed solution approach is robust enough to solve SCEPM, we apply it to solve three case study problems of industrial scale where (1) there is a total of 200 scenarios (i.e. $NS = 200$), and (2) x is set at 1% (i.e. $\kappa = 0.01$) in each of these problems. Essentially, these three problems are similar to the one presented in section 5.6 and the case study in the preceding chapter. But these three problems differ from one another in terms of the number of internal future and existing facilities (i.e. $|\boldsymbol{IF}|$), number of external suppliers, number of external customers, and number of products involved in the manufacturing process stoichiometry of the internal facilities, budget allocated (i.e. CB in numeraire currency) for expansion-related activities, and v values predetermined by decision-makers as shown in Table 5.2.

Table 5.2: Key differences among the case study problems

Parameters	**Case Study**		
	1	**2**	**3**
Number of internal facilities	6	5	6
Number of suppliers	9	10	9
Number of customers	12	9	12
Number of products	4	4	6
CB ($)	5×10^8	3×10^8	5×10^8
***v* ($)**	2×10^9	1×10^9	2×10^9

Table 5.3: Types, initial capacities (kton/year), capacity limits (kton/year), mass balances, primary materials, corporate tax rates for the MNC's facilities in case studies

Facility (f)	Nation (n)	Initial Cap. (Q_{f0})	Max Cap. (Q_f^U)	Min Exp. (Q_f^L)	K_f^C	K_f^D	Corporate Tax Rate (%)
F1	N3	40	50	12	2	3	18
F2	N5	50	-	-	-	-	40
F3	N7	45	-	-	-	-	24
F4	N10	35	-	-	-	-	0
F5	N6	0	85	20	3	6	0
F6	N9	0	70	15	3	5	26

Process mass balances:
(P1): $m_1 = 0.5m_2 + 0.4m_3 + 0.1m_{11}$
(P2): $m_2 = 0.9m_4 + 0.1m_{21}$
(P3): $m_5 = 0.3m_6 + 0.3m_7 + 0.3m_8 + 0.1m_{31}$
(P4): $m_6 = 0.6m_9 + 0.3m_{10} + 0.1m_{41}$

F2, F3 and F4 are primary facilities, while all others are secondary. All these facilities are considered in the three case studies except in Case Study 2 where F4 is excluded. In Case Study 1 and 2, the manufacturing processes of primary and secondary facilities are represented by (P1) and (P2) respectively. In Case Study 3, the manufacturing processes of primary and secondary facilities are denoted by (P3) and (P4) respectively. The first product on the right hand side of the mass balance equation represents the primary material $\pi(f)$ of the facility concerned.

For the purpose of illustrating the problem scope involved in all three case studies, Table 5.3 lists the initial capacity (Q_{f0}), capacity limits (Q_f^L, Q_f^U), primary materials [$\pi(f)$], mass balance equations, corporate tax rate, etc. for each facility while Tables 5.4 and 5.5 shows the values of parameters used to represent the project cost and duration profiles respectively. The readers may obtain the full data for all case studies by contacting the thesis advisor of the author.

Table 5.4: Parameters used the project cost profiles where all dollars are in native currency of internal facilities

Parameters	Facility (f)	k = 1	k = 2	k = 3
$\Delta\overline{q}_{fk}^{C}$ (kton/year)	F1	20	18	N.A.
	F5	25	25	15
	F6	20	20	15
g_{fk}^{C} ($)	F1	3,979,859	4,178,316	N.A.
	F5	3,651,445	2,627,763	2,678,574
	F6	1,752,621	4,118,139	2,230,923
R_{fk}^{C} ($/ton/year)	F1	3522.3	4756.1	N.A.
	F5	3325.1	4535.7	3096.8
	F6	4065.1	4561.4	3131.6

Table 5.5: Parameters used in the project duration profiles

Parameters	Facility (*f*)	k = 1	k = 2	k = 3	k = 4	k = 5	k = 6
$\Delta\overline{q}_{fk}^{D}$ (kton/year)	F1	18	12	8	N.A.	N.A.	N.A.
	F5	15	10	10	10	10	10
	F6	15	10	10	10	10	N.A.
g_{fk}^{D} (month)	F1	9	6	4	N.A.	N.A.	N.A.
	F5	8	10	6	6	5	5
	F6	10	10	8	6	6	N.A.

5.8.1 Case Study Results

We coded SCA in Visual C++ and used CPLEX 10.1 within GAMS (Distribution 22.3) as the standard solver for any MILP or IP model encountered in our new algorithmic procedure. In each of the three case studies, we ran our Visual C++ program on a Windows XP workstation with a Pentium 4 Xeon (2.8 GHz, 2 GB RAM) processor with P = 30 and φ = 10. Breakdown of SCA solution times and key outputs of the procedure in all three case studies are summarized in Tables 5.6 and 5.7 respectively. From the high R^2 values in Table 5.7, it is clear that a good linear correlation between Z_A and Z_S can be established using characteristic scenarios identified by step 5.7.3.2. Figure 5.4 illustrates the return distributions of the MNC's NPV in the three case studies based on the solutions of SCA where the actual VAR at 1% confidence level (i.e. x = 1%) are $\$2.20\text{x}10^9$, $\$1.37\text{x}10^9$ and $\$2.59\text{x}10^9$ respectively (all of which expressed in numeraire currency). It is also important to highlight that similar outputs are obtained when the problems in these case studies are solved again by SCA with different initial solutions in step 5.7.3.1.

Table 5.6: Breakdown of SCA solution time (s)* in case studies

Step	**Case Study**		
	1	**2**	**3**
5.7.3.1	1266.02	1202.54	1948.12
5.7.3.2	0.05	0.02	0.06
5.7.3.4	1990.0	370.41	475.81
5.7.3.5	40.02	39.4	69.48
Total	3296.09	1612.37	2493.47

* Solution time needed by step 5.7.3.3 is negligible.

Table 5.7: Key outputs of SCA in case studies

Output	**Case Study**		
	1	**2**	**3**
$\|\boldsymbol{C}\|$	8	10	5
$\|\boldsymbol{S}\|$	5	4	5
a^*	0.9592	1.002	0.8720
b^*	$-2\text{x}10^8$	$-3\text{x}10^7$	$-6\text{x}10^8$
R^{2*}	0.9386	0.9994	0.9648

* Linear correlation of $Z_A = aZ_S + b$ is determined by adding trendline option in Excel

Table 5.8: Profit and loss of MNC in N5 based on scenario 1 solution of case study 1

t	$PE^{1}_{(N5)t}$ ($)	$NE^{1}_{(N5)t}$ ($)	$TIP^{1}_{(N5)t}$ ($)	$\sum_{t'<t} CFL^{1}_{(N5)t't}$ ($)	$\varepsilon^{1}_{(N5)t}$
1	10,118,575.8	0.0	10,118,575.8	0.0	1.630
2	51,647,347.4	0.0	51,647,347.4	0.0	1.704
3	0.0	10,656,469.5	0.0	0.0	1.584
4	64,342,942.4	0.0	64,342,942.4	0.0	1.732
5	71,125,377.3	0.0	60,468,907.9	10,656,469.5	1.939

Note: All dollars are expressed in native currency of N5. The last column is the currency exchange rates which are in units of a numeraire currency per unit N5 currency

Oh and Karimi (2004, 2006) present and discuss extensively the solution details of their respective case studies to highlight the importance of accounting for regulatory factors in supply chain decision-making processes. Instead of replicating the effort again in this chapter, we focus on a specific solution result to illustrate the importance accounting for carry-forward loss in capacity expansion planning. Table 5.8 shows the profit and loss trend of the MNC in N5 and in terms of N5 currency based on optimal solution in scenario 1 (i.e. χ=1) of case study 1. Due to the loss that the MNC incurs at the end of year 3, its taxable income in year 5 is reduced by more than $10.6 million (in native currency of N5) based on the carry-forward loss policy of N5. Given the corporate tax of 40% in N5 (see Table 5.4), this represents a total tax saving of almost $4.3 million (in N5 currency) for the organization at the end of fifth year in that scenario. Note that the carry-forward loss is used to alleviate the tax payable in year 5 but not in year 4 in the optimal solution (see Table 5.8). This is primarily attributed to the higher currency exchange rate in year 5 compared to that year 4 which in turn results in greater tax savings only if the loss incurred in year 3 is used to offset the corporate tax payable in year 5 instead of year 4. Evidently, the actual net cash flow of the MNC in N5 has been projected more accurately due to the account of carry-forward loss in the problem formulation. In situations where the account of carry-forward loss results in significant tax savings to the MNC, it is likely the optimal capacity expansion plan may differ significantly according to whether or not carry-forward loss is adequately accounted for in the problem formulation.

To evaluate the effectiveness of SCA in terms of solution quality, we also solve the equivalent MILP models of SCEPM with account of all possible scenarios in the three case studies using CPLEX on the same hardware with total solution time limited to one day. In order to cope with the extensive memory requirements in this evaluation study, we selected a CPLEX option which compresses all node files generated by the solver and stores these files in hard disk in all three case studies. In addition, the aggressive scaling option of CPLEX has to be turned on in case study 3 due to large condition number of the basis matrix in this problem. Otherwise, the solver would declare the problem in case study 3 to be infeasible and fail to return any feasible solution. Table 5.9 summarizes the solutions of SCEPM determined by CPLEX and SCA in the three case studies. Clearly, both solution approaches yield capacity expansion plans which are similar to one another. In addition, the ENPVs of their solutions are almost identical. Note that the relative optimality gaps of the CPLEX solutions in the three case studies 0.43%, 0.92% and 0.97% respectively. The long solution time needed by CPLEX to solve SCEPM as an equivalent MILP model with account of all possible scenarios in each of the three case studies is primarily attributed to the large model size. See Tables 5.10 and 5.11 for the sharp contrast in scales of the equivalent MILP models involved when they are solved using CPLEX with account of selected scenarios (in SCA) and all scenarios respectively.

Table 5.9: Expansion volumes (kton/year) and objective functions based solutions of SCA and CPLEX in case studies

Items	Method	Case Study		
		1	2	3
Expansion Volumes (F1,F5,F6)	SCA	(30,34.7,0)	(12,20,0)	(50,20,15)
	CPLEX	(30,35,0)	(12,20,0)	(50,35,15)*
ENPV	SCA	$2.96\text{x}10^{9}$	$1.52\ \text{x}10^{9}$	$3.25\ \text{x}10^{9}$
	CPLEX	$2.96\text{x}10^{9}$	$1.52\ \text{x}10^{9}$	$3.26\ \text{x}10^{9*}$

* The aggressive scaling option of CPLEX has to be turned on in Case Study 3. Otherwise, the solver returns no solution due to infeasibility.

Table 5.10: Number of variables, constraints and zero of equivalent MILP model with account of selected scenarios in step 5.7.3.4

Type	Case study		
	1	2	3
Continuous variables	37,545	28,553	47,100
Binary variables	610	569	520
Constraints	15,643	14,116	17,693
Nonzeros	146,695	112,299	179,307

Table 5.11: Number of variables, constraints and zero of equivalent MILP model with account of all possible scenarios

Type	Case study		
	1	2	3
Continuous variables	563,950	397,763	923,950
Binary variables	6,415	5,415	6,415
Constraints	203,033	172,608	304,033
Nonzeros	2,669,670	1,964,683	4,110,870

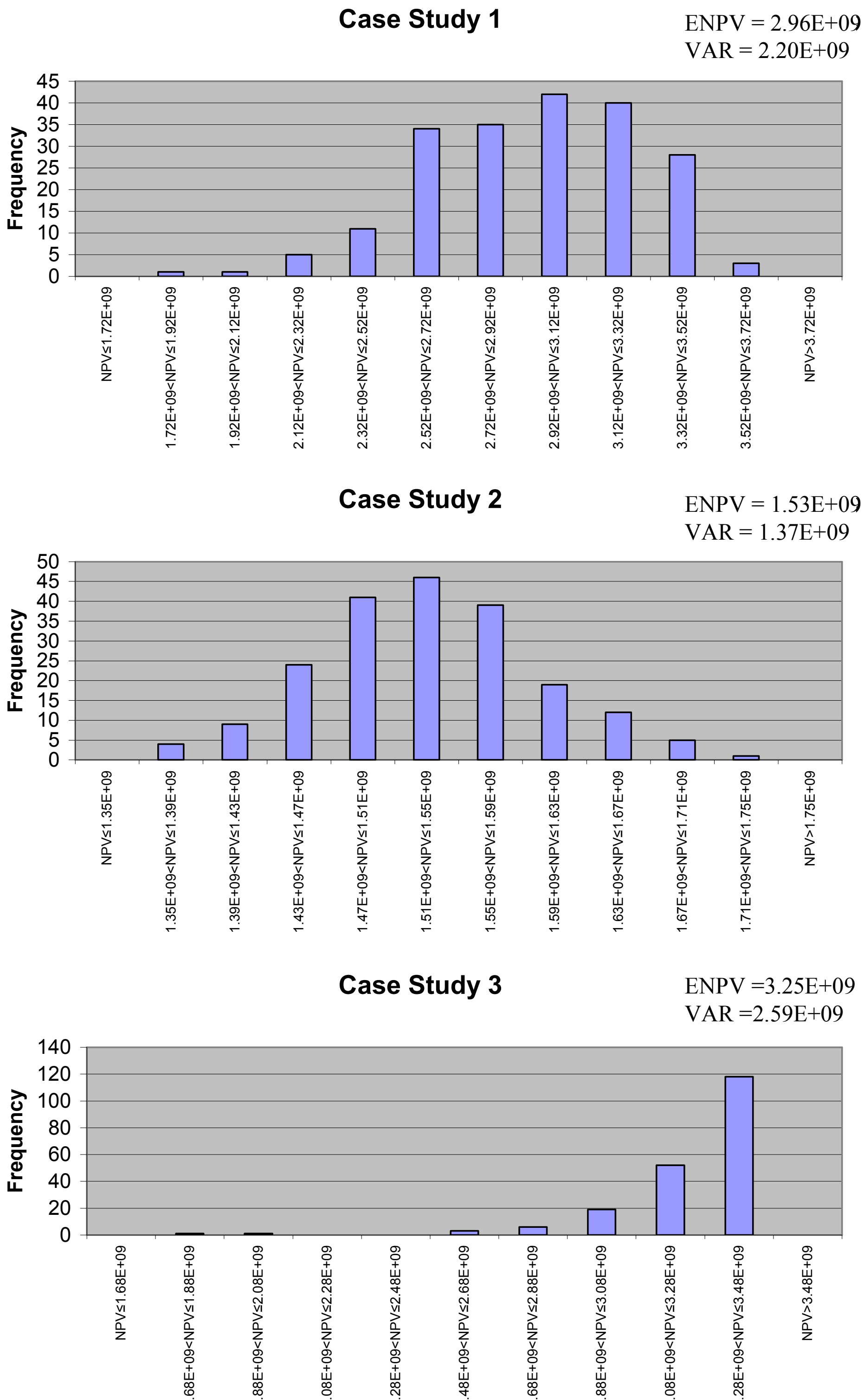


Figure 5.4: Return distributions of three case studies based on SCA solutions

Evidently, the reported results not only demonstrate the computational prowess and robustness of SCA to determine good solutions to SCEPM with small optimality gaps. They also illustrate the computational efficiency of SCA which requires only a fraction of the time needed by CPLEX to determine solutions of similar quality. Moreover, the similarity in the SCA and CPLEX solutions in the case studies has also validated (1) the postulations previously described in section 5.7.3.2 with regards to the two conditions that characteristic scenarios must satisfy, and (2) the effectiveness of the IP model introduced in section 5.7.3.2 as a systematic tool in identification of characteristic scenarios.

5.8.2 Results of Previous Illustrative Example

To demonstrate the ability of SCA to solve SCEPM of industrial scale, we employ it again (also coded in Visual C++ program) to solve the illustrative example cited in section 5.6 where its equivalent MILP model was not solved by CPLEX due to out of memory issue. Using the same hardware as reported previously with P = 30 and $\varphi = 10$, SCA is able to produce a solution which proposes expansion of F1 and F5 by 12 kton/year and 20 kton/year respectively in less than 6900s (see Table 5.12 for breakdown of solution time). This solution yields an ENPV of $\$2.12\times10^9$ and VAR of $\$1.98\times10^9$ (both of which expressed in numeraire currency). Key outputs of SCA are tabulated in Table 5.13 while return distribution of MNC based on the SCA solution is shown in Figure 5.5. Clearly, this exercise has not only demonstrated SCA's ability to solve SCEPM with extensive hardware memory requirement. It has also verified SCA's ability to address SCEPM of industrial scale.

Table 5.12: Breakdown of SCA solution time in illustrative example

Step	Solution Time(s)*
5.7.3.1	5143.83
5.7.3.2	0.27
5.7.3.4	1589.97
5.7.3.5	158.81
Total	6892.88

* Solution time needed by step 5.7.3.3 is negligible.

Table 5.13: Key outputs of SCA in illustrative example

SCA Output	Value
$\|\boldsymbol{C}\|$	7
$\|\boldsymbol{S}\|$	12
a^*	0.7161
b^*	$3\text{x}10^7$
R^{2*}	0.989

* Linear correlation of $Z_A = aZ_S + b$ is determined by adding trendline option in Excel

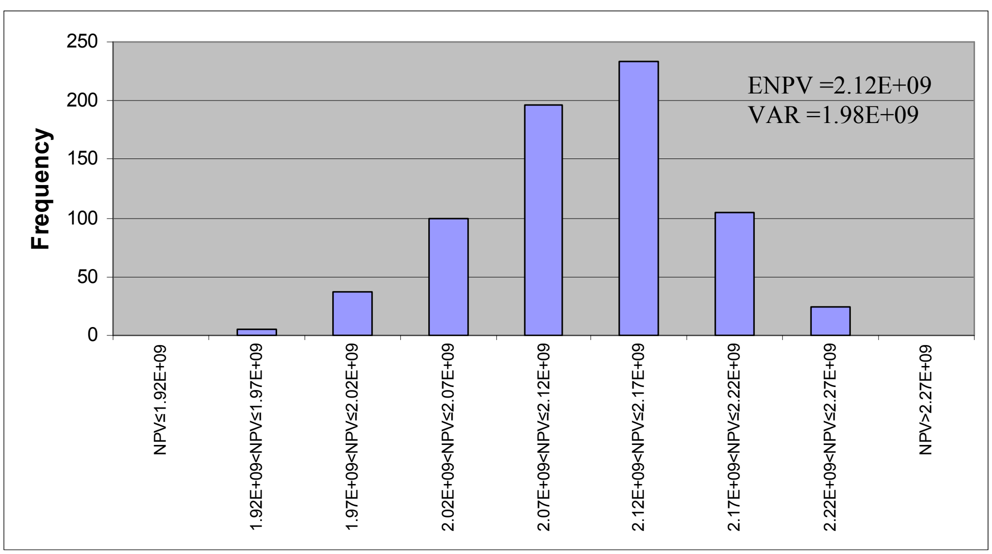


Figure 5.5: Return distribution of illustrative example based on SCA solution

5.9 Discussion

From the case study results, it is clear that SCA is an effective algorithm in addressing SCEPM in three major ways. First, it is able to determine solution which matches to that of an equivalent MILP model of SCEPM. Second, SCA requires only a fraction of total solution time needed by CPLEX to solve the EMIP-A. Third, SCA can also serve as an efficient tool for generation of a return frontier diagram in a capacity expansion planning project which in turn can be used by decision makers to evaluate the quantitative tradeoff between financial return and amount of risk to undertake.

Moreover, the proposed algorithmic procedure also possesses desirable characteristics which make it an attractive option to solve SCEPM and other problem with similar problem structure. In particular, SCA exhibits a highly parallel solution structure which can be exploited for computational efficiency or to avoid scenario of no solution attributed to memory limitation of hardware. This is clearly illustrated by SCA's ability to solve the illustrative example which CPLEX has failed to yield any solution due to out of memory. In addition to that, SCA offers a systematic and effective way of identifying characteristic and CLT scenarios which essentially represent the critical scenarios that need to be considered to respectively (1) estimate the ENPV, and (2) assess conformance of the risk-control constraints in SCEPM. Therefore, solution approaches which are based on artificial intelligence (i.e. genetic algorithm, tabu search and simulated annealing) or evolutionary search (as in Till et al., 2007) can assess the feasibility of any first-stage solution by just solving the second-stage problems of these critical scenarios instead of all possible scenarios. Clearly, this represents a significant computational time saving especially if the number of scenarios involved is large and/or risk-control constraints are tight. As such, the availability of aforementioned critical scenarios has made artificial intelligence based or evolutionary search techniques more computationally efficient and attractive as algorithmic procedures to address SCEPM.

6. Application of SCA to Solve Tanker Refueling Optimization Problem

Primarily, this chapter aims to demonstrate the robustness of the scenario-condensation approach (SCA) which is introduced in section 5.7.3 of previous chapter to address supply chain problems like tanker refueling planning problem which shares similar characteristics as those of SCEP. Readers may refer to Appendix F for a concise overview of refueling practice in the shipping industry.

6.1 Previous Work

Since Merrill Flood's pioneering work in the area of tanker routing and scheduling was published in 1954, many ship routing and scheduling models have appeared in the literature. To date, there are already three papers by Ronen (1983, 1993) and Christiansen et al. (2004) that review the status of ship routing and scheduling research in three different decades. Over the years, ship routing and scheduling models are increasingly more realistic and industrially relevant with several of them being developed in response the industry needs. For example, the sky-rocketing fuel prices in the 1970s escalated the operating costs of vessels and shipping companies began to focus their attention on fueling saving measures which include reduction of vessel cruising speeds. As a result, a string of papers that look into optimizing the vessel speeds with ship routing and scheduling decisions began to appear in the following decade. These papers include those of Benford (1981), Perakis (1985), etc. Benford (1981) introduced an algorithmic procedure which aims to maximize the profits of ship owners through selection of available ships and their respective sea speeds that can fulfill the required service requirements. Perakis (1985) addressed a problem which is similar to that of Benford (1981) and proposed a solution approach that applies calculus to determine the optimal solution. In addition, there are even papers that explicitly aim to optimize vessel speeds without considering routing and scheduling decisions. These papers include Ronen (1982) who presented three closed analytical models which respectively determine the optimal speed of a vessel in three types of leg, namely income generating leg, positioning leg, and mixed leg. Perakis and Papdakis (1987a) proposed nonlinear optimization algorithms to explicitly determine the full load and ballast speeds of vessels with objective of minimizing the total fleet operating costs including lay-up costs for unused vessels. In the second part of their paper, Perakis and Papdakis (1987b) addressed two extended versions of the above problem where one or more cost components are staircase functions of time, and the uncertain cost components have known distributions.

Despite the relatively long history of research on ship routing and scheduling, two fundamental flaws remain among the models that have been developed for ship routing and scheduling purposes. First, most existing models assume ships require negligible time for refueling. This is not necessarily true in practice as it is common among ships to deviate from their respective normal courses, incur any necessary port dues or delay the transit through a canal to refuel at a port with attractively priced fuel. Second, majority of existing ship routing and scheduling models also assume constant unit fuel price in their formulations. Again, this is an unrealistic assumption since fuel prices are highly unpredictable and can exhibit significant variation across refueling ports. Even at a specific refueling port, the unit fuel price can exhibit high volatility over a short time span of a week. To address the aforementioned flaws and meet the practical needs of industry practitioners, it is crucial to develop a supporting tool that can help decision-makers undertake refueling planning of their vessel in the presence of fuel price uncertainty for a given route and scheduling of a ship and its relevant operating constraints. To the best of the authors' knowledge, such a supporting tool remains unavailable in existing literature and this chapter aims to fill up this research gap through introduction of a novel model that can support refueling planning of tankers.

6.2 Problem Description

In our tanker refueling optimization problem (TROP), we assume all relevant operational requirements of the tanker are available. Essentially, the following information of a given tanker is available to the decision-makers:

(1) Total number of port visits (K)

(2) Sequence of port visits and schedules of these visits

(3) Distances (D_k) that tanker needs to sail from end of its k^{th} leg ($1 \leq k < K$) to the next port

(4) Vessel speed (S_k) of tanker during its voyage from end of its k^{th} leg ($1 \leq k < K$) to the next port

(5) Total weight (W_k) of cargos onboard the tanker as it leaves its k^{th} ($1 \leq k < K$) port of visit

(6) Cargos assigned to be loaded and unloaded by the tanker at each port visit

(7) Pick up laycan or time window constraints of all cargos involved

(8) Tank cleaning requirements of tanker over the given planning horizon

(9) Amount of fuel needed for tank cleaning, cargo loading and unloading at the end of each leg

(10) Refueling options which are available at the end of each port visit or leg and their respective unit fuel prices

In addition, the decision-makers only evaluates the possibility of purchasing fuel from the spot market and does not consider the option of fuel purchases through forward contracts. We also assume that the time interval between the start of planning horizon and the tanker's first port visit is sufficiently short so that fuel prices of all refueling options available to the tanker after its first port visit are fixed and known. In contrast, the fuel prices of refueling options available to a tanker at the end of each subsequent port visit ($1<k<K$) are uncertain. In the literature, there are two main ways of representing an uncertain parameter. First, an uncertain parameter can be represented by discrete probability density function. Such representation is also known as scenario-based approach and it requires (1) forecasting all possible future outcomes or scenarios of the uncertain parameter, and (2) assignment of occurrence probability to each of these scenarios. Second, an uncertain parameter can also be represented by continuous probability density function. Essentially, all these two uncertainty representations require collation and analysis of market intelligence information as well as business acumen and experience of individuals. In our problem, we assume the uncertain fuel price of each available refueling option has *NS* scenarios of values and the probability of occurrence each of these scenarios is known. For example, we have a tanker which is due to visit ports P4, P11 and P7 in that order as shown in Figure 6.1. At the start of the planning horizon, the tanker is about to leave port P4 and has three refueling options (denoted by o1, o2 and o3) to choose from. Similarly, after the visit of P11, the tanker has two refueling options (i.e. o4 and o5) to choose from. Note that the tanker has the option of not refueling after the visits of P4 and P11. Moreover, the fuel prices of refueling options o1, o2 and o3 are fixed and

known while those of refueling options o4 and o5 are uncertain which are expressed in multiple discrete scenarios. Basically, the stochastic problem in this illustration entails determination of optimal refueling plan and vessel speeds after the visit of P4 so that all operational constraints are satisfied.

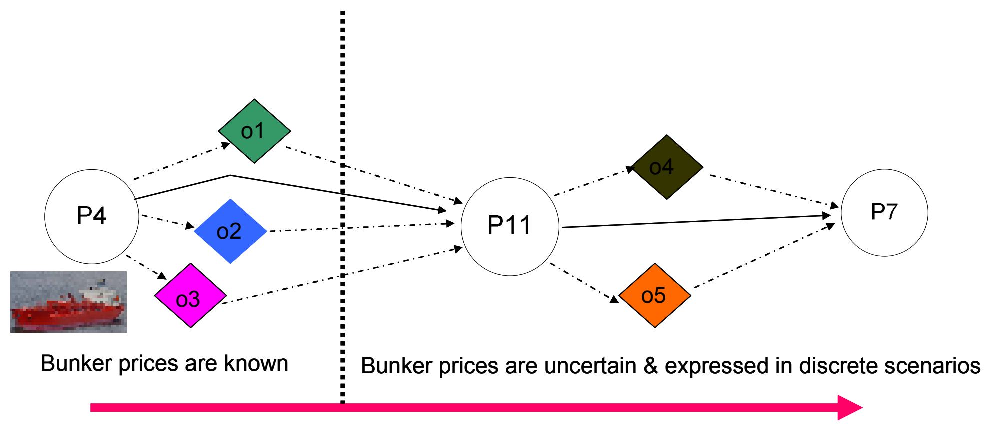


Figure 6.1: Simple illustration of stochastic bunkering planning problem

In our TROP, we aim to determine a refueling plan that minimizes the expected total cost of the tanker which is expected sum of its refueling expenses, port dues and time chartering cost. Essentially, this optimal refueling plan has to satisfy two sets of constraints, namely the operational and financial constraints. As highlighted previously, the operational constraints include the cargo pickup laycan limitations, restrictions posed by fuel tank capacities and relevant operational safety requirements such as those related to minimum safety fuel level and vessel tonnage limit. The financial risk constraints are based on the concept of value-at-risk (see previous chapter for details). These constraints are necessary due to uncertainty-induced variability of our problem objective function and this variability is of concern to the decision makers. Specifically, the decision-makers in our problem want to limit the lower tail-end spread of the tanker's profit distribution. They achieve by setting a target average daily profit (β) for the tanker of interest and requiring a refueling plan where the probability of average daily profit falling less than or equal to this target value to be less than or equal to α.

6.3 Model formulation

Evidently, the abovementioned stochastic problem is complex and difficult to solve especially if there is large number of refueling options and/or large number of price scenarios for every refueling option. To model the refueling decisions to be made at the end of first port visit, we define Q_o as the amount (ton) of bunker fuel to be purchased by the tanker using refueling option o which is available at the end of its port visit. For refueling decisions in subsequent legs ($1<k<K$), we define Q_{ko}^{ξ} as the amount (ton) of bunker fuel to be purchased by the tanker at the end of leg k from option o in scenario ξ ($1<\xi\leq NS$). Note that we assume that no refueling is done by the tanker after its last port visit (i.e. $k=K$). Basically, we need following two binary variables and their respective simplifying notation:

$$x_o = \begin{cases} 1 & \text{if bunkering option } o \text{ at the end of first leg is used} \\ 0 & \text{otherwise} \end{cases}$$

$$x_{ko}^{\xi} = \begin{cases} 1 & \text{if bunkering option } o \text{ of leg } k \text{ in scenario } \xi \text{ is used} \\ 0 & \text{otherwise} \end{cases} \qquad 1<k<K$$

It must also be highlighted that the indices (k, o, ξ, etc) assume their full ranges of values unless stated otherwise.

In practice, a tanker can only be refueled at most once at the end of each port visit. Thus, we have,

$$\sum_o x_o \leq 1 \tag{6.1}$$

$$\sum_{o} x_{ko}^{\xi} \leq 1 \qquad 1<k<K \tag{6.2}$$

Let T_2 and T_k^{ξ} denote the time at which the tanker arrives at a port at the end its second and k^{th} leg ($2<k\leq K$) in scenario ξ respectively. Since the tanker must load its cargos (i) before their respective laycans expire, then,

$$T_2 \leq LPT_i - \frac{1}{2}T_{adm} \qquad i \in \mathbf{I_2} \tag{6.3}$$

$$T_k^{\xi} \leq LPT_i - \frac{1}{2}T_{adm} \qquad i \in \mathbf{I}_k,\ 2<k<K \tag{6.4}$$

where $\mathbf{I}_k$ is the set of cargos to be loaded onto the tanker at the end of its k^{th} leg, LPT_i is the latest pick up time of cargo i ($i \in \mathbf{I}_k$) and T_{adm} is total inspection time needed by the tanker at any port. Note that we assume that the inspection time before berthing and that before leaving the port are both $0.5T_{\text{adm}}$. Moreover, we also assume that the tanker does not pick up any more cargo upon reaching its last port of visit (i.e. $k = K$).

After the tanker loads a cargo i ($i \in \mathbf{I}_k$), then its arrival time at the next port must exceed the earliest time that the cargo is available for pickup, plus the cargo loading time, plus the port administrative time (i.e. half the total inspection time at the port), plus time for sailing to the next port. In other words,

$$T_2 \geq EPT_i + \frac{1}{2}T_{adm} + \frac{V_i}{LR_i} + \frac{D_1}{S_1} + \sum_{o}(\sigma_{1o}x_o + Q_o / RR_{1o}) \qquad i \in \mathbf{I_1} \tag{6.5}$$

$$T_{k+1}^{\xi} \geq EPT_i + \frac{1}{2}T_{adm} + \frac{V_i}{LR_i} + \frac{D_k}{S_k} + \sum_{o}(\sigma_{ko}x_{ko}^{\xi} + Q_{ko}^{\xi} / RR_{ko}) \qquad i \in \mathbf{I}_k,\ 2\leq k<K \tag{6.6}$$

where EPT_i, V_i and LR_i are the earliest pick up time of cargo i ($i \in \mathbf{I}_k$), weight (tonnes) of cargo i and loading rate (tonnes per unit time) for cargo i respectively, , while σ_{ko} and RR_{ko} denote the additional voyage cum port administrative time and refueling rate (tonnes per unit time) respectively if refueling option o at end of leg k is chosen.

Since the tanker could load and discharge multiple cargoes, we must also consider the total time in a port must be greater or equal to the time required for inspections, plus the time for discharging all delivery cargos, plus the time for loading the pickup cargos. Thus, we have,

$$T_2 \geq T_1 + T_{adm} + \sum_{i \in U_1} \frac{V_i}{DR_i} + \sum_{i \in I_1} \frac{V_i}{LR_i} + \frac{D_1}{S_1} + \sum_o (\sigma_{1o} x_o + Q_o / RR_{1o}) \tag{6.7}$$

$$T_3^{\xi} \geq T_2 + T_{adm} + \sum_{i \in U_2} \frac{V_i}{DR_i} + \sum_{i \in I_2} \frac{V_i}{LR_i} + \frac{D_2}{S_2} + \sum_o (\sigma_{2o} x_{2o}^{\xi} + Q_{2o}^{\xi} / RR_{2o}) \tag{6.8}$$

$$T_{k+1}^{\xi} \geq T_k + T_{adm} + \sum_{i \in U_k} \frac{V_i}{DR_i} + \sum_{i \in I_k} \frac{V_i}{LR_i} + \frac{D_k}{S_k} + \sum_o (\sigma_{ko} x_{ko}^{\xi} + Q_{ko}^{\xi} / RR_{ko}) \quad 2<k<K \tag{6.9}$$

where, T_1 is the known arrival time of the tanker to its first port of visit, $\mathbf{U}_k$ denotes the sets of cargos to be unloaded by tanker at the end of its k^{th} leg and DR_i is unloading rate (tonnes per unit time) for cargo i ($i \in \mathbf{U}_k$).

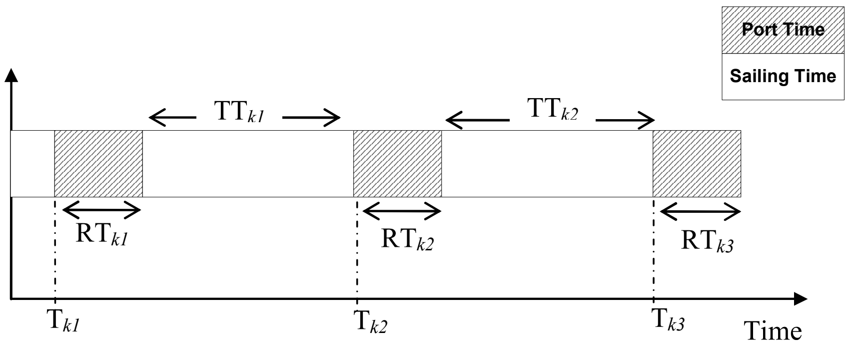


Figure 6.2: Gantt chart of a tanker without refueling activities

If a tanker does not refuel over its planning horizon, the amount of time (RT_k) that it spends at a port at the end of each leg k ($1<k<K$) can be computed based on known vessel speed (S_k) in each voyage leg. Essentially, RT_k ($1<k<K$) can be computed easily based on the difference between the departure time and arrival time of a port and it is inclusive of waiting time, port inspection time, cargo loading and unloading times. See Figure 6.2 for an illustration of RT_k based on the Gantt chart of a tanker with K=3 and no refueling activities where TT_k is the time that the tanker takes to sail from end of leg k to the next port (i.e. $TT_k=D_k/S_k$). In the presence of refueling activities, these port times (i.e. RT_k, $1<k<K$) at the end of second leg and subsequent legs except the last one in scenario ξ may be reduced accordingly (see Figure 6.3). We denote this reduction in port times as δ_k^ξ ($1<k<K$). Evidently, these nonnegative variables have upper limits which are defined as follows.

$$\delta_2^\xi \le RT_2 - (T_3^\xi - \frac{D_2}{S_2} - \sum_o (\sigma_{2o} x_{2o}^\xi + Q_{2o}^\xi / RR_{2o}) - T_2) \tag{6.10}$$

$$\delta_k^\xi \le RT_k - (T_{k+1}^\xi - \frac{D_k}{S_k} - \sum_o (\sigma_{ko} x_{ko}^\xi + Q_{ko}^\xi / RR_{ko}) - T_k^\xi) \qquad 3 \le k < K \tag{6.11}$$

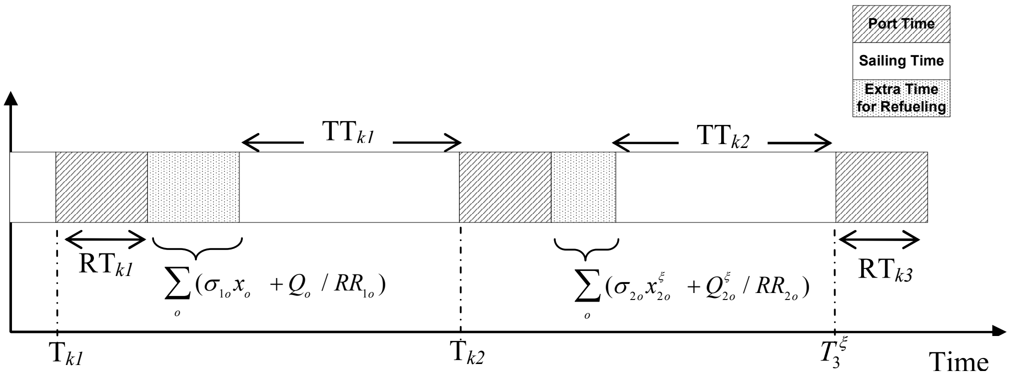


Figure 6.3: Gantt chart of a tanker with refueling activities

Let BFL_k^{ξ} denotes the bunker fuel level of the tanker at the end of its k^{th} leg ($2 \le k \le K$) in scenario ξ prior to its departure to the next port or destination for refueling. Therefore, we have

$$BFL_2^{\xi} = BFL_1 + \sum_o (Q_o - x_o F_{1o}) - FC_2 + \mu \delta_2^{\xi} \tag{6.12}$$

where BFL_1 is the known bunker fuel level of the tanker at the end of its first leg prior to its departure to the next port or destination for refueling, F_{ko} ($1 \le k < K$) is additional fuel consumption due to voyage to refueling port if refueling option o of leg k is chosen, μ is the constant bunker consumption rate (tones per unit time) of the tanker for waiting at port and FC_k ($1 < k < K$) is the total fuel consumed by tanker from start to end of leg k and is inclusive of those used for voyage in the sea, cargo loading, unloading, tank cleaning, waiting and inspection done at the end of leg k. Note that FC_k ($1 < k < K$) can be computed based on a given vessel speed, cargo loading/unloading commitments, tanker cleaning requirements, route and schedule of a tanker where no refueling is done since the amount of fuel needed for sea voyage, tank cleaning, cargo loading and unloading at the end of each leg is known. It is also important to highlight that the component of fuel consumption for waiting at port of FC_k ($1<k<K$) is based on the known speed of vessel in each voyage leg that is previously used to compute RT_k ($1<k<K$).

Similarly, we also have,

$$BFL_2^{\xi} = BFL_{k-1}^{\xi} + \sum_o (Q_{(k-1)o}^{\xi} - x_{(k-1)o}^{\xi} F_{(k-1)o}) - FC_k + \mu\delta_k^{\xi} \qquad 3\leq k\leq K \qquad (6.13)$$

where $\delta_K^{\xi}=0$.

Due to operational safety requirement, a tanker typically has a minimum fuel level limit ($\underline{Q}$). Thus, we also have

$$BFL_1 - \sum_o \tau_{1o} x_o \geq \underline{Q} \qquad (6.14)$$

$$BFL_k^{\xi} - \sum_o \tau_{ko} x_{ko}^{\xi} \geq \underline{Q} \qquad 2\leq k\leq K \qquad (6.15)$$

where τ_{ko} is additional fuel consumption due to the voyage to the refueling destination if refueling option o of leg k is chosen. Note that the second term of equation (6.15) is nil at the tanker's last port visit (i.e. $k=K$) since the vessel does not refuel upon completion of its last leg.

Due to capacity limit, there is also an upper limit ($\overline{Q}$) on how much a fuel can stored in a tanker. To account for this, we need to have the following two constraints.

$$BFL_1 + \sum_o (Q_o - \tau_{1o} x_o) \le \overline{Q} \tag{6.16}$$

$$BFL_k^\xi + \sum_o (Q_{ko}^\xi - \tau_{ko} x_{ko}^\xi) \le \overline{Q} \qquad 2 \le k < K \tag{6.17}$$

To uphold the mathematical legitimacy between Q_o and x_o as well as that between Q_{ko}^ξ and x_{ko}^ξ, we also write the following two equations.

$$Q_o \le \overline{Q} x_o \tag{6.18}$$

$$Q_{ko}^\xi \le \overline{Q} x_{ko}^\xi \qquad 2 \le k < K \tag{6.19}$$

Moreover, a tanker usually has a minimum refueling quantity (Q_{min}) to purchase whenever its refuels. This means that we need the following two constraints.

$$Q_o \ge Q_{\min} x_o \tag{6.20}$$

$$Q_{ko}^\xi \ge Q_{\min} x_{ko}^\xi \qquad 2 \le k < K \tag{6.21}$$

With P_o and P_{ko}^ξ representing the unit fuel price of refueling option o at end of first leg and in subsequent legs ($2 \le k < K$) of scenario ξ respectively, the expected cost the tanker over the planning horizon can be expressed as follows,

$$Z = \sum_{o}(\pi_{1o}x_{1o} + P_oQ_o) + \sum_{\xi}\Pr_{\xi}\left[\sum_{k>1}\sum_{o}(\pi_{ko}x_{ko}^{\xi} + P_{ko}^{\xi}Q_{ko}^{\xi}) + T_K^{\xi}DOC\right] + \sum_{k}PC_k \qquad (6.22)$$

where Pr_{ξ} denotes the probability of occurrence of scenario ξ, π_{ko} is the fixed price (due to port dues and other administrative expenses, etc) of arranging refueling option o at the end of leg k ($1 \leq k < K$), PC_k denotes the port due payable by the tanker for its visit of the port at end of leg k, and DOC is daily operating cost ($/day) of the tanker.

To account for the risk control constraints imposed by the decision-makers who stipulates that the probability of average daily profit falling below or equal to β ($/day) should be less than or equal to α, we need to make two additions to the formulation. First, we introduce the following binary variable

$$Z_{\xi} = \begin{cases} 1 & \text{if average daily profit of tanker in scenario } \xi \geq \beta \\ 0 & \text{otherwise} \end{cases}$$

Then, we add the following three constraints to enforce the risk-control constraints of the decision-makers where M is a maximum possible profit of tanker over tanker.

$$\sum_{i \in G} SR_i - \left(\sum_{o}(\pi_{1o}x_o + P_oQ_o) + \sum_{k>1}\sum_{o}(\pi_{ko}x_{ko}^{\xi} + P_{ko}^{\xi}Q_{ko}^{\xi}) + T_K^{\xi}DOC + \sum_{k}PC_k\right) - T_K^{\xi}\beta \leq Z_{\xi}M \qquad (6.23)$$

$$T_K^{\xi}\beta - \left\{\sum_{i \in G} SR_i - \left(\sum_{o}(\pi_{1o}x_o + P_oQ_o) + \sum_{k>1}\sum_{o}(\pi_{ko}x_{ko}^{\xi} + P_{ko}^{\xi}Q_{ko}^{\xi}) + T_K^{\xi}DOC + \sum_{k}PC_k\right)\right\}$$

$$\leq (1 - Z_{\xi})M \qquad (6.24)$$

$$\sum_{\xi}(1 - Z_{\xi}) \leq \alpha * NS \qquad (6.25)$$

Note that the set **G** denotes the set of cargos that are carried by the tanker over the planning horizon.

This completes our formulation of our tanker refueling planning problem. Basically, this is a mixed integer linear programming (MILP) model with objective of minimizing Z subject to constraints represented by eqns (6.1) to (6.21), (6.23)-(6.25). Clearly, the aforementioned model has a two-stage programming framework where the first-stage problem entails x_o, Q_o, and T_2 as variables and equations (6.1), (6.3), (6.5), (6.7), (6.14), (6.16), (6.18), (6.20) as constraints. The second-stage variables consist of x_{ko}^{χ}, Q_{ko}^{χ}, δ_k^{ξ}, Z_{ξ} and T_k^{ξ} while the corresponding second-stage constraints are (6.2), (6.4), (6.6), (6.8), (6.9), (6.10), (6.11), (6.12), (6.13), (6.15), (6.17), (6.19), (6.21), (6.23)-(6.25).

6.4 Structural Analysis of TROP

Basically, TROP is similar to stochastic capacity expansion problem (SCEP) addressed in the preceding chapter in three major ways. First, both are supply chain problems incorporated with regulatory factors. SCEP is a strategic supply chain problem where regulatory policies pertinent to corporate taxes, import tariffs, duty drawback, carry-forward loss have to be accounted for in its formulation. Similarly, TROP which is basically a fuel supply operation problem entails regulatory policies related to port dues and fuel sales tax imposed by port authorities and customs or revenue authorities respectively. In practice, tanker owners have to pay tariffs to the customs or revenue authorities for fuel purchased at the refueling ports. Typically, this tariff is based on volume of fuel transacted between the supplier and buyer. For example, the authorities in Philippines and Nova Scotia (Canada) impose marine fuel tax at rates of P$0.30 and C$0.011 per litre of fuel respectively.

Second, both SCEP and TROP also entail constraints that reflect quantitatively the amount of risk that the decision-makers are willing to take on the distribution of their respective objective function distribution. The decision-makers in the former problem want a capacity expansion plan where the probability of profit falling below or equal to v be kept less than or equal to κ while those in TROP want a refueling plan where the probability of average daily profit falling less than or equal to β to be less than or equal to α. Third, both formulations of SCEP and TROP have two-stage programming framework with both first and second stage decision variables being mixed integer. As highlighted in previous chapter, such problems are complex and difficult to solve due to the presence of binary variables in the second-stage problems which make the second-stage value functions to be lower semicontinuous with respect to the first-stage variables.

Given the fundamental similarities between TROP and SCEP, it is only natural that solution methodologies that have been developed to address SCEP should remain effective when they are employed to solve TROP. As such, the novel scenario-condensation approach (SCA) that has been designed to address large-scale SCEP (as shown in previous chapter) has the potential of being an alternative heuristic that can effectively solve large-scale TROP. In the following section, we describe TROPs of industrial scale before we explain how SCA can be leveraged to solve these problems.

6.5 Case Study

We consider a tanker with ten ports of visit (i.e. K=10) and schedule as shown in Table 6.1. Note that the sea voyage time (TT_k) of leg k ($1 \leq k < K$), the arrival and departure times of the tanker at each port are based on assumption of a fixed sea voyage speed (13 knots) and no refueling being carried out over the ten-legged voyage. From the operational requirements pertinent to cargo loading and unloading, tank cleaning, port inspection, waiting at ports and sea voyages, the total fuel consumed (FC_k) by tanker from start to end of leg k ($1 \leq k \leq K$) can be computed accordingly and their values are also tabulated in Table 6.1. With the given route of the tanker, the decision-makers are able identify a set of operationally feasible refueling options at the end of these legs and they are also presented in Table 6.1.

Table 6.1: Route and schedule of tanker with the available refueling options

Leg (k)	Port	PC_k (\$)	ETA_k* (days)	ETD_k* (days)	TT_k (days)	FC_k (tonnes)	Available Refueling Options
1	P3	6798	1.62	2.11	2.00	25.92#	o164,o165,o166
2	P14	4045	4.11	4.67	2.12	32.06	o992,o993,o994
3	P29	5714	6.79	7.13	1.77	33.96	o2024,o2025,o2026
4	P12	2820	8.90	10.01	0.63	28.37	o830,o831
5	P23	3829	10.63	10.99	0.69	10.00	o1625,o1626,o1627
6	P27	12006	11.67	12.22	0.82	10.98	o1885,o1886,o1887
7	P13	13525	13.03	13.36	0.13	13.08	o885,o886
8	P14	4045	13.49	14.23	1.73	2.10	o965
9	P16	6561	15.96	16.52	0.35	27.65	o1087,o1088,o1089
10	P3	6798	16.87	17.70	-	27.65	-

* ETA_k and ETD_k are the estimated arrival and departure times of the tanker at the port of each leg k and the times are expressed in days from the start of planning horizon.
# The fuel consumed for the first leg is based on a time scale which starts from start of planning horizon till end of first leg.

The corresponding values of π_{ko}, F_{ko},σ_{ko}, τ_{ko}, RR_{ko} ($1 \leq k < K$) are for each of refueling options shortlisted in Table 6.1 are tabulated in Table 6.2. The set of cargos to be loaded (i.e $\mathbf{I}_k$) onto the tanker, unloaded (i.e. $\mathbf{U}_k$) by the tanker at the end of its k^{th} leg are shown in Table 6.3. The freight rates (SR_i) and weights of all these cargos are listed in Table 6.4. The earliest and latest pick up times (i.e. EPT_i and LPT_i respectively) of cargo i in set $\mathbf{I_k}$ are also tabulated in Table 6.4. The stowage plan of all cargoes involved over the entire voyage of the tanker is illustrated in Figure 6.4. Note that CT #P and CT #S represent the cargo tank IDs while a row in each cell (representing a cargo tank) denotes cargo ID: cargo volume: pick-up port number: discharge port number. For example, cargo C6 (which is loaded and unloaded by tanker during its fourth and tenth ports of visit respectively) is stowed in cargo tanks CT 6P and CT 6S in parcels of 851.4m^3 and 859.1m^3 respectively. This stowage arrangement is denoted in Figure 6.4 by C6: 851.4: 4: 10 and C6: 859.1: 4: 10 in cells of CT 6P and CT 6S respectively. Please also note that a cargo with pick-up port number of 0 means that the cargo is onboard the tanker at time zero.

Table 6.2: Related information of available refueling options

Refuel Option	F_{ko} **(tonnes)**	σ_{ko} **(day)**	τ_{ko} **(tonnes)**	π_{ko} **($)**	RR_{ko} **(tonnes/day)**
o164	1.9334	0.5850	0.7644	659.3	10958.3
o165	1.0791	0.3739	0.7022	819.8	19338.6
o166	1.2445	0.6274	0.3334	626.9	20737.4
o992	0.6042	0.5239	0.1343	798.3	19045.1
o993	1.7756	0.6218	0.3057	932.3	21854.3
o994	1.2980	0.6754	0.0535	857.0	12472.5
o2024	1.7812	0.5578	1.0104	533.1	20687.9
o2025	1.9830	0.4655	1.1400	739.0	20553.3
o2026	1.2706	0.3838	0.9320	627.9	18480.2
o830	1.2090	0.2576	0.7688	951.8	11633.0
o831	1.4365	0.6425	0.5181	870.7	21727.4
o1625	1.8851	0.5357	0.9945	825.4	10771.2
o1626	1.2446	0.3824	0.5476	921.7	11000.6
o1627	1.1937	0.4144	0.8758	684.5	20296.9
o1885	0.7423	0.4878	0.5401	457.6	16405.9
o1886	1.8858	0.3176	0.8858	761.8	15092.9
o1887	0.8400	0.3099	0.2055	404.1	18454.6
o885	1.9796	0.3888	0.3140	937.3	12273.4
o886	0.9481	0.5126	0.8734	500.2	13196.3
o965	1.1228	0.2224	0.1765	542.1	20097.8
o1087	1.1931	0.5580	1.1813	989.1	22684.0
o1088	1.7100	0.4166	0.2740	825.8	19418.1
o1089	0.7784	0.6972	0.7753	685.6	19929.5

Table 6.3: Sets of cargos to be loaded and unloaded at each leg by tanker

Leg (*k*)	**I_k**	**U_k**
1	-	C43, C44, C45, C46
2	-	C47
3	-	C51, C52
4	C6, C10, C30, C31	-
5	-	C10
6	C33	C48, C49, C50
7	-	C33
8	C34, C35	-
9	-	C30, C31
10	-	C6

Table 6.4: Details of cargoes loaded and unloaded by tanker

Cargo (*i*)	**SR_i ($)**	**Weight (tonnes)**	**Density (tonnes/m^3)**	**EPT_i**	**LPT_i**
C6	62760	2092	1.223	8	13
C10	30000	500	0.948	6	11
C30	16000	500	0.865	8	13
C31	32000	1000	1.497	8	13
C33	23999.5	350	1.383	8	14
C34	20000	500	1.04	14	19
C35	8000	200	1.678	14	19
C43	12600	315	1.644	-	-
C44	12600	315	1.565	-	-
C45	12600	315	1.785	-	-
C46	7960	199	1.621	-	-
C47	48425	1490	1.512	-	-
C48	13650	455	1.811	-	-
C49	3150	105	1.564	-	-
C50	15270	509	1.606	-	-
C51	15006.6	210	1.764	-	-
C52	15006.6	210	1.531	-	-

Note: Cargos which are onboard the tanker at time zero have no earliest and latest pick up times.

	Port	Starboard	
CT 1P	C50: 316.9: 0: 6 C34: 480.8: 8: 10	C48: 215.2: 0: 6 C35: 119.2: 8: 10	**CT 1S**
CT 2P	C30: 578.0: 4: 9 C43: 191.6: 0: 1	C45: 176.5: 0: 1	**CT 2S**
CT 3P	C52: 137.2: 0: 3 C31: 668.0: 4: 9	C46:122.8: 0: 1 C10: 527.4: 4: 5	**CT 3S**
CT 4P	C51: 119.0: 0: 3 C33: 253.1: 6: 7	C49: 67.1: 0: 6	**CT 4S**
CT 5P			**CT 5S**
CT 6P	C47: 985.5: 0: 2 C6: 851.4: 4: 10	C44: 201.3: 0: 1 C6: 859.1: 4: 10	**CT 6S**

Figure 6.4: Cargo stowage plan of tanker in case study

At the start of the planning horizon, the unit fuel prices (P_o) of the available refueling options (i.e. o164, o165 and o166) at the end of tanker's first leg are known ($377.551/tonne, $368.816/tonne, $354.823/tonne respectively). In contrast, the unit fuel prices (P_{ko}^{χ}) of the available refueling options in subsequent legs (1<k<K) are uncertain and expressed in 1000 discrete scenarios (i.e. NS=1000). Due to the sheer size of these unit fuel price data, we are unable to present them all fully in tabular formats. The readers may obtain the full data set of unit fuel prices used in this case study by contacting the author's thesis supervisor. The loading (LR_i) and unloading rates (DR_i) of all cargos involved are assumed to be 4800 tonnes per day. In addition, each scenario χ ($1< \chi \leq NS$) has equal chance of occurrence (i.e. Pr_χ = 0.001). The rest of the parameters in our TROP are tabulated in Table 6.5.

Table 6.5: Values of other problem parameters

Parameter	Value
T_1	1.62 day
BFL_1	65 tonnes
$\underline{Q}$	50 tonnes
$\overline{Q}$	180 tonnes
Q_{min}	10 tonnes
β	$3000/day
α	0.01
μ	0.1 tonne/day
M	500000
DOC	$7000/day
T_{adm}	0.25 day

In previous chapter, we introduced a novel solution procedure known as scenario condensation approach (SCA) and demonstrated how it can effectively address problems like stochastic capacity expansion problem (SCEP) with two-stage mixed-integer programming framework. Instead of duplicating the description of the underlying steps involved in SCA, readers may refer to the previous chapter for the algorithmic details of SCA as well as the notation used to describe the solution procedure. Essentially, SCA entails identification of key scenarios (i.e. characteristics and critical lower tail-end scenarios) and solving an equivalent MILP model with account of only these scenarios in the formulation.

6.5.1 Modifications of SCA

The algorithmic procedure of SCA applied in this case study is basically the same as that employed in the case studies of previous chapter. The only difference lies in how the P first–stage solutions are randomly generated. The generation of random first-stage solutions in SCA of in previous chapter entails assignment of a random value between the upper and lower expansion limits as the capacity expansion volume of each facility selected for expansion. Note that the upper and lower expansion limits of each facility are given data in SCEP. Each set of first-stage solutions is then subsequently used to solve the second-stage problem in all scenarios if it does not violate the capital expenditure limit. In this case study, the generation of random first-stage solutions also entails assignment of a random value between the maximum and minimum allowable refueling times as the time employed for refueling purpose (inclusive of voyage to the refueling port) for a selected refueling option (*o*) at the end of the first port visit by the tanker. Note that we do not need to generate random value for T_2 since the latter can be computed accordingly once x_o and Q_o are fixed. We denote the maximum and minimum allowable refueling times of refueling option *o* as $\overline{RFT}_o$ and $\underline{RFT_o}$ respectively. Note that from the time allocated (say κ, where $\overline{RFT}_o \leq \kappa \leq \underline{RFT_o}$) for refueling using a specific refueling option (*o*), the corresponding amount of fuel (Q_o) to be purchased can be computed accordingly as shown below.

$$Q_o = (\kappa - \sigma_{1o}) RR_{1o} \tag{6.26}$$

Unlike the SCA employed to address SCEP in previous chapter, the values of $\overline{RFT}_o$ and $\underline{RFT_o}$ of each available refueling option (*o*) after the first port visit need to be predetermined to ensure feasibility of second-stage problem in all possible scenarios. This is crucial to prevent SCA from expending excessive resource attempting to solve infeasible second-stage problem of any scenario during the initialization step. Essentially, these maximum and minimum allowable refueling times of any refueling option available at the end of the first port visit must be assigned in such a manner that any amount of time allocated for refueling purpose that falls within the limits will not cause the tanker to breach any of the cargo pickup laycan constraints, upper and lower limits of marine fuel level onboard in any of the subsequent legs ($1<k\leq K$).

Clearly, $\underline{RFT_o}$ is the total time needed to refuel to the minimum fuel level (L) of the tanker or total time needed to purchase the minimum refueling quantity (i.e. $Q_{\min}$) based on a selected refueling option (o) after the first port visit, whichever is lower. The former is based on the need to ensure that the tanker's fuel level satisfies lower fuel limit requirement (i.e. equation 6.15) when the tanker employs any of the refueling options (o') that are available at the end of its second port visit (i.e. k=2). Therefore, we have,

$$L = \max_{o'}\left(\max\{\underline{Q}-(BFL_1-\tau_{1o}-FC_2-\tau_{2o'}),0\}\right) \tag{6.27}$$

where, $\max_{i\in\{1,2,3\}}\left(C_i\right) = C_3$ if $C_3\geq C_1$ and $C_3\geq C_2$ and max{A,B} = A if A≥B.

Correspondingly, $\underline{RFT_o}$ can be expressed as follows.

$$\underline{RFT_o} = \max(\sigma_{1o}+\frac{L}{RR_{1o}},\sigma_{1o}+\frac{Q_{min}}{RR_{1o}}) \tag{6.28}$$

The maximum allowable refueling time $\overline{RFT}_o$ of a refueling option (o) after the tanker's first port visit is not only based on capacity limit of the tanker's fuel tank (i.e. $\overline{Q}$). It also has to take into consideration of due times (represented by LPT_i) for pickup of cargos in subsequent legs ($1<k<K$). As such, an additional step has to be undertaken to determine the maximum delay that is permissible to the tanker for refueling purpose at the end of its first port visit without breaching the pickup laycan constraints of all

cargos involved in subsequent legs ($1<k<K$). This step requires determination of the maximum delay that is permissible for the arrival of the tanker in each port from the second legs onwards ($1<k<K$). The maximum permissible delay (MPD_k) in arrival of tanker at each port where there is cargo loading from the second legs onwards ($1<k<K$) is

$$\text{MPD}_k = \min_{i \in I_k}\left(\max\{LPT_i - ETA_k - 0.5T_{adm}, 0\}\right) \quad 1<k<\text{K} \tag{6.29}$$

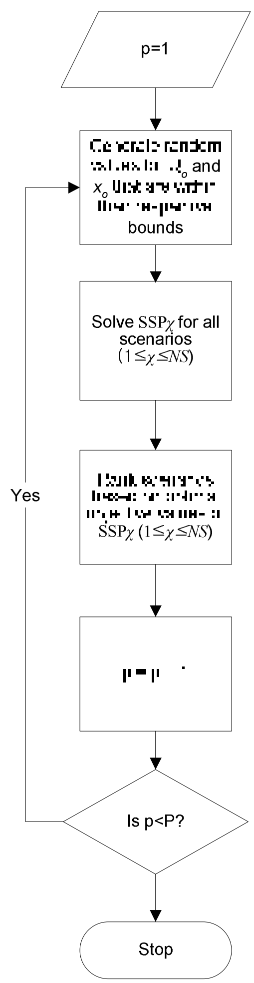
where, $\min_{i\in\{1,2,3\}}(C_i) = C_3$ if $C_3 \leq C_1$ and $C_3 \leq C_2$.

At legs ($1<k<K$) where there is no loading of cargo, MPD_k is assigned a large value. Thus, the maximum allowable refueling time $\overline{RFT}_o$ of a refueling option (o) after the first port visit is,

$$\overline{RFT}_o = \min\left(\min_{2\leq k\leq K}(\text{MPD}_k), \sigma_{1o} + \frac{\bar{Q} - BFL_1 - \tau_{1o}}{RR_{1o}}\right) \tag{6.30}$$

With $\overline{RFT}_o$ and $\underline{RFT}_o$ available for all possible refueling options of the tanker after its first port visit, we can then proceed to randomly generate first–stage solutions that guarantee the feasibility all second-stage problem of all scenarios within the solution framework of SCA. Refer to Figure 6.5 and Appendix C for the underlying algorithmic procedures involved in this case study in the initialization step of SCA and random generation of first-stage solutions respectively. Note that the second-stage problem of scenario χ (SSPχ) has constraints defined by equations (6.2), (6.4), (6.6), (6.8), (6.9), (6.10), (6.11), (6.12), (6.13), (6.15), (6.17), (6.19), (6.21) and objective of minimizing $\sum_{k>1}\sum_{o}(\pi_{ko}x_{ko}^{\xi} + P_{ko}^{\xi}Q_{ko}^{\xi}) + T_{K}^{\xi}DOC$. Essentially, the solution procedure of SCA that follows after its initialization step in this case study is the same as that of SCA procedure described in preceding chapter.

Figure 6.5: Process flow in the initialization step of SCA



6.5.2 Results

We first applied SCA to solve the aforementioned TROP with P = 30 and φ = 10. We coded SCA in Visual C++ and used CPLEX 10.1 within GAMS (Distribution 22.3) as the standard solver for any MILP model encountered in the algorithmic procedure. In this case study, we also ran our Visual C++ program on a Windows XP workstation with a Pentium 4 Xeon (2.8 GHz, 2 GB RAM) processor. The program requires a total solution time of 1459.36s before yielding a refueling plan that entails the choice of o165 as the refueling option to employ with refuel amount of 53.24 tonnes (i.e. $x_{o165} = 1$, $Q_{o165} = 53.24$ tonnes) after the tanker's first port visit. The key outputs of SCA are summarized in Table 6.6.

Table 6.6: Key outputs of SCA in case study

Output	Value
$\|\boldsymbol{C}\|$	5
$\|\boldsymbol{S}\|$	40
a^*	0.8655
b^*	15,793
R^{2*}	0.6231

* Linear correlation of $Z_A = aZ_S + b$ is determined by adding trendline option in Excel

In this case study, the set of characteristic scenarios (***C***) selected by SCA that offers the best fit description on the linear relationship between the objective values of EMIP-S and EMIP-A (see previous chapter for their definitions) has R^2 value of 0.6231. The latter is evidently low relative to the corresponding R^2 values in the three case studies reported in chapter 5. This can be attributed primarily to the greater rank spread of the scenarios involved in this case study compared to those in the previous three case studies. For each of the aforementioned case studies, we plotted (see Figure 6.6) the spread ratio cumulative percentage of all scenarios involved using the P sets of feasible first stage solutions generated in the initialization step of SCA where spread ratio (θ_ξ) of each scenario (ξ) is defined as follows.

$$\theta_{\xi} = (\text{MaxRank}_{\xi} - \text{MinRank}_{\xi})/NS \qquad (6.31)$$

Evidently, the scenarios involved in this case study have wider spread of ranks compared to those of case studies reported in the previous chapter. This means that the number of scenarios which are available for selection as characteristic scenarios (that can satisfy the constraint of equation 5.49 which forbids overlapping of ranks) is less in faction of total number of scenarios (i.e. *NS*) in this case study compared to others. As a result, the selected characteristic scenarios in this case study are not able offer a fit on the linear relationship between the objective values of EMIP-S and EMIP-A that matches those of previous three case studies. In addition, the greater overlapping of ranks among of the scenarios in this case study has also resulted in identification of only five characteristic scenarios even though there are 1000 scenarios (i.e. *NS*=1000) to choose from. This is small relative to the 8, 10, and 5 characteristic scenarios selected in the previous three case studies respectively where there are a total of 200 scenarios (i.e. *NS*=200).

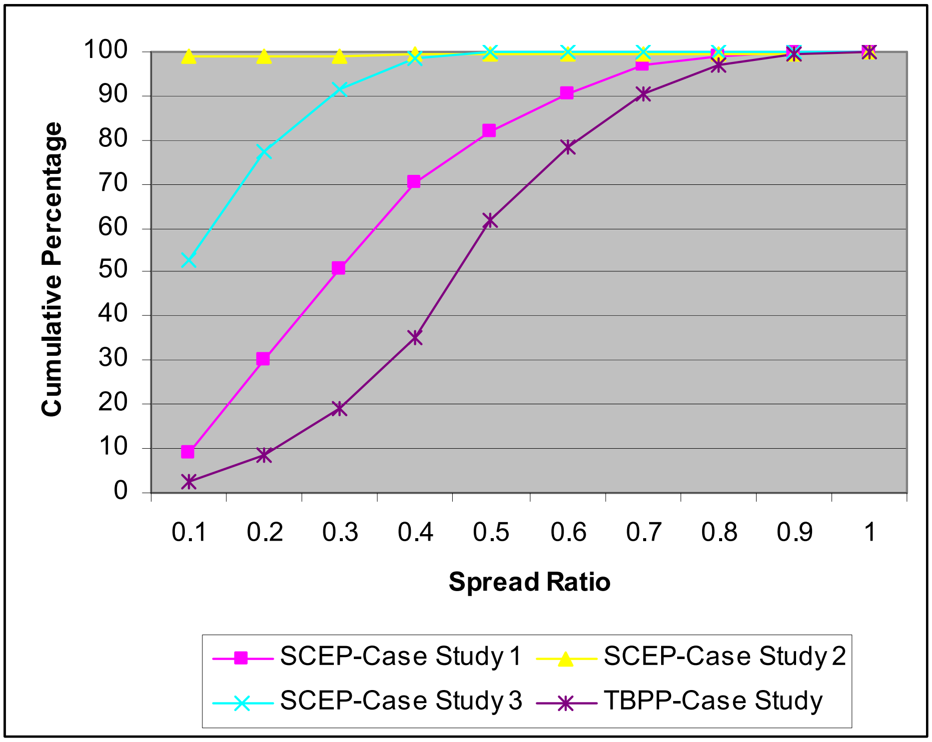


Figure 6.6: Spread ratios of scenarios in case studies

To evaluate the effectiveness of SCA in addressing a TROP relative to commercial solver like CPLEX, we employ the latter solve the equivalent MILP model described in section 6.5 with account of all scenarios on the same hardware with resource limit (i.e. solution time limit) set to be the total solution time (i.e. 1459.36s) needed by SCA to determine its refueling plan. Coincidentally, CPLEX yields a refueling plan which is the same as that of SCA with reported relative optimality gap of only 1.46%. Note that the aforementioned equivalent MILP model involves 45,007 continuous variables, 21,003 binary variables, 106,012 constraints, and 547,041 nonzeros. From these results, it is evident that SCA matches CPLEX both in terms of solution quality and solution time in addressing TROP. To further verify the effectiveness of SCA as a solver of TROP, we repeat the same experimental run on another three TROPs where we first employ SCA to solve each of these problems before CPLEX is used to solve it with resource limit (i.e. solution time limit) set to be the corresponding total solution time needed by SCA. We distinguish these three other TROPs as case studies A, B and C respectively. Essentially, these three TROPs are similar to the TROP reported in the beginning of this section. They only differ from one another in terms of three initial conditions of tanker as shown in Table 6.7.

Table 6.7: Differences of three case studies

Parameters	Case Study		
	A	B	C
BFL_1 (tonnes)	56	65	85
$\underline{Q}$ (tonnes)	50	40	60
Q_{min} (tonnes)	10	10	20

SCA required a total solution time of 1457.52s, 1457.34s, and 1498.93s respectively to determine the refueling plans for case studies A, B and C. The key outputs of SCA are tabulated in Table 6.8. Using the same time resources, CPLEX is able to derive solutions only for case studies A and B with relative optimality gaps of 2.59% and 3.80% respectively. In contrast, CPLEX fails to determine any feasible solution in case study C in 1498.93s. The key solution outputs of SCA and CPLEX in case studies A and B are presented in Table 6.9 while the distributions of tanker's profit based on the solutions of SCA and CPLEX in these two case studies are also illustrated in Figures 6.7 and 6.8 respectively. Note that the profit of the tanker is sales revenue from the carrying of cargos concerned less the port dues, cost of refueling and time chartering the tanker. From Table 6.9, it is obvious that the solutions determined by SCA and CPLEX are comparable in case studies A and B with the former (latter) offering marginally better solution in terms of expected profit (VAR). Given (1) the small relative optimality gaps of 2.59% and 3.80% respectively of CPLEX solutions in these two case studies, and (2) the inability of CPLEX to solve case study C using the same time resource needed SCA to determine its solution, the aforementioned results again reaffirm SCA's robustness and effectiveness to determine good solution to TROPs.

Table 6.8: Key SCA outputs in three case studies

Output	**Case Study**		
	A	**B**	**C**
$\|\boldsymbol{C}\|$	4	5	5
$\|\boldsymbol{S}\|$	36	35	33
A^*	1.1258	1.0202	0.9564
B^*	-10,339	-227.69	6693.6
R^{2*}	0.9189	0.7327	0.6662

* Linear correlation of $Z_A = aZ_S + b$ is determined by adding trendline option in Excel

Table 6.9: Solution details of SCA and CPLEX in case studies A and B

Case Study	**Solution Approach**	**Refuel option to employ**	**Refuel quantity (tonnes)**	**Expected Profit ($)**	**VAR* ($/day)**
A	SCA	o165	62.24	105,146	5,353.1
	CPLEX	o165	111.34	102,927	5,632.9
B	SCA	o165	43.24	112,198	5,746.4
	CPLEX	o165	106.78	108,117	6,001.3

* VAR refers to the profit level of tanker where the probability of falling below or equal to it is α.

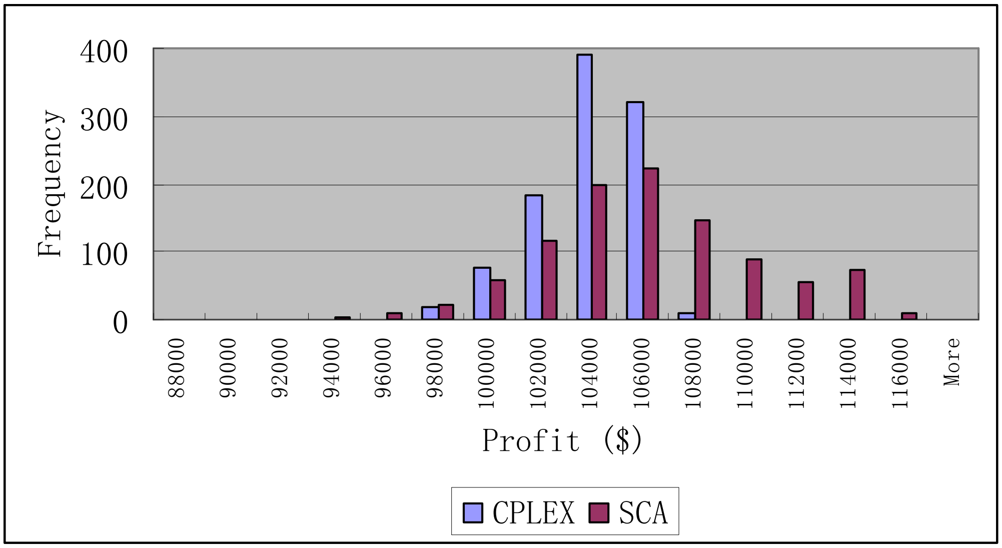


Figure 6.7: Profit distributions of tanker in case study A

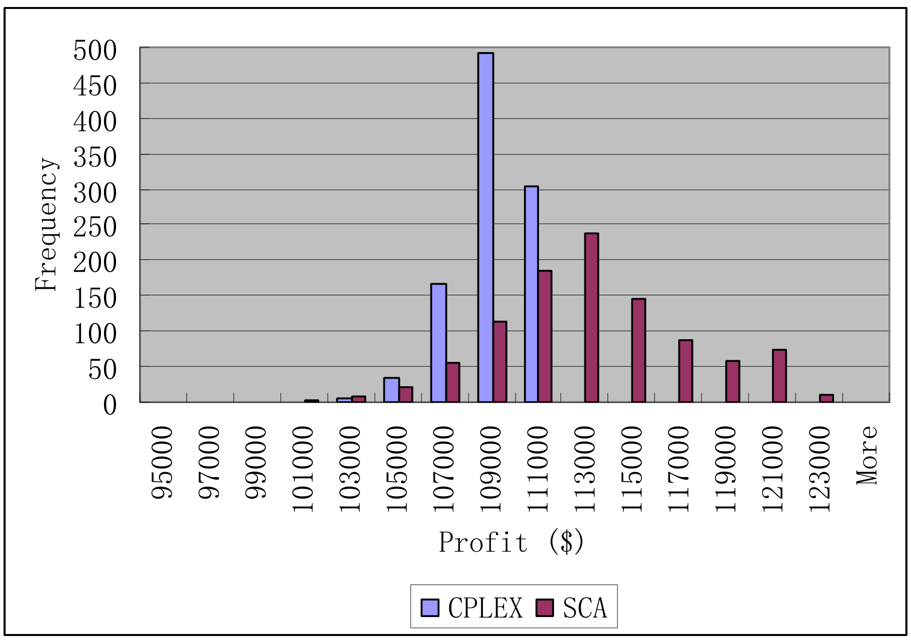


Figure 6.8: Profit distributions of tanker in case study B

Evidently, SCA is an effective algorithm in addressing TROP given its ability to determine solutions with small relative optimality gaps. In addition, it is also able solve problems like the TROP in case study C where CPLEX fails to find a feasible solution using the same time resource needed SCA to determine its solution. Though the selected characteristic scenarios in the case studies of this section are not able offer a fit on the linear relationship between the objective values of EMIP-S and EMIP-A that matches those of results reported in chapter 5, this has not prevented SCA from generating a good solutions to all TROPs discussed in this section. As such, our case study results clearly support comments in previous chapter that SCA possesses desirable characteristics which make it an attractive option to solve problems which share similar problem structure as their SCEP.

6.6 Discussion

To the best of our knowledge, no model has been developed to address TROP. Though the importance of accounting for fuel price uncertainty in operational planning of tankers is intuitive, no study has ever been done to quantify the potential financial benefits of doing so. This chapter makes some primal and significant contributions towards research on tanker refueling planning in two major ways. First, it introduces an unprecedented MILP model that addresses TROP of industrial scale with account of fuel price uncertainty and key operational constraints faced by tanker owners. These constraints include those pertinent to cargo pickup time windows, fuel level and tonnage limits. Second, it also demonstrates how a practical novel solution procedure can be applied to solve similar problem of much larger scale. As highlighted previously, the above novel model can be applied to address refueling planning problems of other vessel types including container ships, reefers, etc. even though the model is developed for tankers that primarily support bulk maritime transportation of chemical cargos.

Nevertheless, there are three other extensions of the TROP addressed in this chapter which are relevant to the tanker industry and which need to be addressed. The first such extension entails inclusion of fuel purchase options under forward contracts within the problem scope of TROP to reflect the industry practice where ship owners purchase their marine fuel either from spot markets (as a single transaction) or on a contract basis. Another possible problem extension consists of encompassing ballast water allocation decisions to manage stability and structural integrity of the vessel in the problem formulation of TROP. Generally, the operators of all sea-carriers must ensure a proper weight distribution of their loads (inclusive of cargos, fuel, fresh water, etc) to uphold the structural integrity and stability of their carriers. As fuel onboard a tanker changes due to refueling or consumption, ballast water may have to be loaded onto specific compartments of the vessel to restore its overall stability. Inevitably, inclusion of ballast water allocation decisions would help to improve the overall realism of TROP. The third possible problem extension involves encompassing vessel speeds as decision variables in the problem scope. In practice, tanker owners may resort to lowering the voyage speeds of their vessels to cut down their fuel expenses since fuel consumption rate of a vessel generally increases with its speed. Recently, Jameson (2008) reported that several major shipping companies like Torm, Orient Overseas Container Line Ltd. (OOCL), Maersk, China Ocean Sipping Company (COSCO) have lowered the cruising speeds of their respective vessels to cope with the rising fuel costs. Generally, fuel consumption rate of a vessel is proportional to the third power of its cruising speed (Ronen, 1993). However, lowering of vessel speed is a viable option only if (1) the longer voyage time of vessel does not result in delay of cargo delivery and/or pickup which is deemed unacceptable by the charterers or shippers, and (2) sum of fuel and other operating costs is reduced. Clearly, the task of deciding the vessel speeds that will satisfy all relevant operational constraints and minimize the overall expenses of ship owners is complex, especially given the nonlinear relationship between fuel consumption rate and vessel speed.

Though the inclusion of additional decision variables and constraints in these three extensions enhances the industry realism of TROP, it also further complicates its mathematical formulation drastically. This in turn may require development of new solution approaches in order to meet the practical needs of end-users. On the whole, these extensions do offer exciting research opportunities, which can significantly enhance decision-making processes of tanker companies in their operational planning of tankers.

7. Conclusions and Future Work

The competition within global chemical industry has intensified over the years due to globalization, rising raw material costs and operating expenses, etc. In their bids to compete in the new economic era, many chemical companies have turned to reconfiguring their supply chain design or/and revamping their supply chain operations. Given the inherent complexity of such strategic and operational problems, it is prudent that chemical companies formulate their plans and policies with adequate assistance from solutions of corresponding supply chain optimization models. However, there are two critical conditions that must be met before chemical companies can appreciate the benefits of employing optimization models to support their supply chain decision-making processes. First, these optimization models must account for all industrially relevant business factors and constraints within their respective supply chain problems of interest so that their solutions are of practical value to the chemical companies. Second, efficient solution methodologies that can meet the practical needs of industry practitioners must be available so that they can truly harness the benefits of these optimization models as their decision-support tools.

7.1 Conclusions

On the whole, this dissertation contributes to chemical supply chain optimization research in three major ways. Firstly, it introduces and classifies the major regulatory factors that can influence strategic decisions in the design and operation of chemical supply chains. In addition, it presents a concise introduction and overview of a not so well-known but important regulatory factor (i.e. duty drawback) which is relevant to the chemical and other industries with multi-product manufacturing processes. Given the global nature of chemical companies due to their geographical spread, overseas material procurement, and international product sales, it is imperative for chemical companies to account for these regulatory factors both in designing their supply chain network of suppliers, manufacturing plants, distribution centers, customers and in managing the flow of materials and information across these supply chain entities. However, it is surprising to note that existing chemical supply chain models in the literature which have incorporated the effects of regulatory factors are few and far between despite the significant impact of regulatory factors on business operations and performance.

To fill the research gap attributed to the lack of models with account of regulatory factors, this dissertation introduces five new chemical supply chain optimization models which essentially constitute its second major contribution to chemical supply chain optimization research. These models include (1) a new MILP model for the deterministic capacity expansion planning and material sourcing in global chemical supply chains, (2) a new LP model for deterministic production-distribution planning in global multi-product manufacturing environment, (3) a new MILP model for extended deterministic capacity expansion planning with realistic representation of the relationship between expansion duration and expansion volume and a more comprehensive account of regulatory factors, (4) a new MILP model which addresses a stochastic capacity expansion planning problem with account of financial risk constraint, realistic representation of the relationship between expansion duration and expansion volume and comprehensive account of regulatory factors, (5) a new MILP model to represent a stochastic tanker refueling planning problem also with account of financial risk constraint and other relevant regulatory factors. To illustrate the importance of accounting for regulatory factors in supply chain decision-making processes, we have also used case studies of industrial scale to highlight the superiority of solutions (i.e. capacity expansion and production-distribution decisions respectively) of the first two new models compared to those of similar models where no regulatory factor is accounted for.

The five new proposed models also possess several features which are absent in most existing models. For example, the generic representation of duty drawbacks in the production-distribution planning model offers flexibility to accommodate stringent regulations (such time limit that may be imposed in drawback regulations on the interval between manufacturing and export of a product) pertinent to duty drawbacks. Moreover, it also provides a unique traceability feature that may be required by the duty drawback regulations of countries concerned. The only previous work (Arntzen et al., 1995) on production-distribution planning which has accounted for duty drawback does not have the aforementioned features. The forth new model also distinguishes itself from others in the literature by not only its comprehensive account of several regulatory factors and realistic representation of the relationship between expansion duration and expansion volume. It also incorporates financial risk control constraint that is widely used in the industry and that can be represented quantitatively in accordance to the risk appetite of industry practitioners. Although the aforementioned five new models are developed with a perspective of the CPI, it is important to highlight that their generic nature makes them applicable to (1) the capacity expansion and production-distribution planning in other manufacturing industries like the pharmaceutical and the consumer electronics industries, or (2) the refueling planning of other ship types such as container ships and other bulk carriers.

The third major contribution of this dissertation is primarily attributed to the development of novel solution approach to address stochastic capacity expansion planning problem with financial risk control constraint. In particular, the new algorithmic procedure exhibits a highly parallel solution structure which can be exploited for computational efficiency or to avoid scenario of no solution due to be memory limitation of hardware. Through application of the new solution approach on several case studies of industrial scale and comparison of their results with those derived by commercial solver, the new solution approach has clearly demonstrated its robustness to determine good solutions of realistic problems of industrial scale efficiently. This is a definitely major milestone in methodology development since none of the existing solution methodologies can solve large-scale stochastic capacity expansion problem or other similarly structured problems (such as stochastic tanker refueling planning problem) with risk control constraint as efficiently as our proposed approach.

7.2 Future Work

Though this dissertation has to some extent narrowed the research gap in chemical supply chain optimization, there are three key areas which deserve future research attention. We present these three areas of future work in the following sections.

7.2.1 Comprehensive Account of Regulatory Factors

Among all existing models in the literature that have been developed to address supply chain problems, only few of them have accounted for regulatory factors in their model constructions. Among the regulatory factors that have been incorporated into these few models, it is interesting to note that there are regulatory factors which are accounted for in some models but not others or vice versa. Moreover, there are also other regulatory factors such as repatriation taxes, withholding taxes, transfer pricing policies, etc. which have not be accounted for in any of the existing models. Clearly, there is still lack of global supply chain optimization models which comprehensively cover all key regulatory factors that may have a significant impact on the bottom line performance of corporate organizations. Inevitably, the complexities of a supply chain models increase as more regulatory factors are accounted for in them. As such, ample research opportunities in chemical supply chain optimization domain remain available and they are pertinent to the development of (1) models with comprehensive account of regulatory factors, and (2) solution methodologies that can efficiently address these models.

7.2.2 Disruption Management

Over the years, the world has been hit by a series of unexpected turbulent events that exposed the vulnerability of modern supply chains. The September 11 terrorist attacks in 2001, the labor strikes which cause West Coast port shutdown in 2002, the massive power outages that affected much of northeastern United States and Canada in 2003, the obliteration of oil refining and exploration facilities near the Gulf Coast by hurricane Katrina in 2005 are instances of turbulent events that have wrecked havoc to scores of supply chains. Many companies, which were ill prepared, have suffered heavy losses because their supply chains do not have the agility to respond effectively and efficiently to these disruptions. As a result, many multinational companies across practically all industries are beginning to look into ways of revising their supply chain configurations and practices so that they can operate in the event of serious disruption and in the most cost-effective manner. It is evident that this increased awareness of risks associated with supply chain disruptions has attracted interests from academics in this field of research in recent years. Development of supply chain operation models or frameworks that can serve as decision support tools in the presence of disruptions or to anticipate and prepare for disruptions is likely an emerging area that researchers may venture into.

7.2.3 Account of More Realistic Operational Constraints and Factors

There are several possible extensions of our proposed capacity expansion and production-distribution planning models which will enhance their industrial realism and application potential. One such extension involves using our production-distribution model as a basis for handling uncertainty in problem parameters via scenario-planning approach. A second possible extension which is valid for both capacity expansion and production-distribution models entails incorporation of non-linear relationship between raw material consumption and merchandise production which inherently complicate the drawback computations. Finally, another possible extension for the three new models may also appear in the form of accounting for economies scales in transportation freight expenses. Clearly, all these extensions are relevant to the manufacturing world as they reflect real challenges and operational constraints posed to the manufacturers. Therefore, future work should be focused on improving the capacity expansion and production-distribution planning models' formulations and development of practical solution methodology that can solve the improved models efficiently so that industrial applicability of our models can be expanded further.

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Appendix A: List of Papers That Address LAPs

Authors	Title	Year
Balachandran, V.; Jain, S.	Optimal facility location under random demand with general cost structure	1976
Brown, G.; Graves, G; Honczarenko, M.	Design and operation of a mutlicommodity production/distribution system using primal goal decomposition*	1987
Cohen, M.; Lee, H.	Resource deployment analysis of global manufacturing and distribution networks*	1989
Cooper, L.	Location-allocation problems	1963
Franca, P.; Luna, H.	Solving stochastic transportation-location problems by Generalized Benders Decomposition	1982
Geoffrion, A.; McBride, R.	Lagrangean relaxation applied to the capacitated facility location problem	1978
Goetschalckx, M.; Vidal, C.; Dogan, K.	Modeling and design of global logistics systems: A review of integrated strategic and tactical models and design algorithms*	2002
Harkness, J.; ReVelle, C.	Facility location with increasing production costs	2003
Jucker, J.; Carlson, R.	The simple plant-location problem under uncertainty	1976
Karkazis, J.; Boffey, T.	The multi-commodity facilities location problem	1981
Kaufman, L.; Eede, M.; Hansen, P.	A plant and warehouse location problem	1977
Kouvelis, P.; Rosenblatt, M.; Munson, C.	A mathematical programming model for global plant location problems: Analysis and insight*	2004
Kuehn, A.; Hamburger, M.	A heuristic program for locating warehouses	1963
Laporte, G.; Louveaux, F.; Hamme, L.	Exact solution to a location problem with stochastic demands	1994
LeBlanc, L.	A heuristic approach for large scale discrete stochastic transportation-location problems	1977
Louveaux, F.; Peeters, D.	A dual-based procedure for stochastic facility location	1992
Maranzana, F.	On the location of supply points to minimize transport costs	1964
Santoso, T.; Ahmed, S.; Goetschalckx, M.; Shapiro,A.	A stochastic programming approach for supply chain network design under uncertainty*	2005
Sridharan, R.	Lagrangean heuristic for the capacitated plant location problem with single constraints	1993
Tcha, D.; Lee, B.	A branch-and-bound algorithm for the multi-level uncapacitated facility location problem	1984
Tsiakis, P.; Shah, N.; Pantelides C.	Design of multi-echelon supply chain networks under demand uncertainty*	2001
Warszawski, A.	Multi-dimensional location problems	1973
Weber, A.; Carl, F.	Theory of location of industries	1929
* LAP is addressed concurrently with production-distribution problem		

Appendix B: List of Papers That Address CEPs

Authors	Title	Year
Barchi, R.; Sparrow, F.; Vemuganti, R.	Production, inventory and capacity expansion scheduling with integer variables	1975
Giglio, R.	Stochastic capacity models	1970
Hiller, R.; Shapiro, J.	Optimal capacity expansion planning when there are learning effects	1986
Klincewicz, J.; Luss, H.; Yu, C.	A large-scale multilocation capacity planning model	1988
Lee, H.; Lee, I.; Reklaitis, G	Capacity expansion problem of multisite batch plants with production and distribution*	2000
Leondes, C.; Nandi, R.	Capacity expansion in convex cost networks with uncertain demand	1975
Li, S.; Tirupati, D.	Dynamic capacity expansion problem with multiple products: Technology selection and timing of capacity additions	1994
Liu, M.; Sahinidis, N.	Optimization in process planning under uncertainty	1996
Manne, A.	Capacity expansion and probabilistic growth	1961
Maravelias, C.; Grossmann, I.	Simultaneous planning for new product development and batch manufacturing facilities	2001
Papageorgiou, L.; Rotstein, G.; Shah, N.	Strategic supply chain optimization for the pharmaceutical industries	2001
Paraskevopoulos, D.; Karakitsos, E.; Rustem, B.	Robust capacity planning under uncertainty	1991
Sahinidis, N.; Grossmann, I.; Fornari, R.; Chathrathi, M.	Optimization model for long range planning in the chemical industry	1989
Sahinidis, N.; Grossmann, I.	Reformulation of the multiperiod MILP model for capacity expansion of chemical processes	1992
Veinott, A.; Wagner, H.	Optimal capacity scheduling-I	1962
Veinott, A.; Wagner, H.	Optimal capacity scheduling-II	1962
Wagner, H.; Whitin, T.	Dynamic version of the economic lot size model	1959
* CEP is addressed concurrently with production-distribution problem		

Appendix C: List of Papers That Address SCEPs

Authors	Title	Year
Arntzen, B.; Brown, G.; Harrison, T.; Trafton, L.	Global supply chain management at Digital Equipment Corporation	1995
Chandra, P.; Fisher, M.	Coordination of production and distribution planning	1994
Chen, C.; Wang, B.; Lee, W.	Multiobjective optimization for multienterprise supply chain network	2003
Cohen, M.; Fisher, M.; Jaikumar, R.	International manufacturing and distribution networks: A normative model framework	1989
Cohen, M; Moon, S.	An integrated plant loading model with economies of scale and scope	1991
Dhaenens-Flipo, C.; Finke, G.	An integrated model for an industrial production-distribution problem	2001
Gjerjrum, J; Shah, N.; Papageorgion, L.	Transfer prices for multienterprise supply chain optimization	2001
Jackson, J.; Grossmann, I.	Temporal decomposition scheme for nonlinear multisite production planning and distribution models	2003
van den Heever, S.; Grossmann, I.; Vasantharajan, S.; Edwards, K.	A Lagrangean decomposition heuristic for the design and planning of offshore hydrocarbon field infrastructures with complex economic objectives*	2001
Vidal, C.; Goetschalckx, M.	A global supply chain model with transfer pricing and transportation cost allocation	2001
Wilkinson, S.; Shah, C.; Pantelides, C.	Integrated production and distribution scheduling on a Europe-wide basis	1996
Williams, J.	Heuristic techniques for simultaneous scheduling of production and distribution in multi-echelon structures: Theory and empirical comparisons	1981

Appendix D: Examples of Drawback Regulations

Regulation Subject	Examples
Process Registration	Under the Brand Rate of Duty Drawback Scheme (an individual drawback system) in India, an exporter must make an application to the Directorate of Drawback in a prescribed format along with documentary evidence on the quantities of inputs employed to manufacture the export, payment of duties, etc. within 60 days from the date of export of goods. After verifying documentary evidence, the Directorate of Drawback will authorize a basis of drawback claim to the exporter. This basis, which defines how the duty refund is computed, is valid for the particular export shipment and may be extended to future shipments subject to the availability of necessary supporting evidence.
Product Substitution	Manufacturers in the USA and EU nations may substitute domestic inputs for imported inputs in producing merchandise destined for export and still receive a refund of duty paid on the imported inputs. Such substitution is permitted, only if the domestic and imported inputs are of the same commercial quality, technical characteristics, or tariff classification.
Drawback Computation	Taiwan uses four methods to compute duty drawback rates. They are based on raw material criteria, fixed amount (specific duty) criteria, fixed percentage (ad valorem duty) criteria, and special provisions for certain components. For the computation of MD, EU nations adopt three main methods, namely quantitative scale method based on compensating products, quantitative scale method based on import goods, and value scale method.
Drawback Transfer	In the USA and EU nations, there are provisions that permit a manufacturer to transfer its right to claim the drawback for its product to another party.
Time Limits	In general, duty drawback is available in the USA, when imported merchandise is destroyed or used to manufacture an article that is exported within five years of import. However, US companies can claim for MD on petroleum derivatives, only if the export of finished products occurs within 180 days of manufacture.
Export Destinations	Both Common Market of Southern Cone (Mercosur) and NAFTA members have eliminated duty drawbacks to goods subsequently exported to their regional partner's markets.

Appendix E

Procedure for Generation of Feasible First Stage Solution in SCA

The following two steps are repeated for each facility ($f \in \boldsymbol{IF}$) which are shortlisted for capacity expansion or new construction (i.e. $Q_f^L > 0$).

Step 1: Randomly generate a real number between 0 and 1.0

Step 2: If the random number is greater than U[1],

> $y_f = 1$ and facility f will be expanded by an amount (q_f) which is randomly generated between Q_f^L and Q_f^U inclusive

otherwise

> facility f will not be expanded or constructed (i.e. $y_f = 0$)

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[1] In the reported case studies of chapter 5, U is set to be 0.2.

Appendix F: An Overview of Refueling by Ships

The global chemical trade achieved an impressive 14% average annualized growth between 2000 and 2006 to hit more than US$1.24 trillion in 2006 as reported by World Trade Organization (2007). To support this growing chemical trade which often requires maritime transportation of liquid chemical cargos in bulk between chemical processing facilities and manufacturers worldwide, the capacity of oil, chemical, and liquid gas tankers (300 gross tons and over) grew 3% annually between 2001 and 2005 to reach 368.4 million deadweight ton (dwt) at the beginning of 2005 (Heideloff et al., 2005). However, it is not all plain sailing to the tanker owners. The shipping sector which has enjoyed a boom in the past five years is now gearing itself for slower growth. In recent years, all ship owners have to contend with the constant threat of weakening voyage earnings due to high fuel prices which have almost doubled from 2006 to 2008 at one stage. With fuel expenses contributing up to 90% of a tanker daily operating cost, a prudent refueling plan and sound management of vessel's fuel consumption are crucial to the profitability of tanker owners, especially in current unfavorable business operating environment where global recession is looming due to the financial turmoil in United States and Europe.

The fuel that is used to run a ship is also commonly known as marine fuel or bunker fuel. Essentially, marine fuel is graded based on it viscosity which is the measurement of its internal resistance to flow at 50^{o}C and is measured in units of centistokes (cst). Majority of commercial marine vessels use marine fuel with viscosity in values of 180cst, 380cst, and 500cst with the most common being 380cst. Fuel with lower viscosity is generally sold at a premium price due to higher percentage of distillate fuel used in the blending process. Typically, ship owners purchase their marine fuel from spot markets (as a single transaction) or on a contract basis where the purchases are made under forward contracts. They can purchase their marine fuel either directly from major oil companies, independent physical suppliers or indirectly through third parties like traders and brokers. While marine fuel is sold at nearly every port involved in ocean-going trade, sales of the majority of marine fuel are concentrated among a limited number of ports in strategic locations where there are high ship traffic volume or high trade volume. Generally, these ports are located near major trade routes that allow ships to make stopover without a major deviation from their voyage schedule and they include the Panama and Suez canals, ports located along major straits such as Singapore, Gibraltar, Fujairah, Istanbul and ports located in the middle of open sea routes such as Malta, Southern Africa, Canary Islands and many of the Caribbean islands.

The process of loading marine fuel into a ship's fuel tank is also known in the industry as refueling. Correspondingly, ports that offer sales of marine fuel are also known as refueling ports. Marine fuel is mainly delivered to ships in two ways. First, refueling barges (which pull up alongside a ship to deliver the marine fuel) can transfer marine fuel to ships at rates from 200 to 1500 metric tons per hour. In 2005, it was reported by Marine and Energy Consulting Limited that ship-to-ship refueling deliveries accounted for approximately 80% of total marine fuel delivered. Second, marine fuel can also be delivered to ships through pipelines at berths where ships have physical access to pipelines. On average, pipelines can deliver marine fuel at a rate of 450 metric tons per hour.

In practice, ship operators make their refueling decisions after monitoring market prices and trends through the use of trade publications/indices or brokers and searching for the best possible prices on their trade route. Prior to the arrival in a port, the ship owner or a broker working on behalf of the ship owner will typically make contact with fuel suppliers in the port in which the ship intends to refuel and receive quotations for the marine fuel required. The refueling process will then proceed if the parties involved can reach an agreement of the refueling price and timelines. To keep their total operating expenses low, ship owners are always on the lookout for low cost refueling opportunities. Thus, they may be willing to deviate slightly from their respective normal courses, incur any necessary port dues or delay the transit through a canal to refuel at a port with attractively priced fuel. However, it is also crucial that these refueling decisions are made with consideration of constraints related to (1) pickup or delivery laycans of cargos in voyages after the refueling activities, and (2) tonnage limits of tankers. This is to ensure that the refueling activities of tankers do not result in violation of their respective cargo pickup and delivery laycan constraints, and their respective weight limits in subsequent voyages of the tankers.

Unfortunately, fuel prices are highly unpredictable and can exhibit significant variation across refueling ports. Given the above-mentioned operational constraints that all tanker owners have to contend with, an optimal tanker refueling plan that is not obvious and requires more than the experience and judgment of individuals. To the best of the authors' knowledge, none of the existing models in literature have been developed specifically for operational planning of tankers. It is also important to highlight the novel model that is proposed in this chapter can be applied to address refueling planning problems of other vessel types including container ships, reefers, etc. even though the model is developed for tankers that primarily support bulk maritime transportation of chemical cargos. This is possible primarily because refueling planning problems of all vessel types share similar problem characteristics and constraints. As such, the results, comments and findings that the rest of this chapter makes with regards to research in the area of tanker refueling planning are also applicable to refueling planning of other vessel types.

Publications and Conference Presentations

1. Oh, H-C; Karimi, I. Regulatory factors and capacity-expansion planning in global chemical supply chains. *Industrial and Engineering Chemistry Research* **2004**, *43*(13), 3365-3380.
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2009