FACILITY LOCATION, CAPACITY ACQUISITION AND TECHNOLOGY SELECTION MODELS FOR MANUFACTURING STRATEGY PLANNING

A THESIS
SUBMITTED TO THE DEPARTMENT OF INDUSTRIAL ENGINEERING
AND THE INSTITUTE OF ENGINEERING AND SCIENCE
OF BİLKENT UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

By
Vedat Verter
February, 1993

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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a dissertation for the degree of Doctor of Philosophy.

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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a dissertation for the degree of Doctor of Philosophy.

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Tek başına zoru başarmanın
bana en yakın örneği, annem,

Gönül Verter'e

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Abstract

FACILITY LOCATION, CAPACITY ACQUISITION AND TECHNOLOGY SELECTION MODELS FOR MANUFACTURING STRATEGY PLANNING

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February, 1993

The primary aim of this dissertation research is to contribute to the manufacturing strategy planning process. The firm is perceived as a value chain which can be represented by a production-distribution network. Structural decisions regarding the value chain of a firm are the means to implement the firm's manufacturing strategy. Thus, development of analytical methods to aid the design of production-distribution sytems constitutes the essence of this study. The differentiating features of the manufacturing strategy planning process within the multinational companies are especially taken into account due to the significance of the globalization in product, factor, and capital markets.

A review of the state-of-the-art in production-distribution system design reveals that although the evaluation of strategy alternatives received much attention, the existing analytical methods are lacking the capability to produce manufacturing strategy options. Further, it is shown that the facility location, capacity acquisition, and technology selection decisions have been dealt with separately in the literature. Whereas, the interdependencies among these structural decisions are pronounced within the international context, and hence global manufacturing strategy planning requires their simultaneous optimization. Thus, an analytical method is developed for the integration of the facility location and sizing decisions in producing a single commodity. Then, presence of product-dedicated technology alternatives in acquiring the required production capacity at each facility is incorporated. The analytical method is further extended to the multicommodity problem where product-flexible technology is also available as a technology alternative. Not only the arising models facilitate analysis of the trade-offs associated with the scale and scope economies in capacity/technology acquisition on the basis of alternative facility locations, but they also provide valuable insights regarding the presence of some dominance properties in manufacturing strategy design.

Keywords: Manufacturing Strategy, Production-Distribution Systems, Facility Location, Capacity Acquisition, Technology Selection, Global Manufacturing.

Özet

ÜRETİM STRATEJİSİ PLANLAMA İÇİN YER SEÇİMİ, KAPASİTE SATIN ALMA VE TEKNOLOJİ SEÇİMİ MODELLERİ

Vedat Verter
Endüstri Mühendisliği Doktora
Tez Yöneticisi: Doç Dr. M. Cemal Dinçer
Şubat, 1993

Bu çalışmanın ana amacı, üretim stratejisi tasarımı sürecine katkıda bulunmaktır. Her firma, belirli girdilerin, belirli aşamalardan geçerek ürün ve/veya servise dönüştürüldüğü bir katma-değer zinciri olarak ele alınabilir. Bu bağlamda, üretim-dağıtım serimleri firmaların modellenmesinde etkin bir araçtır. Bir firmanın üretim stratejisi, o firmanın katma-değer zincirinin yapısına ilişkin uzun vadeli kararlar içerir. Üretim-dağıtım serimlerinin tasarımına yönelik analitik yaklaşımların geliştirilmesi, bu çalışmanın özünü oluşturmaktadır. Ürün, faktör ve sermaye pazarlarında gözlemlediğimiz küreselleşme nedeniyle, çokuluslu şirketlerde üretim stratejisi tasarımı sürecinin ayırdedici nitelikleri bu çalışmada özellikle gözönüne alınmıştır.

Üretim-dağıtım serimi tasarımı üzerinde yapılan bir literatür taraması şu sonucu açığa çıkarmıştır: Bugüne kadar, strateji seçeneklerinin değerlendirilmesi ile ilgili birçok çalışma yapılmakla birlikte, önerilen yaklaşımlar üretim stratejisi seçeneklerinin belirlenmesinde yetersiz kalmaktadır. Ayrıca, yer seçimi, kapasite satın alma ve teknoloji seçimi problemleri bugüne dek

ayrı ayrı incelenmiştir. Halbuki, bu yapısal kararlar arasındaki ilişkiler özellikle uluslararası ortamda ön plana çıkmaktadır. Bu nedenle, global üretim stratejisi tasarımı yapısal kararların birlikte eniyilenmesini gerektirir. Öncelikle, bir ürünün üretiminde, tesis yeri seçimi ve kapasite satın alma kararlarının entegrasyonuna yönelik bir analitik yaklaşım geliştirilmiştir. Daha sonra, bu modele teknoloji seçimi kararları da dahil edilmiştir. Ayrıca, sözü edilen tek ürün modeli, çok sayıda ürünün üretimine yönelik, geleneksel/esnek teknoloji seçimi, kapasite ve tesis yeri kararlarının birlikte alınmasına olanak sağlayacak şekilde geliştirilmiştir. Önerilen yaklaşım, teknoloji seçeneklerine ilişkin ölçek ve çeşitlilik ekonomilerinin incelenmesi yanında, üretim stratejisi tasarımında varolan dominans özellikleinin de belirlenmesine yardımcı olmuştur.

Anahtar Kelimeler: Üretim Stratejisi, Üretim-Dağıtım Serimleri, Yer Seçimi, Kapasite Satın Alma, Teknoloji Seçimi, Küresel Üretim.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

A firm's manufacturing activity provides a reliable basis for being successful in the product markets. Thus, manufacturing performance is an important strategic weapon for both achieving and sustaining competitiveness. Long term goals for manufacturing performance and policies adopted to achieve those goals constitute the *manufacturing strategy* of a firm. Design and implementation of a manufacturing strategy is conceived to be crucial especially when there is intensive rivalry, as in international markets. There are two main approaches to the manufacturing strategy planning problem: descriptive frameworks and analytical models. In general, descriptive frameworks provide an understanding of the firm's environment as well as its internal structure to aid formation of the policies that will presumably enable the firm to attain a better position in its future environment. Analytical approaches however, prescribe the best action plan for manufacturing in order to maximize the firm's performance. Classical economic theory and mathematical programming have long been in use for modeling the firm behavior in product markets, the decisions suggested by these models being policy alternatives for achieving strategic goals. A survey of the prevailing literature reveals that the descriptive and analytical studies on manufacturing strategy have articulated in a rather fragmented manner. This study demonstrates that these two modes of analysis complement each other especially for global manufacturing strategy planning.

Cost, *quality*, *delivery performance*, and *flexibility* are the most common criteria to evaluate performance of a manufacturing system. Firms need to develop their own performance measurement schemes in order to both operationalize their long term goals in terms of the above criteria and monitor the implementation of their manufacturing strategy. Relative priorities of these objectives however, are dictated by the particular strategy being implemented and hence, differ from firm to firm. It should be noted that firms are not in a position to choose between cost and quality or dependability and flexibility objectives. Empirical studies did not justify the existence of such tradeoffs suggested in early conceptual work on manufacturing strategy. In accordance with the intensive rivalry in global markets, *innovativeness* and *time-based competition* are emerging as important manufacturing objectives.

Policies that enable a firm to meet its long term goals comprise a collection of strategic decisions. In their recent review, Leong et al. [96] pointed out the consensus among several authors about the strategic decision areas for manufacturing. These include *structural* decisions associated with facilities, capacity, technology, and vertical integration as well as *infrastructural* decisions associated with production planning and control, quality, organization, workforce, new product development, and performance measurement systems. In general, structural decisions constitute long term investments whereas infrastructural decisions mostly address the people and systems that run manufacturing activity.

In strategy planning, the manufacturing activity has to be conceived within the context of the corporate hierarchy. A typical three-level hierarchical model of a corporation is depicted in Figure 1.1. A corporation comprises a collection of *Strategic Business Units* (SBUs) each functioning in a particular industry in order to serve a well-defined market segment. Naturally, an SBU consists of several functional units such as purchasing, marketing, finance, personnel, R&D, and manufacturing. An *industry* however, is defined to be a collection of rivals competing directly with each other via the products/services they produce. Strategy planning aims achievement of a long-term sustainable competitive advantage at each SBU, and hence at the corporate level.

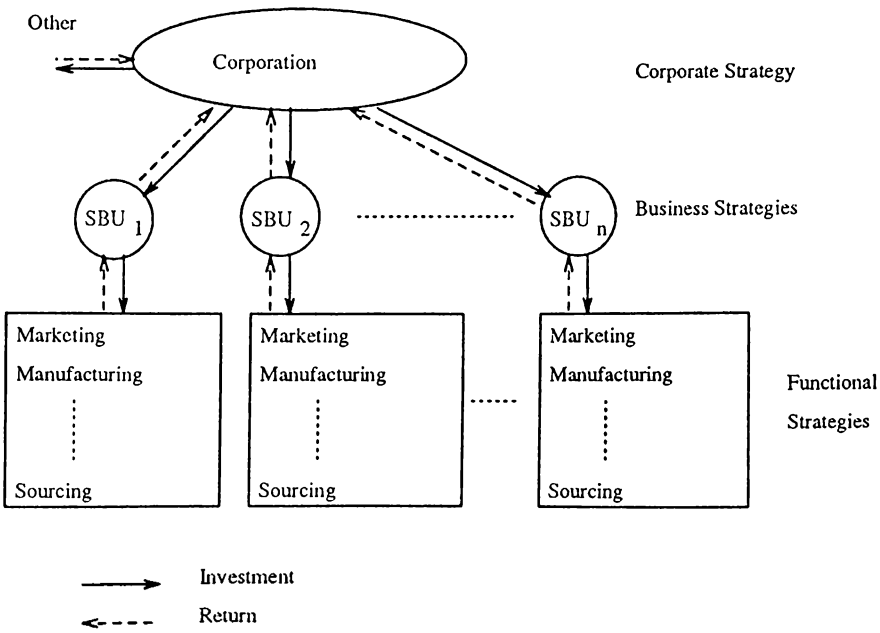

Figure 1.1: A three-level corporate hierarchy

This requires consistency of the strategies designed and implemented at all hierarchical levels of the corporation. Therefore, manufacturing strategy cannot be formed without considering its interactions with the business and corporate strategies as well as with other functional strategies.

Corporate strategy planning involves decisions regarding the business portfolio of a corporation. That is, the long term goals and policies for the collection of industries to compete in are determined by the corporate strategy. As pointed out by Naylor and Thomas [109] the allocation of strategic investments to the SBUs is an interface between the corporate and business strategies. Hence, in designing its business strategy, each SBU is constrained by the availability of strategic resources provided by the corporation, and needs to be consistent with its mission dictated by the corporate strategy. Business strategy however, provides a framework for the marketing, manufacturing, sourcing, and other functional strategies. We perceive the firm as an SBU operating in a particular industry, and use the terms firm and company interchangeably. Although, many firms belong to corporations in reality, analysis of the strategic issues regarding that interaction is out of the scope of this study. Our focus however, will remain on the consistency of the manufacturing and business strategies in a firm.

Since the beginning of 1980's the world has been going through an era of restructuring. The end of cold war between super-powers, rapid liberalization movements within the socialist block, geographical enlargement and economical strengthening of the European Community and rise of the Asia-Pacific rim via industrial growth of countries like Japan and South Korea are some of the striking examples. This restructuring process is accelerated by the continual transformation of the closed national economies to open economies all over the world. In most industries firms are now exposed to global competition. Globalization of product markets provides an opportunity for scale economies. However, it becomes more difficult for the firms to survive even in their domestic market against the global rivals. Therefore, all firms need to understand the dynamics of global competition, analyze the specifics of their industry, assess the strengths and weaknesses of their own production-distribution system, and adopt explicit strategy formulation and implementation processes.

In response to the trend toward opening closed national economies to international competition and hence globalization of markets, firms tend to restructure themselves into multi-activity settings. This stems from the motivations to explore the tradeoffs between inbound-outbound logistics costs and plant operation costs as well as to take advantage of the inefficiencies in the international product, factor, and capital markets. Globalization of firms however, increases the organizational complexity which requires development of appropriate ways to model and analyze the firm behavior within the international context. Production-distribution networks provide an effective tool in modeling global firms. A typical production-distribution network is depicted in Figure 1.2. Here, nodes represent the vendors, production plants, distribution centers, and warehouses of the firm, and the customer zones whereas arcs represent the flow of items. Note that firms implement their manufacturing strategy via the facility location, capacity acquisition, technology selection, and product mix decisions at each node of their production-distribution system. Time-phasing and financing of these investments naturally constitute important elements of the decision process. Since it allows incorporation of all of the structural and some of the infrastructural strategic decision categories, the producton-distribution system design problem can be regarded as an analytical framework for manufacturing strategy planning. Clearly, improvements in designing international production-distribution systems will contribute to the formation of global manufacturing strategies.

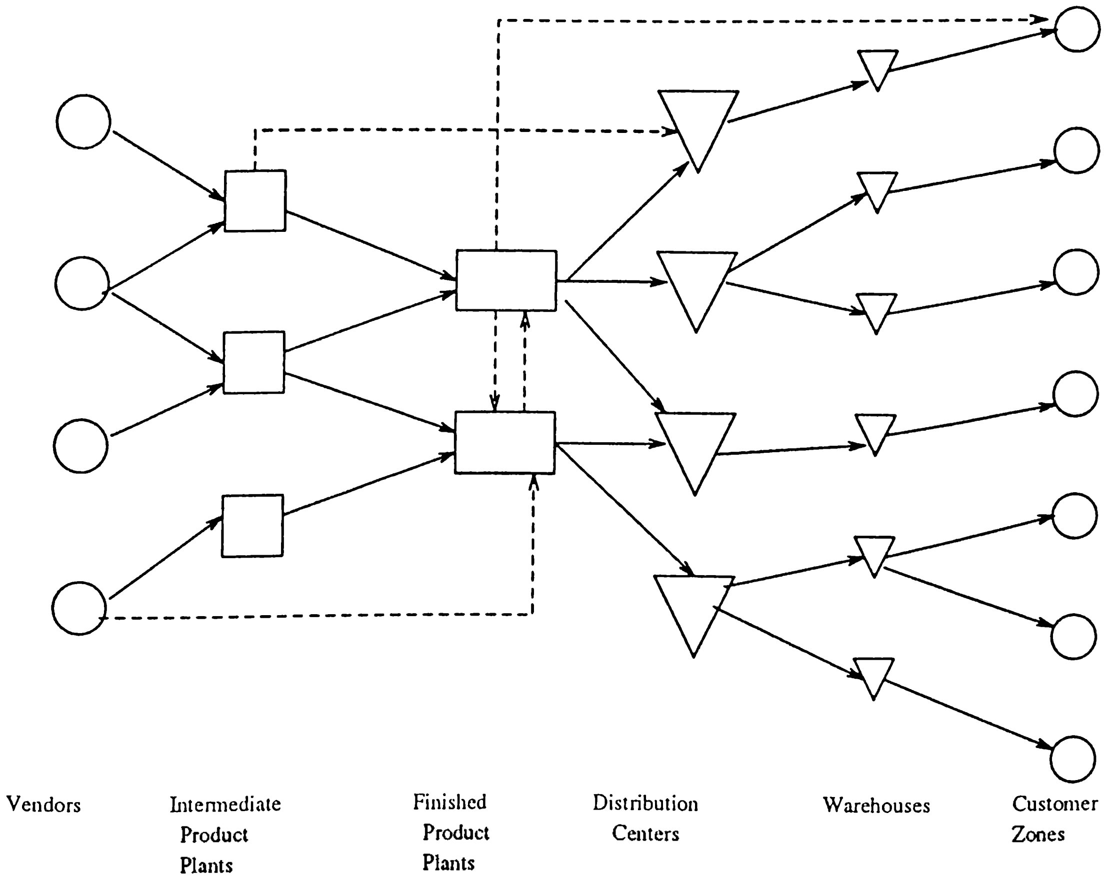

Figure 1.2: Production-distribution network

The primary objective of this dissertation research is to contribute to the manufacturing strategy planning process. Development of analytical methods for designing production-distribution systems is conceived to be the major task in achieving the research objective. The dynamics of manufacturing strategy design in multinational companies are especially taken into account due to the globalization of product, factor, and capital markets. It is necessary to ensure that the manufacturing strategy will be consistent with the company strategy. Thus, Chapter 2 presents the descriptive methods for strategy planning, which constitute a framework for the detailed analysis to be performed via the analytical approaches presented in this thesis. Chapter 2 also provides a review of the literature on production-distribution system design which reveals that the existing methods are lacking the capability to assist management in determination of the manufacturing strategy options. Therefore, Chapter 3 focuses on the structural decisions during the manufacturing strategy planning process. It is observed that the facility location, capacity acquisition, and technology selection decisions have been dealt with separately in the literature. These decisions however, are interdependent for global firms, and hence global manufacturing strategy planning requires simultaneous optimization of the location, capacity, and technology investments. Chapter 4 presents an analytical approach for the single-commodity facility location and sizing problem. In Chapter 5 the basic model is extended to incorporate the presence of technology alternatives in acquiring the required production capacity. Then, the method is further generalized to optimize the location, sizing, and technology selection decisions in the multicommodity setting. Chapter 6 discusses the major contributions of this dissertation research as well as the directions for future research.

Chapter 2

Production-Distribution System Design for Manufacturing Strategy Planning: A Review

There are two basic categories of problems pertaining to the management of production-distribution systems:

i) *Design problems*; How to structure the system?

ii) *Material flow problems*; How to manage the flow of items?

The distinguishing characteristic of a design problem is that it requires a large capital outlay for implementation. That is, the solution process of design problems involves medium-long term decisions which are mostly irreversible in the short run. Whereas, material flow problems are concerned with short term decisions such as production, inventory, and transportation planning etc. Note that however, manufacturing strategy of a firm essentially constitutes the goals and policies for the future structure of its production-distribution network. Hence, the multicommodity, multi-echelon production-distribution system design problem is an integral part of the manufacturing strategy planning process. Global firms however, have their production/distribution facilities located in a variety of countries so as to take advantage of the inefficiencies in the international product, factor, and capital markets. Hence, the production-distribution network of a global firm would normally have a multi-echelon structure (as in Figure 1.2) where the items flow across national boundaries. This further allows the firm to exploit the tradeoffs between transportation and operation costs. Moreover, it is a common practice to produce and distribute various products via the same production-distribution network in order to take advantage of the economies of scope.

This chapter aims to show that the descriptive literature on manufacturing strategy planning justifies utilization of the production-distribution design techniques in strategy design, and to provide an assesment of the state of the art in production-distribution system design on which the literature is rather sparse. Aikens [1] provided a comprehensive account of the facility location models for distribution planning problems. An application-oriented review of mathematical models and solution algorithms for designing production-distribution systems can be found in Moon [107]. Section 2.1 provides a selective review of the vast literature describing the business and manufacturing strategy planning processes. The competitive strategy framework is emphasized due to its relevance to the analytical models for production-distribution system design. Section 2.2 discusses the factors that need to be taken into account during the process of manufacturing strategy planning within the international context. In Section 2.3 the literature pertaining to the domestic version of the production-distribution system design problem is reviewed. Incorporation of distinguishing features of the international environment are presented in Section 2.4. A critical evaluation of the prevailing literature is provided in the final section.

2.1 The manufacturing strategy planning process

Gilbert et al. [51] provided a review of the state-of-the-art in strategy. They presented a classification of the prevailing literature on business strategy into six frameworks namely: Harvard Policy, Portfolio, Competitive Strategy, Stakeholder Management, Planning Process, and Seven-S. The first three frameworks share some quite fundamental features such as, an attempt to match internal structure of firms with their external environment, and confinement of the strategy problem solely to the managerial level, and hence are called the *managerial models* of strategy. Stakeholder Management however, conceives a firm as a set of relationships among stakeholders rather than a collection of processes that converts inputs to outputs for providing returns to stockholders. Planning Process framework is concerned with the formalization of the strategy planning process to ensure the necessary organizational interactions for strategy formulation. The Seven-S framework provides an extension of the formalization idea via indicating the necessity to incorporate strategy-structure relationship in a more comprehensive scheme which also includes systems, style, skills, staff, and superordinate goals. Note that, although each framework has pros and cons in assisting strategy planning, the descriptive approaches as a whole provide management with several strategy alternatives from different viewpoints.

Harvard Policy framework developed at the Harvard Business School since the beginning of 1950's is the ancestor of many other studies in the field. It essentially constitutes a systematic questioning process for investigation of the firm specific material, technical, financial and human resources, and the environment to aid the strategy formulation and implementation processes. Portfolio framework however, aims to come up with the universal laws for classification of the SBUs according to their competitive power. This would enable a more realistic statement of performance targets for SBUs which leads to a better deployment of a firm's strategic resources. The Competitive Strategy framework dwells on the idea that long term performance of a firm is a function of the industry forces and the extent to which the managers are able to position the firm among and against these forces. In his seminal work Porter [114] described the opportunities for success of a company as a function of the forces at work in the industry. These forces are relative bargaining power of buyers, relative bargaining power of suppliers, threat of new entrants, threat of substitute products, and intensity of rivalrous activity among competitors. Analysis of the industry forces can provide a sound basis for designing successful strategies only if it is accompanied with an investigation of the internal structure of the firm. Porter [114] proposed the value chain analysis in determining the competitive advantages of a firm.

The Competitive Strategy framework is essentially concerned with the achievement of a profit level above the industry average. Porter [117] provided a set of *generic strategies* for the firms to achieve and sustain above average returns: Cost leadership, Differentiation, Cost focus, and Focused differentiation. According to Porter [115] the cost leader is not merely a low cost producer but the lowest cost producer in the industry. This leads to an above average performance by charging prices at or near the industry average. Differentiation constitutes creating value for the buyer via a unique dimension which is important for the buyer's value chain. This enables commanding above average prices which translates into above average returns if production costs are at or near industry average. Cost focus or focused differentiation becomes necessary when the firm cannot attain a leadership in the market as a whole. In this case, a firm may choose to serve a particular target market segment with distinctive needs. Commitment to one and only one of the generic strategies is strongly recommended for exploring the competitive advantages of a firm.

Despite the fact that Porter's work has been quite popular among managers and very influential in academia, there are many criticisms. Gilbert et al. [51] accepted the strength of the value chain idea and the operationality of the framework. However, they noted that complexity of the value chain analysis may defer timely decisions in some instances, and that people are not very important in Porter's work. Further, various external factors such as government are not given enough attention. The framework dwells heavily on the concept of industry, boundaries of which may be hard to identify in many cases. Hendry [60] reported that exceptions to the rule that cost leadership and differentiation are incompatible, are so many which make the rule virtually worthless. This also causes confusions in having a clear understanding of the generic strategies. It is further noted that extending the model beyond the single product-group industries and business units is quite problematic.

Several authors have spent considerable effort in assuring the consistency of manufacturing strategy with business strategy as well as with other functional strategies a predominant example being the work of Fine and Hax [40]. Kotha and Orne [87] aimed at capturing the manufacturing implications of generic business strategies in devising their generic manufacturing strategy model. Extending the ideas due to Hayes and Wheelwright [58], [59], manufacturing function is perceived as a three dimensional structure, the dimensions being process structure complexity, product line complexity, and organizational scope. Factors leading to the high or low levels in each of these dimensions are further identified, and analyzed. In this context, manufacturing strategy constitutes a movement in the three dimensional space from a point that designates the current manufacturing structure to a target point implied by the generic business strategy being implemented. Although their representation of manufacturing structure remains quite descriptive, the work of Kotha and Orne [87] achieves the fit between strategy and structure via an integration of the classical concepts on manufacturing strategy with Porter's Competitive Strategy framework. Empirical studies on the implementation of generic manufacturing strategies will presumably provide substantial insight in manufacturing strategy planning.

Cohen and Lee [19] presented a paradigm for manufacturing strategy planning. They stressed incorporation of the following issues in a framework for the evaluation of manufacturing strategy alternatives: economies of scale and scope in manufacturing; behavior of manufacturing costs in conjunction with plant focus, production system flexibility, and product line complexity; interactions between the decisions, costs, and performance throughout the value chain; impacts of adoption of new technology; and vertical integration, supplier sourcing and material management. The Cohen and Lee [19] paradigm aims to identify a *manufacturing mission* as suggested by Skinner [124], which essentially is a weighted average of performance requirements associated with cost, quality, service, and flexibility measures, in terms of each product segment. Each *strategy option* is evaluated with respect to the manufacturing mission requirements, the product market structure, and the cost/performance capabilities of the manufacturing system. Cohen and Lee [19] developed an integrated software system to operationalize their model which is used in the consulting practice of Booz, Allen and Hamilton Inc. As another example of such normative frameworks, Breitman and Lucas [10] reported the worldwide use of PLANETS (The Production, Location Analysis NETwork System) throughout General Motors, in helping managers to decide what products to produce; when, where and how to make these products; which markets to pursue; which resources to use; how to ship; and where and when to make capital investments.

2.2 Manufacturing strategy planning within the international context

In his pioneering article Levitt [97] noted that "companies must learn to operate as if the world were one large market - ignoring superficial regional and national differences." It is necessary to make a distinction between multinational corporations and global firms. The former operates in a number of countries while each subsidiary is run as a domestic firm. Whereas, the latter operates as if the entire world were a single entity. There are several distinguishing features of the international environment which have to be taken into consideration for global manufacturing strategy planning.

According to classical economic theory, the *law of comparative advantages* provides a basis for international transactions. That is, trade will be mutually advantageous if countries are relatively more efficient in producing different goods. Ideally, an international equilibrium will be attained when exports and imports of individual countries reach a balance in their own currency. Exchange rates among currencies provide the means for adjustment of the international disequilibrium. This is apparent from the following theorems on the relationships between exchange rates, interest rates and price levels: *Purchasing Power Parity* (PPP) states that exchange rates off-set the differences between national price levels of freely tradeable goods, and *International Fisher Effect* (IFE) states that exchange rates off-set the differences between interest rates for different currencies. These fundamental exchange rate relationships however, are based on some assumptions such as; perfect product markets (no transportation cost or time, no barriers to trade), perfect financial markets (all relevant information is reflected in prices, no taxes, no transaction costs, no controls), and future certainty. These assumptions are quite unrealistic in many cases, since product and capital markets are not "perfect" and the future is not known with certainty. Deviations from PPP exist due to lags in market responses, transportation costs, national differences in the price ratios of internationally traded goods to domestically traded goods, government interventions and risk expectations. Furthermore, deviations from IFE exist due to the availability of subsidized financing and differentials in corporate tax rates. In addition to the various arbitrage opportunities provided by these imperfections, uncertainities regarding future exchange rates, interest rates and price levels cause various types of risks the firms have to undertake when designing their manufacturing strategy. Distinguishing features of the international environment and their potential impacts on firm behavior are depicted in Table 2.1.

Porter [114], [115] proposed the conceptualization of a firm's activities as a *value chain.* This is due to the perception of a firm as an organization which creates value for its buyers. A typical value chain consists of *primary activities* such as purchasing, production, distribution, marketing, and servicing products, and *support activities* such as R&D, and human resources management. It is necessary to analyze the linkages among these activities as well as the linkages between the entire value chain and the firm's buyers and suppliers. Firms would be able to identify their *competitive advantages* to the extent that they know the strengths and weaknesses of their value generation process.

Phenomena	*Effect*
Deviations from PPP	goods arbitrage opportunity
Deviations from IFE	financial arbitrage opportunity
Price uncertainty	market risk
Exchange rate uncertainty	currency risk
Government interventions	political risk
Quotas, local content rules	constrain flow of items
Tariffs, duties	increase transaction costs
Cultural, taste differences	product tailoring
Language, skill differences	human factors management

Table 2.1: Distinguishing Features of the International Environment

Kogut [85] described the interplay of the firm specific competitive advantages and the location specific *comparative advantages* for global firms. Every firm should identify and control the critical success factors in its value chain for serving the buyers' needs. Global firms however, have facilities located in different countries. This requires the value chain analysis to address the differences between countries in terms of production factor costs as well as institutional and cultural issues which affect the manufacturing strategy decisions. Hence, global strategies should be designed so as to take advantage of the interrelations between competitive and comparative advantages. Kogut [86] pointed out the importance of creating *operational flexibility* within the corporation in order to benefit from being global. Operational flexibility provides the capability to explore arbitrage and leverage opportunities. Arbitrage opportunities include; production shifting in response to changing circumstances in factor markets, information arbitrage, tax minimization via transfer pricing, and financial arbitrage via subsidized loans. Leverage opportunities arise from global coordination and may be a hedge against political risk among other things.

Porter [117] provided a paradigm to assess the attractiveness of a nation as a home base for an industry. (Note for comparison that his earlier work aimed to assess the attractiveness of an industry for a firm.) A home base for a global firm's activities in an industry is the country which reaps the profits and which is usually where the majority of production and management takes place. Porter [117] identified the determinants of national advantage as; factor conditions, demand conditions, related and supporting industries, and firm strategy, structure, and rivalry. Government and chance are perceived as the factors influencing these determinants. Implementation of Porter's paradigm in the analysis of a selection of industries in ten countries provided valuable insights regarding the dynamics of global competition.

In their introduction to the special issue of *Management Science* Day, Farley and Wind [25] identified integration of theoretical contributions in relevant disciplines, and hence development of new methods of analysis as a viable research direction for strategy planning. In accordance with the above observation, this study presents methods for designing international production-distribution systems to enhance the analytical treatment of the theory regarding the driving forces of international competition. Perceiving the global firm as an international value chain facilitates analysis of the value creation process, and determination of the firm's competitive abilities. Production-distribution networks constitute an operational representation of the value chain concept, since it is possible to model each value generating activity as a node in these networks. Note that the primary activities of the value chain are affected by the structural decisions during the strategy planning process. Whereas, the infrastructural decisions affect the support activities. Thus, not only the production-distribution networks provide an effective tool in modeling the global firms, but they also enable us to strengthen the linkages between the descriptive and the analytical approaches for manufacturing strategy planning.

In addition to the issues critical to global operations such as configuration, logistics, sourcing, planning, technology transfer, and risk management, globalization also requires addressing the changes in firm structure including joint ventures, strategic alliances, franchising and licencing, as well as the need for international cross-functional coordination such as that of manufacturing and marketing as emphasized by Hill [61]. This study however, is not intended to be a comprehensive account of all the theoretical and empirical work relevant to the globalization phenomenon. Therefore, the interested reader is referred to the recent bibliography in Lawrence and Rosenblatt [94] and to the books edited by Porter [116] and Ferdows [36]. The focus of this thesis will remain on the analogy between the value chain concept and the production-distribution network models. Thus, the perception of the (global) firm as a (international) value chain justifies utilization of the methods for production-distribution network design in a rigorous pursuit of the problems in planning manufacturing strategy.

2.3 Domestic production-distribution systems

Warszawski [144] reported one of the earliest work on multicommodity problems. The simple plant location problem is generalized to incorporate product specific fixed costs of opening plants at the potential locations. This cost structure requires the restriction of each plant to produce a single commodity. The plant loading and location decisions are provided simultaneously. Warszawski [144] devised a heuristic algorithm whereas, Neebe and Khumawala [110] suggested a branch and bound procedure for this class of problems. Akinc [2] analyzed the capacitated multicommodity problem where plants are capable to produce more than one commodity. That is there are fixed costs associated with all possible plant loadings in addition to the fixed costs of opening plants. The branch and bound procedure of Akinc and Khumawala [3] for the single-commodity capacitated problem has been extended for solving the problem.

Kaufman, Eede and Hansen [77] suggested a generalization of the Efroymson and Ray [28] algorithm, for simultaneous location of uncapacitated single-commodity plants and warehouses. It is also possible to utilize their model for locating two echelons of warehouses given the locations of production plants. Capacitated, multicommodity, multi-echelon formulations are mostly focused on location of a single echelon of warehouses on the basis of existing production facilities. Elson [29] presented one of the pioneering studies where the existence of different customer service levels is analyzed. Availability of management options to expand existing distribution centers (DCs) in addition to opening new ones is also incorporated. Proposed optimization procedure however, decomposes the commodity flows into the plant-to-DC and the DC-to-customer portions.

Geoffrion and Graves [49] provided the most influential work on the multicommodity production-distribution system design problem. Given a set of production plants each with known capacity, the authors were concerned with locating a single echelon of DCs and assigning those DCs to customer zones in order to satisfy the demand. The model formulation is as follows:

$$\text{Minimize} \quad z = \textstyle\sum_{p,i,d,j} c_{pidj} X_{pidj} + \sum_d [F_d Y_d + v_d \sum_{p,j} D_{pj} Z_{dj}], \qquad (2.1)$$

subject to

$$\textstyle\sum_{d,j} X_{pidj} \leq S_{pi}, \qquad \forall p, i, \qquad (2.2)$$

$$\textstyle\sum_{i} X_{pidj} = D_{pj} Z_{dj}, \qquad \forall p, d, j, \qquad (2.3)$$

$$\textstyle\sum_{d} Z_{dj} = 1, \qquad \forall j, \qquad (2.4)$$

$$\underline{V}_d Y_d \leq \textstyle\sum_{p,j} D_{pj} Z_{dj} \leq \overline{V}_d Y_d, \qquad \forall d, \qquad (2.5)$$

$$\text{Linear configuration constraints on Y and/or Z}, \qquad (2.6)$$

$$Y_d, \quad Z_{dj}, \in \{0,1\}, \qquad \forall d, j, \qquad (2.7)$$

$$X_{pidj} \geq 0, \qquad \forall p, i, d, j, \qquad (2.8)$$

where

p = index for commodities,

i = index for the existing production plants,

d = index for potential DC sites,

j = index for customer zones (CZs),

S_{pi} = production capacity of plant i for commodity p,

D_{pj} = demand for commodity p in CZ j,

$\underline{V}_d, \overline{V}_d$ = minimum, maximum allowed annual throughput for DC d,

F_d = annualized fixed setup cost of opening DC d,

v_d = variable unit cost of throughtput for DC d

c_{pidj} = unit cost of producing and shipping commodity p from plant i to CZ j through DC d.

The decision variables are:

X_{pidj} =amount of commodity p produced and shipped from plant i to CZ j through DC d,

Y_d = 1 if DC d is opened, 0 otherwise,

Z_{dj} = 1 if DC d serves CZ j, 0 otherwise.

Constraints (2.2) are supply constraints and (2.3) ensure that demand from each CZ will only be satisfied by a DC assigned to serve that CZ. The *single-sourcing* of CZs by DCs is imposed by constraints (2.4). That is the model suggests construction of a *dominant* DC for each CZ which fully serves the demand. Constraints (2.5) keep the total annual throughput of each DC between the required limits. They also enforce that a closed DC cannot be assigned to serve a CZ. Linear configuration constraints (2.6) allow representation of managerial requirements about the selection of DC sites and the DC-CZ assignments in the model. The objective is to minimize the sum of total production, transportation, DC construction and operation costs.

Geoffrion and Graves [49] adopted a variant of the Benders [7] decomposition that solves the master problem as a feasibility problem. This is primarily in order not to waste effort solving a master problem to optimality when there are only a few Benders cuts to represent the subproblem at the earlier iterations. Their algorithm also describes how to synthesize the dual solutions to the single-commodity transportation sub-subproblems to obtain dual solutions to the multicommodity transportation subproblem. The authors reported application of the solution technique to a real problem for a major food firm with 17 commodity classes, 14 plants, 45 possible DC sites, and 121 CZs. They also mentioned another large scale application for a major manufacturer of hospital supplies.

Moon [108] extended the problem formulation to incorporate the nonlinearities in DC throughput costs due to economies of scale. He presented an application of the Generalized Benders Decomposition devised by Geoffrion [48] to the nonlinear production-distribution system design problem. Approximate dual prices are generated by solving linear (instead of concave) subproblems which are then adjusted to better represent the concavity in throughput costs. These adjusted dual prices are incorporated in the Benders cuts. The computational results are reported to be encouraging.

Van Roy [139] presented an extended application of the Geoffrion and Graves [49] model for multi-level production-distribution planning and transportation fleet optimization. The problem belongs to a liquified petroleum gas company with 2 commodities (propane and butane), 2 refineries, 10 potential bottling plant locations, 40 potential depot locations, 40 potential breakpoints (transporters' home sites), and 200 customer regions. Location and capacity expansion decisions associated with the bottling plants, depots and breakpoints are given together with the decisions concerning the transportation fleet size, and the transportation shift systems and schedules. Note that, this problem requires optimization of the location decisions related with three echelons of the production-distribution system compared to the single-echelon model of Geoffrion and Graves [49]. The problem was solved using a matrix generator for network-like problems and MPSARX (Van Roy and Wolsey [141]), a general-purpose mathematical programming software system augmented with automatic reformulation and cut generation features.

Cohen, Lee and Moon [21] presented an integrated model for production-distribution system design as an implementation of the manufacturing strategy paradigm suggested by Cohen and Lee [19]. The model formulation is as follows:

$$\text{Minimize} \quad z = \textstyle\sum_i F_i Y_i + \sum_{p,i} v_{pi} X_{pi} + \sum_{v,i,r} c_{vir} Q_{vir} + \sum_{i,i',p} c_{ii'p} Q_{ii'p} \qquad (2.9)$$
$$+ \textstyle\sum_d [F_d Y_d + \sum_{p,j} v_{pd} D_{pj} Z_{dj}] + \sum_{p,i,d,j} c_{pidj} Q_{pidj},$$

subject to

$$\text{MINP} \le \textstyle\sum_i Y_i \le \text{MAXP}, \qquad (2.10)$$
$$Y_i = 1 \quad \text{for}, \qquad i \in \text{IFIX} \; (2.11)$$
$$\textstyle\sum_i Q_{vir} \le S_{vr}, \qquad \forall v, r, \quad (2.12)$$
$$\textstyle\sum_p U_{rp} X_{pi} \le \sum_v Q_{vir}, \qquad \forall i, r, \quad (2.13)$$
$$\textstyle\sum_p R_{pi} X_{pi} \le \sum_i CAP_i Y_i, \qquad \forall i, \quad (2.14)$$
$$\underline{S}_{pi} Y_i \le X_{pi} \le \overline{S}_{pi} Y_i, \qquad \forall p, i, \quad (2.15)$$
$$X_{pi} + \textstyle\sum_{i'} Q_{i'ip} - \sum_{i'} Q_{ii'p} - \sum_{p'>p} U_{pp'} X_{p'i} \ge \sum_{d,j} Q_{pidj}, \qquad \forall p, i, \quad (2.16)$$
$$Y_d = 1 \quad \text{for}, \qquad d \in \text{DFIX}, (2.17)$$
$$\underline{V}_d Y_d \le \textstyle\sum_{p,j} D_{pj} Z_{dj} \le \overline{V}_d Y_d, \qquad \forall d, \quad (2.18)$$
$$\textstyle\sum_d Z_{dj} = 1, \qquad \forall j, \quad (2.19)$$
$$\textstyle\sum_i Q_{pidj} = D_{pj} Z_{dj}, \qquad \forall p, d, j, \quad (2.20)$$
$$Y, \quad Z, \in \{0, 1\}, \qquad \forall i, d, j, \quad (2.21)$$
$$Q, \quad X \ge 0, \qquad \forall p, i, d, j, v, r, \quad (2.22)$$

where in addition to the previous notation;

r = index for raw materials,

p = index for intermediate and finished products,

v = index for vendors,

F_i = annualized fixed cost of opening plant i,

MINP, MAXP = minimum, maximum number of plants to be open,

IFIX = set of plants that are fixed open,

DFIX = set of DCs that are fixed open,

CAP_i = aggregate production capacity at plant i,

R_{pi} = utilization rate of the aggregate capacity at plant i per unit product p,

$\underline{S}_{pi}, \overline{S}_{pi}$ = minimum, maximum production volume for product p at plant i,

c_{vir} = unit cost for raw material r purchased and transported from vendor v to plant i,

v_{pi} = unit variable production cost for product p at plant i,

S_{vr} = supply capacity of vendor v for raw material r,

U_{rp} = utilization rate of raw material r per unit product p,

$U_{p'p}$ = utilization rate of intermediate product p' per unit of finished product p. (The utilization matrix U is upper triangular to account for the hierarchical use of products in the bill of material.)

The decision variables are:

Q_{vir} = amount of raw material r purchased from vendor v by plant i,

X_{pi} = amount of product p produced at plant i,

$Q_{ii'p}$ = amount of intermediate product p shipped from plant i to i',

Q_{pidj} = amount of product p shipped from plant i to market j through DC d,

Y_i = 1 if plant i is opened, 0 otherwise,

Y_d = 1 if DC d is opened, 0 otherwise,

Z_{dj} = 1 if DC d serves CZ j, 0 otherwise.

Production plant and DC locations, DC-CZ assignments, and flow of raw materials, intermediate and finished products through the system are simultaneously provided so as to minimize the sum of plant / DC construction and operation costs, raw material purchase costs, and transportation costs. Constraints (2.10), (2.15), and (2.18) ensure that the number of open plants, production volume at each plant, and DC throughput levels are within their upper and lower limits. Constraints (2.11) and (2.17) fix certain production plants and DCs open as a managerial policy. Customer demand need to be fully satisfied due to (2.20), taking into account the production capacities represented by (2.14) and the raw material supply constraints (2.12). Constraints (2.13) and (2.16) establish the raw material utilization limits and the intermediate product balance respectively. Each CZ is sourced by a single DC due to the constraints (2.19). The model locates a single-echelon of DCs each having product dependent throughput costs v_{pd} compared to the average throughput costs v_d of Geoffrion and Graves [49]. Note also that, a single-echelon of product plants are located each capable of producing the full set of intermediate and finished products (indexed by p). If any of the plants is not capable of producing product p then this has to be represented in the model by setting $\overline{S}_{pi}$ to zero.

Cohen, Lee and Moon [21] made a special effort to capture the scale and scope economies in production costs. The base level production costs at each plant are adjusted via a production cost multiplier which is a function of the capacity utilization rate and the number of products produced. Thus, the model is a large scale mixed-integer mathematical program with a nonlinear objective function. The authors devised an iterative solution procedure controlled by a model hierarchy. The algorithm requires an initial plant configuration to be provided. Then, a DROP/ADD heuristic is utilized to generate a new plant configuration with either one less or one more plant. The current DC configuration is taken as input and initial DC-CZ assignments are either carried out by an assignment heuristic or provided by management. The first submodel deals with the product mix, inbound and outbound optimization which is a linearly constrained nonlinear mathematical program. A simplex based algorithm is suggested for solving this subproblem. Submodel 1 provides plant production capacities as an input to the submodel 2 which is a distribution system design problem solved by the Geoffrion and Graves [49] procedure. Submodel 2 provides new DC configuration and DC-CZ assignments for the next iteration of submodel 1. The DROP/ADD heuristic is activated for a new plant configuration upon convergence of the subproblem iterations.

Cohen and Moon [22] employed the model described above to investigate the impact of production scale economies, manufacturing complexity and transportation costs on production-distribution systems. They analyzed the behavior of optimal solutions in response to variations in the input parameters of the production-distribution system design problem. It has been observed that economies of scale and scope as well as transportation costs can significantly affect the system structure. Transportation costs tend to affect various echelons simultaneously whereas plant fixed costs tend to be dominant in structuring the system despite various offsetting factors.

Recently, Cohen and Moon [23] presented an integrated plant loading model with economies of scale and scope. The plant loading problem takes the configuration of plants and DCs, and the DC-CZ assignments given, in order to optimize the product mix at each facility and the flow of materials through the production-distribution system. Note that, this problem corresponds to the first subproblem of Cohen, Lee and Moon [21]. In Cohen and Moon [23] cost of complexity is captured via a fixed cost of assigning a product line to a plant They represented economies of scale by the aid of a piecewise linear concave production cost function (compared to the nonlinear representation in Cohen, Lee and Moon [21]). A variant of Benders decomposition is suggested for solving this plant loading problem.

2.4 International production-distribution systems

The previous section enables the reader to trace the development of methods for production-distribution system design and their validation through real life applications. These models allow for the incorporation of multiple echelons of facilities, multiple commodities, and the nonlinearities due to economies of scale and scope that are inherent in international networks, and hence provide valuable insights in designing such systems. Note that however, the analytical approaches mentioned above are confined to a cost minimization objective. This creates a deficiency in dealing with the uncertainties associated with product markets which happen to be crucial in the international context. A significant line of research is focused on the *international plant location problem* (IPLP) to remedy this weakness. Unfortunately, the improvements in the incorporation of uncertainty are offset by the fact that IPLP addresses a very simplistic (single commodity, single echelon) production-distribution system.

Pomper [112] provided one of the earliest studies on international investment planning. He proposed a model to assist management in the evaluation of alternative manufacturing policies on a *global* basis. The model prescribes the optimal time-phasing of the location, technology and capacity investments as well as the optimal flow of materials throughout the future network. Pomper [112] analyzed the *single-commodity, single production stage* firms. He assumed that the multicommodity, multi-echelon structures can be decomposed into these easier to handle type of elements. Uncertainty in the environment is modeled by an *uncertainty tree* to represent the time-phased relationships among the environmental scenarios each occur with a certain probability conditional to the previous state of the environment. The expected present value of consolidated cash flow is maximized. Financial decisions are not considered although, Pomper [112] accepted that the international financial markets are not perfect. Economies of scale in production costs and in investment costs associated with the alternative technologies are approximated via fixed-charge linear functions. Dynamic programming is used to model and solve the international investment problem where a *manufacturing state* is defined to be the number of plants of each technology in each country. An alternative mixed-integer programming formulation of the problem is also presented which is claimed to be superior in large scale applications. Pomper [112] reported an application of his model to a mature agricultural chemical product of a US-based multinational chemical company.

Kendrick and Stoutjesdijk [79] devised an investment project evaluation model. The *single-country* based firms are analyzed taking into account their international activities such as imports and exports. Their model can be conceived as a manufacturing strategy planning tool since the chosen investments constitute means to implement the manufacturing policies. Decisions prescribed by the *multiproduct, multiperiod* model are; increments to the capacities of production units, shipments from plants to markets and among plants, exports, imports, domestic purchases of production factors, and by-product sales. The only set of integer variables in the mathematical program represents the capacity expansion decisions. Economies of scale in capacity acquisition is represented via a fixed-charge linear approximation. A *two-stage* production structure is incorporated and the future is assumed to be known with certainty. Net present costs are minimized to satisfy the demand by upgrading the current system via capacity expansion investments. Kendrick and Stoutjesdijk [79] suggested usage of the general-purpose integer programming softwares for solving their model.

Cohen, Fisher and Jaikumar [17] proposed a normative framework for strategic management of the international production-distribution systems. The firm's product mix, production plant locations, capacities and production technologies are taken as given and the raw material sourcing, production, and market supply decisions are optimized. The *multicommodity, multiperiod* model seeks to maximize the net present value of the after-tax profits in the numeraire currency of the firm. Many of the international issues are incorporated such as duties and tariffs, currency exchange rates, differences in corporate tax rates in each country, market penetration strategies, and local content rules. Economies of scale in raw material purchasing is represented by the availability of a set of vendor contract options. There are fixed costs of plant loading which can be interpreted as costs of *complexity*. Furthermore, the fixed plant loading costs enable representation of the economies of scale in production via several "pseudo-products" corresponding to the various cost rates associated with different levels of production. Production is assumed to have a *single-stage* structure and production plants are modeled to have capacity limits both in terms of the overall product mix and on a per product basis. The Cohen, Fisher and Jaikumar [17] model is a mixed-integer nonlinear program. Nonlinearity in the objective function is caused by the co-existence of the *financial decisions* namely, transfer prices and overhead allocations together with the *operational decisions*. Hence, the authors suggested a hierarchical solution procedure. First step involves optimization of the operational variables concerning vendor contract selection, plant loading, purchasing, production, and market supply decisions on the basis of a fixed level of the financial variables. Second step solves for the optimal values of the financial variables, given optimal levels of the operational variables provided by step 1. This provides input for the next iteration of the first step. Cohen, Fisher and Jaikumar [17] suggested adoption of a mean-variance framework for incorporation of the price and exchange rate uncertainty in the international markets. The authors also encouraged utilization of transfer prices for tax minimization purposes as well as for country-decomposed implementation of global manufacturing strategies.

Cohen and Lee [20] reported application of a variant of the Cohen, Fisher and Jaikumar [17] model in a multinational company manufacturing personal computers. In the Cohen and Lee [20] study the product structure is modeled to include major components, subassemblies, and finished products. Obviously this increases the tradeoff capability. However, it should be noted that the model is *deterministic* and *single-period* which may partly offset the above enhancement. Cohen and Lee [20] perceived global manufacturing strategy as a collection of *component strategies* which are designed at various echelons of the production-distribution system. Component strategies are associated with the raw material sourcing, plant charter, and distribution/market supply activities. Firms have *policy options* for each of the component strategies.

Various combinations of these policy options constitute the ***global policy options*** for the firm. The Cohen and Lee [20] model is essentially a ***strategy evaluation model*** since provision of the set of available global policy options is required by the solution procedure. A particular global policy option is translated into the *structural decisions* of the model in an interactive manner. That is values of the indicator variables are fixed in order to evaluate the global policy option under consideration. Cohen and Lee [20] specified the following zero-one decision variables:

- Assignment of finished products and subassemblies to plants,
- Assignment of vendors to plants for each major component and subassembly,
- Assignment of vendors to DCs for each finished product that is sourced directly from vendors to DCs,
- Assignment of supply links from plants to DCs and from DCs to CZs,
- Transfer pricing policies for assigning transportation costs for intermediate and finished goods from one plant to another,
- Transfer pricing policies for assigning transportation costs of finished goods from plants to DCs,
- Determination of whether demands from a market region are to be satisfied.

Then, the remaining problem is a large scale linear program which involves material flow decision variables that denote the quantities of major components, subassemblies and finished products transported through the production-distribution system, and production decision variables that denote the quantities of items manufactured at the plants.

Recently, Huchzermeier [69] presented a model for global manufacturing strategy planning under exchange rate uncertainty. He suggested a multinomial approximation to the stochastic exchange rate process. A stochastic dynamic programming formulation is developed for evaluation of the global manufacturing strategy options. An *option* O_t defines all operational and financial policies together with the structure of the production-distribution system at period t. State of the firm at the beginning of period t is determined by the current realization i of the exchange rates denoted by vector e^i_{0t}, and O_{t-1}. Hence, the recursion function is:

$$V_t(e^i_{0t}, O_{t-1}) = Max_{O_t \in \Omega_t}\{P_t(e^i_{0t}, O_{t-1}, O_t) + \Phi_t \sum_j \pi_{ij} V_{t+1}(e^j_{0,t+1}, O_t)\}, \quad (2.23)$$

where

$V_t(.)$ = discounted value of the firm at period t, given the adoption of O_{t-1} and the realization of e^i_{0t},

Ω_t = set of available global manufacturing strategy options at period t,

Φ_t = risk adjusted discount factor for period t,

π_{ij} = the stationary transition probability from exchange rate realization vector i to exchange rate realization vector j.

The profit at period t is:

$$P_t(e^i_{0t}, O_{t-1}, O_t) = SP_t(e^i_{0t}, O_t) - \delta(O_{t-1}, O_t), \quad (2.24)$$

where

$SP_t(.)$ = expected global after-tax profits for operating under O_t and e^i_{0t},

$\delta(.)$ = switching cost from O_{t-1} to O_t.

At each period, the subproblem SP_t is formulated as a stochastic program with recourse in order to also incorporate the demand uncertainty. This subproblem formulation constitutes a variant of the Cohen and Lee [20] model. Huchzermeier [69] suggested a hierarchical procedure for solving the integrated model. Computational tractability however, decreases as the number of exchange rate processes and the number of demand scenarios increase. Nevertheless, his study provides a valuable contribution to the state-of-the-art in global manufacturing strategy planning.

2.5 Discussion

The existing methodology for international production-distribution system design is in need of several enhancements to better capture the dynamics of global competition. First, the models should be improved to incorporate all the relevant competitive priorities such as quality, delivery performance and flexibility rather than focusing on cost as a predominant objective. Second, it is crucial that the strategy design process should address all the factors that lead to competitive advantage, not just the structural decisions alone. Third, it should be realized that a production-distribution network represents only the internal structure of the firm and its linkages with the buyers and suppliers. A comprehensive model of global competition however, requires incorporation of actions of the firm's current and potential competitors as well as government interventions which may require a game-theoretic setting.

Manufacturing strategy planning involves decisions regarding the future structure of the firm's production-distribution network. In terms of their capability in assisting the strategy planning process, the prevailing literature on production-distribution system design can be classified into two categories:

i) *Strategy Evaluation Models:* These models concentrate on more comprehensive problems which mostly have an international nature. Complexity of these problems however, results in the loss of computational tractability when the model is treated in its entirety. Thus, the evaluation models require specification of the set of available global manufacturing strategy options. This set is used to fix values of the structural (integer) variables in the model. The remaining model in the (continuous) flow variables can then be used to evaluate the strategy option under consideration.

ii) *Strategy Generation Models:* These models focus on the relatively simpler problems such as domestic production-distribution system design and the IPLP. This enables the model to provide some of the structural and the material flow decisions simultaneously. It is however, still quite cumbersome to provide exact solutions to the arising mathematical programs which necessitates development of heuristic algorithms in many cases.

The literature review reveals that the existing analytical models for international production-distribution system design are lacking strategy generation capability. Thus, the strategy design process is constrained to the strategy options envisaged by the management. This means that identification of the optimum strategy plan is conditional to its provision by the management as a viable strategy alternative. It is further observed that the prevailing strategy generation models mostly provide only locational decisions regarding the structure of a production-distribution network. As mentioned before however, the structural decisions in strategy planning include the size, technology content, vertical integration, and product mix of the facilities as well as their location. Thus, the remainder of this thesis is devoted to the development of analytical methods that incorporate a wider range of structural decisions. This will presumably contribute to the generation of strategy options in planning global manufacturing strategies.

Chapter 3

An Integrated Evaluation of the Facility Location, Capacity Acquisition and Technology Selection Decisions

Emergence of global markets is one of the phenomena that characterize the last decade. Rapid improvements in communication technology caused a standardization in demands of people living in different geographical regions. This provides a significant opportunity for the firms to explore the economies of scale in manufacturing. Thus, multinational companies started adopting an integrated management approach which aims reducing the effects of national boundaries. This represents a movement away from the classical style of managing multinationals: Operating as a domestic firm in each country. Hence, emergence of global markets enhanced the emergence of global firms. Due to the intensive competition in global markets, manufacturing performance is conceived as an important strategic weapon for both achieving and maintaining competitiveness. Cost, product/service quality and flexibility are the most common criteria to evaluate performance of a manufacturing system. Long term goals of a firm in terms of the above performance measures and policies adopted to achieve those goals constitute the manufacturing strategy.

Production-distribution networks provide an effective approach in modeling global firms. In this type of a network, nodes represent the semi-finished/finished product plants, distribution centers and warehouses whereas, arcs represent the flow of items. Firms implement their manufacturing strategies via the following decisions at each node of their production-distribution system:

- Facility location,
- Capacity acquisition,
- Technology selection,
- Product mix,
- Time-phasing of investments, and
- Financial planning.

Global firms have facilities located in different countries. This requires treatment of several additional factors such as price and exchange rate uncertainty, imposed by the international environment.

We envision facility location, capacity acquisition and technology selection decisions as building blocks for the management to design manufacturing strategies. At this point, it should be emphasized that the location, capacity and technology decisions should be consistent with each other at each plant. Further, consistency of the plant level decisions with the overall manufacturing strategy should be ensured.

We claim that design of effective manufacturing strategies requires a thorough understanding of the possible impacts of the location, capacity and technology decisions. Hence, this chapter [1] is organized as follows: In Section 3.1 we review the literature on facility location. In order to better capture the dynamics of the international environment, the international plant location problem is

[1]The discussions in this chapter draw heavily on Verter and Dincer [142]

presented in a separate subsection. Section 3.2 is devoted to the capacity acquisition decisions. In many cases, presence of uncertainty associated with the future values of some significant parameters necessitated the development of different models to incorporate this phenomenon.Thus, both facility location and capacity acquisition under uncertainty are presented separate from their deterministic versions in Section 3.1 and in Section 3.2 respectively. The common trend toward capital intensiveness in technology selection and the flurry of literature inspired by the availability of the advanced manufacturing technologies are covered in Section 3.3. In the final section we provide some comments on the existing literature and suggest an avenue for future research.

3.1 Facility location

Location problem primarily involves the selection of sites for one or more facilities to serve a spatially distributed set of customers. This is clearly a *microeconomic* definition of the problem where the term facility stands for either manufacturing plants, warehouses of a firm or public facilities such as fire stations, schools, ambulance or emergency medical services. An extensive bibliography on normative microeconomic location models can be found in Domschke and Drexl [27]. *Macroeconomic* location theories on the other hand, analyze the distribution of industries, economic sectors or urban areas in space. Ponsard [113] provided a comprehensive survey of the macroeconomic location literature.

The underlying spatial topology has great impact on the model structure and hence provides a well-accepted feature for categorizing the vast literature on facility location accumulated over the last twenty-five years. Francis et al. [46] classified locational models as planar models, warehousing models, network models and discrete models. Planar location models presume the spatial topology to be a plane. That is the number of possible locations is infinite and *planar distances* represent the distances traveled. Furthermore, travel costs are assumed to be proportional to distance and fixed costs are ignored. These models do not have extensive data requirements and are amenable to solution methods which require less computational effort, due to their continuous structure. Since the underlying assumptions are unrealistic in many cases, planar models can provide some insight to the problem rather than accurate solutions. Network location models make use of the underlying network structure. Here *network distances* which are lengths of shortest routes, represent travel distances and the network itself constitutes the set of possible locations. In the case of multifacility location, the travel is assumed to be from the closest facility. The reader is referred to Tansel et al. [133], [134] for an extensive survey on network location models. Selecting from a finite set of possible locations is the distinguishing feature of discrete location models. Fixed costs of opening plants at the selected sites are also incorporated in the model. That is the discrete models can provide a more accurate representation of the system being analyzed. The increased model realism however, should be traded off against the increased computational effort necessary to deal with the mixed integer structure of these models. Aikens [1] presented a survey of discrete location models for distribution planning. He reviewed 23 models covering a wide range of problems from the single-commodity, uncapacitated facility location to the multi-commodity, capacitated, multi-echelon versions. A recent book edited by Mirchandani and Francis [106] provides a reference for the state of the art in discrete location theory. Warehousing models on the other hand involve location of items inside the warehouse. As Francis et al. [46] noted these models can be considered as mixed location models since they share aspects of both planar and discrete location models.

In general, the objective is to locate facilities so as to minimize a cost expression which is a function of the facility-customer and/or facility-facility travel distances (or times). It is possible to classify the facility location problems with respect to the structure of the cost expression. The objective of *minisum* problems is to minimize the sum of costs which is usually valid for plant location decisions. *Minimax* problems however, aim to minimize the maximum cost of having access to a public facility. The minisum and minimax problems have special cases when the spatial topology is a network, which are called *p-median* and *p-center* problems respectively. This is of course a broad classification of the numerous types of objectives studied in the location literature. Recently, Brandeau and Chiu [9] reviewed more than 50 representative problems in location research. Their taxonomy is based on types of objectives as well as decision variables and system parameters of the problems.

3.1.1 The simple plant location problem

The *simple plant location problem* (SPLP) involves locating an undetermined number of facilities to minimize fixed setup costs of opening plants plus linear variable costs of serving clients. This is the basic discrete location problem where the facilities are assumed to have unlimited capacity. Furthermore, the problem is static (single period), deterministic, single-commodity and has no transshipment points. Krarup and Pruzan [88] provided an excellent survey of the literature on SPLP including solution properties and computational techniques. They also established the relationships between SPLP and set packing, set covering and set partitioning problems and thus, demonstrated that SPLP belongs to the NP-complete class of problems.

Let n denote the number of markets (indexed by j) and m denote the number potential plant locations (indexed by i). The simple plant location model can be formulated as follows:

$$\begin{aligned}
&\text{Minimize} \quad z = \textstyle\sum_{i\in I}\sum_{j\in J} C_{ij}x_{ij} + \sum_{i\in I} F_i Y_i, && && (3.1)\\
&\text{subject to} \quad \textstyle\sum_{i\in I} x_{ij} = 1, && \forall j, && (3.2)\\
&\qquad 0 \le x_{ij} \le Y_i, && \forall i,j, && (3.3)\\
&\qquad Y_i \in \{0,1\}, && \forall i, && (3.4)
\end{aligned}$$

where

I,J = the sets of potential plant locations and markets respectively,

F_i = the fixed setup cost of opening plant i,

C_{ij} = the total production and transportation cost of supplying all of market j's demand from plant i,

x_{ij} = proportion of market j's demand satisfied by plant i,

Y_i = 1 if plant i is opened, 0 otherwise.

Constraints (3.2) guarantee that each market's demand will be fully satisfied, and constraints (3.3) ensure that markets receive shipments only from open plants. Note that, the variable costs are linear and thus, the model needs some modifications if there are economies of scale in production and transportation costs. Moreover, for any given set of open plants it is possible to determine the optimal assignment of markets to plants by solving a transportation problem.

One of the earliest attempts to solve SPLP is the *pairwise interchange* heuristic of Kuehn and Hamburger [89]. Although almost three decades old, their two sets of test problems (K & H) having 50 markets, 16 and 25 potential plants respectively, still provide a standard for comparing computational efficiencies of different algorithms. A comparison of exact and approximate methods for solving SPLP can be found in Thizy, Wassenhove and Khumawala [136]. Our review however, is confined to the exact methods since very efficient algorithms which guarantee optimal solutions for SPLP are available. Efroymson and Ray [28] adopted the branch and bound technique to solve SPLP. Actually, they worked on a different formulation which replaces the constraints (3.3) with the following:

$$0 \leq \sum_{j\in J} x_{ij} \leq nY_i, \quad i = 1, ..., m. \tag{3.5}$$

This is a compact formulation having a set of (integer) solutions identical to that of (3.2)-(3.4). LP relaxation however, can quite easily be solved by inspection. Efroymson and Ray reported solving 50 plant 200 customer problems in ten minutes on the IBM 7094. Their model is called the *weak formulation* due to the fact that the LP relaxation does not provide tight lower bounds of SPLP. Khumawala [80] extended the work of Efroymson and Ray by proposing efficient branching and separation strategies for branch and bound.

He demonstrated the impact of these strategies by solving K & H at most in 17 seconds on a CDC 6500.

It has been realized that the LP relaxation of the *strong formulation* (3.1)-(3.4) yields tight lower bounds which are often (integer) solutions to SPLP. Erlenkotter [33] took advantage of this to device his *dual-based* algorithm. He obtained impressive results by solving K & H in 0.1 seconds and some 100 plant 100 customer problems in 5 seconds on the IBM 360/91. The algorithm is based on solving (condensed) dual of the LP relaxation, which involves only the multipliers corresponding to constraints (3.2). The simple ascent and multiplier adjustment procedure quite often produces optimal dual solutions. Even when, only dual feasible solutions are provided, it is still possible to obtain tight lower bounds by using complementary slackness. This dramatically increases the computational efficiency of the branch and bound procedure.

In many cases it is more realistic not to assume unlimited capacity plants. This version is called the *capacitated plant location problem* (CPLP). The following constraints are appended to the SPLP formulation:

$$\textstyle\sum_{j\in J} D_j x_{ij} \leq S_i, \quad i = 1, ..., m, \tag{3.6}$$

where

D_j = the demand of market j,

S_i = the capacity of plant i.

Van Roy [138] provided a cross decomposition algorithm for solving CPLP. The essence of his algorithm is to obtain a SPLP structure by dualizing the capacity constraints. The Lagrangian relaxation provides values for the location and allocation variables given a set of multipliers. The locational decisions are then used to fix the integer variables and solve CPLP as a transportation problem to obtain improved multiplier values. However, it may be necessary to solve an appropriately defined LP at some iterations to update the multipliers. Van Roy solved the capacitated K & H under 1 second (except the last two which needs at most 3.08 seconds) on the IBM 3033. This outperforms the algorihms by Guignard and Spielberg [53] and Akinc and Khumawala [3]. Recently, Beasley [5] devised an efficient algorithm for CPLP. He reported solving problems involving upto 500 potential locations and 1000 customers on a Cray-1S.

Van Roy and Erlenkotter [140] provided an efficient algorithm for the (uncapacitated) *dynamic plant location problem.* The aim is to select the time-staged establishment of plants so as to minimize the total discounted costs for meeting the spatial distribution of demand over time. A dual-based procedure is incorporated in a branch and bound scheme. The K & H (with 10 time periods) were solved within 1 second on the IBM 3033.

3.1.2 Plant location under uncertainty

SPLP provides two types of decisions simultaneously:

- **Locational decisions**; the number and locations of plants to be opened,
- **Allocation decisions**; the assignment of markets to open plants.

In practice, there is a time lag between the investment decision and completion of plant construction. Length of the time necessary for having the plant in place and operating is not totally controlable by the firm. That is, the locational decisions are made prior to the realization of quantities demanded, prices and costs. Since at least one of the above factors is exogenous, it is more realistic to analyze the plant location under uncertainty. This requires addressing the firm's attitude toward risk.

In its simplest form (3.1)-(3.4), SPLP does not distinguish between markets in terms of profitability and requires the firm to fully satisfy each market. Therefore, a direct implementation of that formulation presumes an implicit prescreening of markets by the management. We will present a reformulation of SPLP with a profit maximization objective where the model enables the firm to choose among markets when setting its shipment targets. This is particularly necessary when there are considerable price differences between markets and will aid our statement of the *simple plant location problem under uncertainty* (SPLPU). Let,

P_j = the unit selling price in market j,

c_{ij} = the unit cost of producing and shipping from plant i to market j

X_{ij} = the quantity shipped from plant i to market j.

We will take the freedom to also use the previously defined notation in the following formulation:

$$\begin{array}{llll} \text{Maximize} & \pi = \sum_{i \in I} \sum_{j \in J} (P_j - c_{ij}) X_{ij} - \sum_{i \in I} F_i Y_i, & & (3.7) \\ \text{subject to} & \sum_{i \in I} X_{ij} \leq D_j, & \forall j, & (3.8) \\ & 0 \leq X_{ij} \leq Y_i D_j, & \forall i, j, & (3.9) \\ & Y_i \in \{0, 1\}, & \forall i. & (3.10) \end{array}$$

Presuming the firm can predict the future cost structure relatively easily, Jucker and Carlson [74] addressed different control strategies for dealing with price and demand uncertainty. Their classification is based on exogenous versus controlable variables and ex ante (before resolution of the uncertainty) versus ex post decisions. They recognized four types of firms:

- Quantity-setting firm (agribusiness),
- Price-setting firm producing to order (monopoly),
- Price-taking firm producing to order (public utility),
- Price-taking firm producing a perishable good (newsboy).

The SPLPU literature however, is concentrated on the agribusiness case where the firm ex ante sets the quantities to be produced and sold (up to a maximum of D_j). Market prices are functions of these quantities and uncertainty. This seems to be a valid assumption for modeling firms when the product markets are not regulated. Hodder and Jucker [65] mentioned a further reason for their focus on the quantity-setting firm to be the relative ease of incorporating interrelated demand uncertainty across markets via correlated random prices.

There are alternative ways of modeling the firm's risk preferences. Jucker and Carlson [74] proposed a mean-variance framework which has long been in use for optimal portfolio selection (see Markowitz [103]). Here variance of total profit is used as a measure of risk which is traded off against the expected value of total profit. That is, the firm is going to maximize $V = E(\pi) - \lambda var(\pi)$. Then, SPLPU can be stated as follows:

$$\text{Maximize } V = \sum_{i\in I}\sum_{j\in J} E(P_j - c_{ij})X_{ij} - \sum_{i\in I} F_i Y_i - \lambda var(\sum_{i\in I}\sum_{j\in J} P_j X_{ij}), \quad (3.11)$$

$$\text{subject to} \quad (3.8)\text{-}(3.10).$$

In order to see the impact of incorporating the market prices note that

$$V = \sum_{i\in I}\sum_{j\in J} E(P_j)X_{ij} - \lambda var(\sum_{i\in I}\sum_{j\in J} P_j X_{ij}) - z. \quad (3.12)$$

Here, λ is a nonnegative parameter that represents the level of risk aversion of the firm. Determination of λ itself is a crucial problem. Howard [67] provided a good account of techniques for the assesment of λ. The mean-variance objective function ignores any possible skewness in the probability distribution of total profit but, adequately represents an expected utility maximizer. This representation is exact when utility is a quadratic function of total profit or when probability distribution of total profit is two parameter and symmetric such as Normal distribution. Hodder [62] suggested adoption of the financial market approaches to model SPLPU. He utilized the Capital Asset Pricing Model of Sharpe [122] for illustration purposes. In this case the model takes the form

$$\text{Maximize} \quad V_M = E(\pi) - \lambda_M cov(\pi, R_M), \quad (3.13)$$

$$\text{subject to} \quad (3.8) - (3.10).$$

where R_M represents the value of the market index and λ_M denotes the market measure of risk aversion. That is, the covariance of total profit with the market index (*systematic risk*) is traded off against the expected value of total profit. In this way, the problem is formulated from the shareholders' point of view; minimizing the non-diversifiable risk. Variance of total profit on the other hand, represents the *total risk* which usually is the concern of managers. Each model has pros and cons in terms of model realism and computational efficiency. Note that, (3.13) is a linear objective function compared to the quadratic structure of (3.11). For a detailed comparison of the above models within an international context see Dincer and Hodder [26].

It is possible to trace the development of SPLPU models via analyzing the way in which uncertainty is incorporated. The model of Jucker and Carlson [74] assumed the random variables are independent. That is,

$$P_j = v_j - w_j \sum_{i \in I} X_{ij} + \epsilon_j, \tag{3.14}$$

$$\epsilon_j \sim N(0, \sigma_j^2), \quad cov(\epsilon_j, \epsilon_k) = 0 \;\; \forall j, \forall k \neq j. \tag{3.15}$$

These represent the independent random shifts of linear market demand curves as a price generating mechanism. Their solution procedure is based on this rather restrictive assumption. Hodder and Jucker [65] allowed for correlated prices;

$$P_j = b_j(P_0 + \epsilon_j). \tag{3.16}$$

Here, b_j is a (positive) market adjustment parameter for the common random factor P_0 with mean $\overline{P}$ and variance σ^2. Hodder and Dincer [63] adopted a multifactor price generating mechanism where random prices are expressed as a linear combination of orthogonal factors.

Efroymson and Ray [28] observed that for any given set of open plants, the optimal allocation decisions for SPLP can be obtained by allowing each market to be supplied from the "closest" plant. Such a *dominant* plant has the least unit variable supply cost (independent of the quantity produced and transported to the market under consideration) among the open plants. Existence of a dominant plant for each market leads to a significant increase in computational efficiency of the branch and bound procedure. This is because dominance enables decomposition of a *nodal problem* into n easily solved subproblems. Linearity of the unit variable supply costs is a sufficient condition for dominance to hold. Jucker and Carlson [74] employed the linearity assumption which together with their independence (of the random prices) assumption provided significant simplifications in the solution of SPLPU. Hodder and Jucker [65] showed that dominance still holds when the random prices are correlated. This enabled them to devise their efficient algorithm for the nodal problems. See also Carlson, Hodder and Jucker [14] for a generalization of that algorithm.

3.1.3 The international plant location problem

SPLP has a challenging version within the international context where there are national boundaries between potential plant locations and customer zones (markets). The *international plant location problem* (IPLP) is stochastic by nature due to the randomness in price and exchange rate movements. There are further features of the international business environment, such as import tariffs and quotas, differential tax rates and subsidized financing which differentiate IPLP from SPLP. National governments provide subsidized financing (as well as low tax rates) to attract multinational companies to locate production plants in their country. Multinational companies on the other hand, use foreign financing packages to hedge against international price and exchange rate fluctuations. Thus, financing decisions are an integral part of IPLP due to risk reduction strategies as well as locational incentives via subsidized interest rates.

The literature on IPLP is sparse. Pomper [112] provided a multiperiod, dynamic programming formulation for designing international investment strategies. To incorporate uncertainty, he employed a scenario approach which can essentially be considered as deterministic. The pioneering work in modeling the interaction between international location and financing decisions is due to Hodder and Jucker [64]. That model however, is restricted to a deterministic setting. Hodder and Jucker [66] extended their previous work to incorporate uncertainty, ignoring financing decisions. They presented a single period model where a multinational company is assumed to be a mean-variance decision maker. They modeled the random deviations from the Law of One Price which asserts that arbitrage forces will tend to equalize prices for identical commodities selling in different national markets. Their single factor price generating mechanism is as follows:

$$P_j e_{1j} = b_j(P_1 + \epsilon_j), \tag{3.17}$$

where

P_1 = the random price in the home country with mean $\overline{P_1}$ and variance σ_p^2,

e_{1j} = the units of the numeraire currency per unit of currency j.

Note that, although price uncertainty is explicitly taken into account, the way exchange rate uncertainty incorporated is rather implicit.

Location and financing decisions are intertwined, especially within an international environment. This is because, availability of subsidized financing and/or preferential tax treatment may increase attractiveness of a potential location. Furthermore, financing in different currencies can be used as a hedge against price and exchange rate uncertainty. Hodder and Dincer [63] developed a model for simultaneous analysis of the international location and financing decisions. The mixed integer program has a quadratic objective function due to adoption of the mean-variance framework. They suggested a multifactor approach to diagonalize the variance-covariance matrix in the objective function. This results in a considerable reduction in the computational difficulty of solving IPLP. Recently, Min [105] suggested a chance-constrained goal programming model in order to incorporate the presence of dynamism and multiple objectives in the locational decisions of multinational firms. At this stage, IPLP can adequately be considered as one of the building blocks of our major problem; designing global manufacturing strategies.

3.2 Capacity acquisition

In the previous section, we reviewed the literature on facility location decisions which lead to the spatial distribution of manufacturing plants and warehouses of a firm. Since construction of production plants requires significant capital outlays, and frequently takes a few years, the locational decisions are irreversible, except in the long run. That is, unless establishment of new plants or relocation of the existing plants are under consideration, firms serve the customer zones from the already selected sites. Hence, once implemented the facility location decisions constrain the pursuit of a firm's manufacturing strategy.On the basis of the spatial distribution of facilities, the capacity acquisition and technology selection decisions provide the means to satisfy the demand over time.

Capacity expansion problem (CEP) involves decisions about the sizes, locations and times of capacity expansions to serve a spatially distributed set of customers. When there are more than one product, type of the acquired capacity is also important. Capacity contraction may turn out to be optimal, given the existing capacity and the demand pattern. It should be noted however, the literature on capacity decisions is mainly focused on CEP. At this point, we will assume that capacity contractions (if necessary) can be achieved by appropriate capacity type conversions. Otherwise, the models need modifications to capture the dynamics of the contraction process. An extensive review of the operations research literature on CEP can be found in Luss [99].

3.2.1 The capacity expansion problem

Given the pattern of demand over time, a capacity expansion process is characterized by sizes, locations and times of the expansions as well as types of capacity acquired. CEP aims to find an optimal set of expansion decisions which enables the firm to satisfy demand over a prespecified time horizon.

Objective is to minimize the discounted costs associated with the expansion process.

The pioneering work on capacity expansion is due to Manne [101]. He examined the optimal degree of excess capacity to be built into a plant while there is economies of scale in capacity acquisition. His analysis also included the case where backlogs of unsatisfied demand are allowed. Another key reference is the book edited by Manne [102] the first part of which is devoted to case studies on the aluminum, caustic soda, cement and nitrogenous fertilizer industries of India. The second part includes theoretical papers by Srinivasan, Erlenkotter, Veinott and Manne. Their work is important in terms of further exploring the single-facility case and introducing the two-facility CEP.

Rather than reviewing the vast literature on capacity expansion (see Luss [99]), our aim is to describe the components of CEP which lead to a categorization of various capacity problems. Elements affecting expansion decisions are the following:

- Planning horizon and Discount rate,
- The set of feasible expansion sizes,
- Demand pattern,
- Capacity acquisition costs and Other cost factors,
- Number of facilities and Number of products involved.

CEP is a dynamic problem by nature and may be formulated over either an infinite time horizon or a discrete period finite time horizon. Since CEP involves medium to long term decisions discount rate may have a significant impact on the final outcomes. It is a common practice to analyze the robustness of the optimal capacity plans to overcome the estimation problems about future discount rates. Primary decision variables in a CEP formulation are the expansion sizes. Thus, it makes a big difference in terms of computational complexity whether expansion sizes may take on any value or they must be selected from a set of discrete alternatives. It is obvious that for practical problems, the continuous case is much simpler. Capacity problems are further classified according to the nature of knowledge about demand; deterministic or probabilistic. Literature on capacity expansion under uncertainty is reviewed in the next section. Pattern of demand over time may be linear (constant growth rate), exponential (geometric growth rate) or decreasing with a saturation level. Discrete-horizon problems are generally solved for arbitrary demand growth.

CEP dwells on the trade off between the economies of scale in capacity acquisition and cost of holding excess capacity. Capacity acquisition cost functions are usually concave (e.g. the power cost function) to represent the economies of scale. Other popular functions are the fixed charge cost function and the piecewise concave cost function. The latter is particularly useful for modeling availability of different technologies for different ranges of expansion sizes. Structure of the shortage costs depends on whether or not backlogs are allowed. Some formulations of CEP also include idle capacity costs, congestion costs , maintenance costs and inventory holding costs.

Capacity expansion problems and the available techniques to solve them can be classified according to the number of facilities involved in the expansion process; *single-facility problems*, *two-facility problems* and *multifacility problems.* For the single-facility CEP, an expansion process is characterized by only the sizes and times of the expansions if the facility produces a single product. When there are more than one facility, location of each expansion also becomes important since it is possible to satisfy demand from either of the facilities at the expense of some transportation cost. The *multifacility-type* CEP is the most general form of the problem where type of each capacity acquisition must also be specified due to the fact that there are more than one product in the system.

Let m denote the number of existing facilities (indexed by i) and T denote the number of periods (indexed by t) in the planning horizon. A special case of the multifacility-type CEP where each facility owns a different capacity type can be formulated as follows:

$$\text{Minimize} \quad C = \sum_{t=1}^{T} \sum_{i=1}^{m} [f_{it}(s_{it}) + \sum_{\substack{k \in I \\ k \neq i}} g_{ikt}(w_{ikt}) + h_{it}(E_{it})], \tag{3.18}$$

$$\text{subject to} \quad E_{it} = E_{i,t-1} + s_{it} + \sum_{\substack{k \in I \\ k \neq i}} (w_{kit} - w_{ikt}) - D_{it}, \qquad \forall i, t, \tag{3.19}$$

$$E_{i0} = E_{iT} = 0, \qquad \forall i, \tag{3.20}$$

$$E_{it} \geq 0, \quad s_{it} \geq 0, \quad w_{ikt} \geq 0, \qquad \forall i, t, \tag{3.21}$$

$$k = 1, .., m, \quad (k \neq i),$$

where

I = the set of existing facilities,

D_{it} = demand increment for product i for additional capacity in period t, ($D_{it} \geq 0$),

E_{it} = excess capacity of facility i at the end of period t,

$f_{it}(.)$ = capacity expansion cost function of facility i in period t,

$g_{ikt}(.)$ = capacity conversion cost function of facility i associated with conversions to facility k in period t,

$h_{it}(.)$ = capacity holding cost function of facility i associated with carrying excess capacity from period t to period $t + 1$,

s_{it} = expansion size of facility i in period t,

w_{ikt} = amount of capacity converted from facility i to facility k in period t.

The appropriate discount factors are assumed to be already included in the cost functions. Further, demand increments, expansions and conversions are assumed to occur at the beginning of each period. We would like to make a few remarks on the above model. Note that, index i refers to facility i producing product i using capacity type i. Thus, the set of existing facilities is identical to both the set of capacity types and the set of products. Since demand increments and capacity expansions are restricted to nonnegative values, the model does not allow for capacity contraction. Similarly, shortages are not allowed due to the nonnegativity constraints on excess capacity. Contractions (shortages) can be incorporated into the model by relaxing those nonnegativity assumptions and modifying the expansion (holding) cost function to represent contraction (shortage) costs for negative arguments.

CEP can also be formulated as a dynamic programming (DP) problem. State space consists of the excess capacity variables, and the costs associated with optimal plans over subhorizons are obtained from a network flow representation of CEP. The network includes a single source node for capacity expansions, other nodes to describe facilities at discrete time periods and arcs to represent expansion, conversion and excess capacity variables. When the objective function is concave, it is well known that the extreme point solutions are optimal. Note that, the extreme point solutions correspond to the extreme flows of the network. Zangwill [145] showed that an extreme flow in single-source networks has at most one positive incoming flow into each node. This property of extreme flows considerably decreases the effort necessary to compute the cost figures required by the DP formulation.

The single-facility CEP corresponds to a single-state DP problem which can be solved in polynomial time (polynomial of T). Even this simplest version of CEP becomes NP complete however, when the cost functions are not concave or when there are unequal upper bounds on capacity expansions. The two-facility CEP can also be formulated as a single-state DP problem by realizing that at most one of the two state variables will be positive at any state (time period). Since it is only possible to reduce the dimension of the state space by one, DP formulation does not provide a valuable tool for the multifacility problems. The efforts to solve multifacility CEP are concentrated more on the development of heuristic approaches. See for example Erlenkotter [32] for the Minimum Annual Cost algorithm or Fong and Srinivasan [43], [44], [45] for their capacity exchange heuristic. Recently, Lee and Luss [95] provided some results about computational complexities of various multifacility-type CEPs.

3.2.2 Capacity expansion under uncertainty

In his seminal paper Manne [101] analyzed the single-facility CEP when demand is a stochastic process. He used a continuous random-walk pattern to model demand over an infinite time horizon. Mean and variance of the normally distributed demand increments are increasing linear functions of time. Capacity acquisition costs are represented by a power cost function. Manne's model aims to provide the optimal expansion sizes to minimize the expected discounted costs of the expansion process. He showed that the optimal level of expected discounted costs and the optimal size of capacity increments increase as the variance of the growth in demand increases. This surprising result is due to the fact that the mean of his demand function increases with its variance.

Giglio [50] provided a comprehensive account of the stochastic capacity models. He developed a series of models to handle time stationary and nonstationary demand functions. The simplest model is for capacity expansion under stationary, probabilistic demand. In this case, there will be a single capacity acquisition such that the probability of not meeting demand equals to the cost per dollar of profit. For nonstationary demand, Giglio also assumed that mean is linearly increasing with time. Unlike Manne [101] however, mean and variance of demand are independent. Giglio suggested utilizing modified deterministic models to obtain approximate solutions to stochastic problems. Another relevant reference is the article by Meyer [104] where he presented a theory of monopoly pricing and capacity choice under uncertainty.

Jucker, Carlson and Kropp [73] examined capacity expansion decisions of a firm producing a single product to satisfy uncertain demand in several regions via regional warehouses. The capacity to be built into the single production plant and warehouse capacities to be leased are determined simultaneously. Unlike most of the CEP literature, a single-period model is constructed and the concavity assumption associated with the capacity acquisition cost function is relaxed. They assumed a price-setting (or price-taking) firm maximizing its expected profits and suggested an efficient solution algorithm which is exact only if in each region the cumulative distribution function of demand is piecewise linear. A generalization of their procedure can be found in Carlson, Hodder and Jucker [14].

Eppen, Martin and Schrage [30] developed a model and software to analyze the multiproduct, multiplant, multiperiod capacity planning problem of General Motors. The planning horizon consists of 5 years (periods) where the fifth year represents the steady state to be reached during years 5 through infinity. Since it is not possible to have exact information about demand over such a time horizon, risk is incorporated into the model via a scenario approach. A scenario corresponds to demand and sales price estimates for each period for all the products involved in the analysis. The problem is further complicated due to the existence of a set of distinct retooling (expansion) alternatives for each plant. Retooling decisions for 5 years have to be made before the resolution of demand uncertainty (followed by a production plan) at each year. Eppen et al modeled this process as a stochastic mixed integer linear program with recourse where the first stage involves the capacity expansion decisions. Recourse stage corresponds to the selection of production quantities. Objective is to maximize the expected (discounted) profit constrained by management's concerns about risk. That is, instead of utilizing the mean-variance framework a new measure of risk is devised; *expected downside risk.* Let,

$\hat{\pi}$ = target profit,

$d_{\hat{\pi}}(\pi)$ = downside risk of profit π for target $\hat{\pi}$
where, $d_{\hat{\pi}}(\pi) = max\{(\hat{\pi} - \pi), 0\}\ for\ \pi \in R^1$ and

$\Phi(\pi)$ = probability mass function of profit π.

Then, the expected downside risk of target $\hat{\pi}$ is

$$EDR[\hat{\pi}] = E[d_{\hat{\pi}}(\pi)] = \sum_{\pi \in R^1} \Phi(\pi) d_{\hat{\pi}}(\pi) \tag{3.22}$$

First, the model is solved without any risk constraint and then successive constraints on the $EDR[0]$ are appended to the model in order to reduce the risks associated with future profits. Solution process includes generation of histograms of profit (using Monte Carlo sampling) for every solution. This is in order to elicit risk preferences of management and to construct the relevant constraints on expected downside risk. Since the number of integer variables is quite large, the authors had to resort to a mainframe optimizer. Eppen et al reported solving (within 1.2 percent of the optimum) a problem with 160 binary variables in 1.3 CPU hours on a VAX 8650.

Bird [8] provided a different stochastic programming with recourse approach to the capacity planning problem (again in General Motors). His model has a quadratic objective function in the recourse stage which involves both production and pricing decisions. A direct two stage solution method is suggested rather than converting the problem to a one stage nonlinear program.

Dantzig and Glynn [24] analyzed potential role of parallel processors for planning under uncertainty. The general multi-stage stochastic problem seems to remain intractable due to the proliferation of possible outcomes as the number of stages increases. Thus, their research is focused on facilities expansion problem under uncertainty as a subclass of the general multi-stage problem. Number of possible outcomes (scenarios) remains constant at each stage for this class of problems. That is because expansion decisions are finalized at the beginning of the first stage and alternative realizations of random demand at any stage do not change the state of the system in terms of those decisions. Nested dual-decomposition is used to solve the problem. Master problem aims to minimize the expected cost and provides lower bounds to the subproblem while receiving cuts to improve the solution at each iteration. Subproblem breaks down into sub-subproblems one for each stage (period). Every sub-subproblem is composed of independent problems one corresponding to each scenario. If the number of scenarios is not large, then it is possible to solve the subproblem by having that many parallel processors at each stage. In the case of a large number of possible random events (or when demand has a continuous probability distribution), Dantzig and Glynn suggested usage of Monte Carlo importance sampling and assignment of sampling tasks to parallel processors. Their ongoing research constitutes a valuable contribution to the solution methodology of the capacity expansion problem under uncertainty.

3.3 Technology selection

Capacity acquisition decisions indicate sizes of the facilities to be established at the sites selected via the facility location decisions. At any plant, the designated amount of capacity can be acquired in terms of different technology alternatives. That is, *capacity types* in the capacity expansion context constitute *technologies* in the more general technology selection problem. Hence, firms pursue their capacity expansion plans by choosing among a set of alternative technologies. Since manufacturing technology is subject to a continual improvement process, the set of alternative technologies changes over time. Hence, selecting the best time for adoption of a new technology is a problem by itself. The interested reader is referred to Fine [38] and the references therein for the literature on optimal timing of technology adoption. Here, we will assume that the alternative technologies are given and review the literature on selection of the most appropriate technology. Alternative technologies may have different cost, quality and flexibility implications. Note that, manufacturing strategy of a firm includes goals in terms of the attributes mentioned above. Therefore, technology selection decisions constitute means to achieve strategic goals and should be in accordance with manufacturing strategy.

Product life cycles have been shortening as the international competition intensifies. Productivity, flexibility, service time, quality and reliability as well as costs have become the major considerations for survival in the international markets. Thus, firms have been adopting the advanced manufacturing technologies to move towards more *automation* and *integration* in order to sustain their competitiveness. Automation refers to the substitution of machines for human functions. Robots, numerically controlled machine tools, automated material handling systems, automated inspection systems and flexible manufacturing systems have been quite popular alternatives for technology decisions over the last decade. Integration on the other hand, is the reduction or elimination of the physical, temporal and organizational buffers. *Computer Integrated Manufacturing* (CIM) is usually the ultimate goal for the firms where managers believe in the (hard to quantify) benefits of integration. CIM is integration of the entire manufacturing system through the use of integrated systems and data communications. In order to improve the efficiency, implementation of CIM should be accompanied by the new managerial philosophies such as Just-in-Time Manufacturing, Quality Function Deployment and Design for Manufacturability. Fine [37] provided an account of the new developments in manufacturing technology.

Flexible Manufacturing Systems (FMSs) deserve special emphasis here. An FMS is a collection of numerically controlled machine tools connected by an automated material handling system which are operated under central computer control. The primary feature of FMSs is their capability to process a medium variety of parts with low to medium demand volume without requiring significant setup times and costs. That is FMSs provide the operational flexibility of job shops while approaching the machine utilization of highly-automated transfer lines.An overview of FMSs can be found in Huang and Chen [68] and Kusiak [92].

In general, the significant capital outlays required for the FMS installation projects are undertaken in order to achieve a strategic goal; *manufacturing flexibility*. However, Jaikumar [72] noted that, with few exceptions FMSs installed in the United States show an astonishing lack of flexibility mainly due to managerial problems. This observation underlines the importance of understanding flexibility in manufacturing. That is it does not seem to be realistic to expect high efficiency from these systems unless methodologies for evaluating them and monitoring their performance are available. Unfortunately, the literature on flexibility has not settled down to a standard theoretical framework consisting of rigorous definitions yet. There are at least 50 different terms for various types of flexibilities that can be designed into an FMS. Sethi and Sethi [121] made an important contribution by carefully defining several kinds of flexibilities and analyzing the interrelationships among them. They also clarified purposes of each flexibility type and suggested means to obtain them together with some measurement and evaluation techniques. Their work however, remains far from being a taxonomy of manufacturing flexibility.

There are alternative approaches for technology evaluation in order to solve the technology selection problem. Physical measures such as flow times, queuing times, lead times, inventory levels, production rates, and work in process are major concerns of the performance evaluation models. That line of research aims to analyze the technologies in terms of their operational impacts. Since we are dealing with the strategy problem we are only concerned with an aggregate feedback from the operational level. Thus, the performance evaluation models are not in the scope of this review. The interested reader is referred to Buzacott and Yao [13]. Economic evaluation models on the other hand, examine the technologies on the basis of their financial impacts. Thus, these models provide a valuable tool for strategy designers. Economic evaluation dwells on estimates of the costs and benefits of installing advanced manufacturing technology. It should be noted that obtaining those estimates or even quantifying some of the costs and benefits is a problem itself in many cases. We will focus our attention to the single firm models in the following sections. This is primarily in order to ease the exposition and should not be interpreted as an underestimation of the game-theoretic models which capture the interdependence between technology decisions of several firms. Fine [38] provided an excellent review of the economic evaluation models including the literature on multiple firm models.

3.3.1 The technology selection problem

Historically, capital-intensive technologies have been developed as challengers for labor-intensive technologies. This represents a shift from low fixed - high unit variable cost structures to high fixed - low unit variable cost structures. Classical discounted cash flow techniques have been widely used to justify these new technology acquisitions. Benefits of the automated manufacturing systems however, are far beyond the economies of scale provided by the conventional capital-intensive technology. Singhal et al. [123] summarized the benefits attributed to automated manufacturing systems as:

- Lower direct manufacturing costs,
- Improved product quality,
- Economies of scope,
- The ability to respond rapidly to changes in design and demand, and
- Flexibility in scheduling around equipment breakdowns.

Some of the benefits to be traded off against the significant capital outlays of these investments are not easy to quantify. This constitutes the backbone of the criticism of the usage of traditional engineering economy models to justify advanced manufacturing technology. Further criticism stems from the emphasis of the discounted cash flow techniques on short term returns rather than long term strategy and their presumed determinism about the future. Kaplan [76] on the other hand, stated that it is not the models' but the managers' responsibility to judge whether the gap between costs and *quantifiable* benefits are outweighed by the anticipated nonquantified benefits. Kulatilaka [90] provided a synthesis of the capital budgeting problems dealing with financial, economic and strategic issues concerning the decision to invest in advanced manufacturing technology. We envision the following literature as valuable contributions to enlarge the set of available managerial tools for the analysis, evaluation and justification of advanced automation.

Hayes and Wheelwright [58] hypothesized that firms should locate themselves on the diagonal of the product-process life cycle matrix. That is the technology decisions should be in accordance with the evolution of a product from a one-of-a-kind prototype to a high-volume highly standardized item. This requires the production process to be upgraded from a job shop to a highly automated assembly line as the product matures. In Hayes and Wheelwright [59] three alternative market entrance-exit strategies which actually govern the technology decisions are suggested. These strategies are:

- Early entry - early exit from the market,

- Early entry - remain in the market and,
- Late entry after market maturation.

It is worthwhile to mention that the second strategy corresponds to a movement from labor-intensive toward capital-intensive technology.

Fine and Li [41] developed a single product technology choice model in order to formally analyze Hayes and Wheelwright's hypothesis. In their model demand is a deterministic function of time following the product life cycle pattern. The firm has only two alternative technologies; labor-intensive and capital-intensive the former having a lower break-even point. Fine and Li [41] formulated the problem as a dynamic program and came up with six alternative technology strategies. The optimal strategy is chosen on the basis of the cost structure. In spite of the fact that the early entry-exit strategy (which is meaningful only for multiproduct settings) is not included, their action space is larger than that of Hayes and Wheelwright. In the single product, stochastic, dynamic model of Cohen and Halperin [18], each technology is represented by its purchase cost, per period operating cost and per unit production cost. They concluded that an optimal technology sequence should have nonincreasing per unit production costs which justifies the trend toward more capital intensiveness in technology selection decisions.

In the case of facing capacity shortage for a certain product, a firm can either purchase the necessary amount of capacity or convert some of the excess capacity for other products (if any) to satisfy the demand. Clearly, the trade off is between capacity acquisition costs and capacity conversion costs. Early work in the literature is focused on the two-facility type problem which becomes a special case of the two-facility CEP when conversion costs are negligible. General-purpose equipments provide an opportunity to produce more than one item without any capacity conversion cost. Kalotay [75] is one of the first who analyzed a problem where an expensive general-purpose equipment capable of producing two items and a cheaper specialized equipment are the technology altenatives. He provided a lower bound for the optimum for the cases of linearly and exponentially growing demand over an infinite time horizon. Kalotay's results indicate that the specialized equipment would eventually be used for linearly growing demand which is not necessary for exponential growth.

3.3.2 Choice of flexible technology

FMSs enable the firm to process a variety of items with small changeover costs. Analysis of the economies of scope provided by FMSs versus the economies of scale provided by highly automated transfer lines constitutes a very important dimension of the technology selection problem. As pointed out earlier, this requires a comprehensive understanding of the structure as well as possible operational, tactical and strategic benefits of FMSs.

Flexibility is the ability of a system to cope with changes effectively. Although flexibility is the essential feature of FMSs, it should be realized that every manufacturing system is flexible to a certain degree. Several conceptual frameworks have been developed in the literature in order to enhance the understanding of flexibility. Mandelbaum [100] defined *action flexibility* as the capacity for taking new action to meet new circumstances and *state flexibility* as the capacity to continue functioning effectively despite the change. Gupta and Buzacott [56] put forward the *sensitivity* and *stability* concepts to represent two aspects of flexibility. Sensitivity is related to the degree of a change tolerated before a deterioration in performance takes place. The higher the degree of a tolerable change the less sensitive the system is to that change. Given that a system is sensitive to a certain change, stability shows the maximum size of a disturbance for which the system can still meet the performance targets via some corrective action. Notice that the above concepts are defined on the basis of change characteristics.

There are various types of internal and external changes to which a system is exposed over time. Since coping with a certain type of change does not necessarily imply the ability to handle all possible changes, several types of flexibilities are defined in the literature. In their seminal paper, Browne et al.

[11] provided the following:

- **Machine flexibility** ; the ease of making the setups and changeovers required to produce a given set of part types,
- **Process flexibility** ; the ability to produce a given set of part types via alternative processes,
- **Product flexibility** ; the ability to alter the set of part types produced,
- **Routing flexibility** ; the ability to process a given set of part types via alternative routes,
- **Volume flexibility** ; the ability to operate profitably at different volumes,
- **Expansion flexibility** ; the capability of easily adding capacity,
- **Operation flexibility** ; the ability to interchange the ordering of operations, and
- **Production flexibility** ; the universe of part types that can be produced.

Carter [15] pointed out that different types of changes and hence the associated flexibilities affect the system in different timeframes. For example, expansion flexibility is required in medium to long run whereas, routing flexibility results in the ability to handle machine breakdowns in the short run. Thus, firms should select manufacturing technologies less sensitive and highly stable with respect to the changes influencing their performance. Recently, Suresh [129] provided a more operational definition: Flexibility is the capability of a system as well as the ease to accomodate changes. *Capability* represents whether or not a system is able to cope with a change and *ease* refers to the cost of any necessary corrective action. Given a change, a system is capable if either it is insensitive or sensitive and stable, ease of the former being zero.

Over the last decade, there has been a growing body of literature on analysis of the choice of flexible technology. We are going to classify the prevailing analytical models on the basis of their different motivations for adoption of FMS. Despite the fact that scale economies is not the main motivation for FMS investments, it is worthwhile to note the lack of consensus in the literature on the cost aspects of flexible technology. It is commonly accepted that FMSs require higher initial investments than dedicated technology. Variable production costs however, are treated in different ways by different authors. Li and Tirupati [98] presumed that the variable operation costs are linear functions of volume and ignored them to simplify their model. Fine and Li [41] and Fine and Freund [39] assumed that the variable production costs are linear and technology independent. The technology independence assumption is validated via claiming the dominance of material costs to other variable cost factors for all advanced manufacturing technologies. Hutchinson and Holland [71] and Gupta et al. [57] suggested that FMSs have higher varible operation costs than dedicated transfer lines. Their assumption is justified on the grounds that, FMSs are more prone to breakdowns due to their structural complexity. We accept that all of the above assumptions have some merit as well as simplify the solution procedures. Our suggestion however, is not to claim generality of any of these assumptions and adopt the most appropriate one depending on the problem instance.

Shortening of product life cycles has speeded up the adoption of flexible technology. This is because FMSs provide the ability to rapidly introduce new products. Hutchinson and Holland [71] compared dedicated and flexible technologies via simulating their effects on manufacturing performance. Their problem includes multiple products with demands following (different) life cycle patterns. When the firm is exposed to a stochastic product stream FMSs become more preferable as the rate of new product introduction increases and as the average volume per part produced decreases. Fine and Li [41] extended their own single product model to include multiple products. This enabled them to capture the impact of availability of flexible technology on the technology selection paradigm. Their interesting results established possible optimality of producing a single item using flexible technology at some stages of the product and process life cycles. Li and Tirupati [98] constructed a mathematical program for selecting the optimal mix of dedicated and flexible technologies and timing of capacity additions to satisfy the deterministic demand over a finite planning horizon. They developed several heuristics for the single-facility multi-product problem.

Due to their capability of processing a variety of parts, FMSs also provide means for responding flexibly to future uncertain demand. That is, flexible technology can be acquired as a hedge against uncertainty. Fine and Freund [39] developed a two-stage stochastic quadratic programming model to analyze the choice between dedicated and flexible technologies under uncertainty. Capacity decisions in the first stage constrain the production amounts in the second stage where the product markets may be in different states with discrete probabilities. Optimal technology mix is selected via maximizing the expected profit. Fine and Freund [39] implicitly assumed a monopolist firm by presuming that it will be possible to sell the quantity which maximizes the expected profit. The authors derived the necessary and sufficient conditions for purchasing flexible capacity from the following model:

$$\text{Maximize } V_F = -f_F(s^F)-\sum_{i=1}^{m} f_i(s_i)+\sum_{k=1}^{K} p_k \sum_{i=1}^{m}[R_{ik}(X_{ik}^F+X_{ik})-C_F(X_{ik}^F)-C_i(X_{ik})], \tag{3.23}$$

$$\text{subject to} \quad X_{ik} \leq s_i, \quad \forall i,k, \tag{3.24}$$

$$\textstyle\sum_{i=1}^{m} X_{ik}^F \leq s^F, \quad \forall k, \tag{3.25}$$

$$s^F \geq 0, \;\; s_i \geq 0, \quad \forall i, \tag{3.26}$$

$$X_{ik}^F \geq 0, \;\; X_{ik} \geq 0 \quad \forall i,k, \tag{3.27}$$

where m denotes the number of available dedicated technologies (indexed by i), F denotes the flexible technology which can produce all of the m products and K denotes the number of possible states of the world (indexed by k) and

p_k = probability of being in state k,

$f.(.)$ = capacity acquisition cost function,

$C.(.)$ = variable production cost function,

$R_{ik}(.)$ = revenue function of product i in state k,

s_i = amount of dedicated capacity of type i purchased,

s^F = amount of flexible capacity purchased,

X_{ik} = amount of product i processed by dedicated technology in state k,

X_{ik}^F = amount of product i processed by flexible technology in state k.

Fine and Freund [39] assumed that capacity acquisition and variable production costs are linear and the latter are technology independent. Further, downward-sloping linear demand curves are assumed which makes the revenue functions quadratic. The problem is nontrivial only if the flexible technology is cheaper than the sum of all dedicated technologies but more expensive than each of them. By the aid of a two-product example it is demonstrated that perfect negative correlation between product demands is the case when the flexible technology is most preferable. Gupta et al. [57] modeled a similar problem with quite different assumptions. In their two-product model, product demands have a continuous joint distribution and the amounts of products sold cannot exceed realized demands. The second stage of their stochastic program is a linear one due to the rather stringent assumption about the revenue functions being linear. Gupta et al. [57] paid a special attention to the dependence of the optimal investment policy on previously available capacities. This is an important contribution since the firms do not start from scratch in many cases. Further, they posed the problem of determining the *optimal degree* of flexibility. Solution of this challenging problem will increase the understanding of FMSs via incorporating the partially flexible machines in the set of alternative technologies.

Naturally, we emphasized the strategic motivations of FMS adoption. No need to say there are other motivations such as the interactions between flexibility and different types of inventories. See for example Caulkins and Fine [16] for a model that explores the interaction between flexible technology and seasonal inventories.

Notice that all of the analytical models presented above focus on the acquisition of product-flexible manufacturing technology. However, flexibility is a multidimensional concept as clarified by the type definitions. Some authors attempted to capture the dynamics of this multidimensionality. Falkner and Benhajla [35] suggested the usage of the multi-attribute decision methods whereas, Stam and Kuula [128] and Kuula and Stam[93] employed multiple criteria optimization for FMS selection decisions.

There are several other works in the literature on the selection of flexible technology which we have not been able to review in this chapter in order not to lose the focus of our presentation. However, we believe that the convex programming model of Burstein [12] which incorporates production and technology selection decisions, the stochastic dynamic program of Kulatilaka [91] which provides a value for the ability of FMSs to cope with a wide range of types of uncertainty, the approach of Triantis and Hodder [137] which uses the contingent claims pricing methodology to value FMS investments, the works of Suresh [131], [130] and Suresh and Sarkis [132] on the phased implementation of FMSs, and the model of Park and Son [111] (see also Son and Park [126] and Son and Park [127]) for economic evaluation of the advanced manufacturing systems are promising lines of research for the development of more comprehensive tools to support the technology selection decisions.

3.4 Concluding comments

It is evident from the preceding sections that the facility location, capacity acquisition and technology selection problems were dealt with separately in the literature. That is, the facility location models presume that the capacity levels at each plant will be given whereas, the capacity expansion models dwell on a given set of open plants. Further, the dynamic nature of the capacity expansion models is mostly reduced to a single-period representation in the technology selection models. Given the complexity of each of the location, capacity and technology problems by itself, this rather fragmented development of the literature is quite natural.

It should be noted however, cost structures of alternative technologies may be different at various locations. Furthermore, capacity acquisition costs may depend on location and fixed costs of opening plants at some locations may be functions of the maximum capacity to be purchased. These interrelations are fostered within an international environment where national governments offer location specific advantages. Thus, we claim that separate treatment of the facility location, capacity acquisition and technology selection decisions are not justified especially for the design of global manufacturing strategies.

Here, we would like to give reference to the work of Hurter and Martinich [70] on the production-location problem. They observed that the prices of inputs may depend on locations and developed a theory for simultaneous determination of the optimal location and the optimal input mix for each facility. By analogy, we suggest that research on integrated analysis of the location, capacity and technology decisions would constitute a fruitful avenue. The remainder of this thesis presents the development of an integrated model for facility location, capacity acquisition and technology selection which will presumably aid the design of global manufacturing strategies.

Chapter 4

Facility Location and Capacity Acquisition

A company might consider investing in the construction of new facilities for a variety of reasons, such as, increasing its production capacity of an existing product, or extending its product range by new product introduction, or entering new markets with the existing and/or new products. Here *facility* refers to the smallest productive entity that manufactures a single commodity (or, at most a single family of commodities). A *plant* however, refers to a collection of facilities in the same location, and hence in general will be producing multiple commodities. Construction of a new facility therefore, might mean expansion of an existing plant if it takes place at that site, or otherwise would require opening a new plant.

In many investment projects, decisions regarding the location and the size of a new facility to be established are interrelated since capacity acquisition costs are location dependent. A typical example being new facility investments in the international context, where subsidized financing as well as low tax rates are provided by the national governments to attract the multinational companies to locate production plants in their country. In this case, it is clear that not only the fixed costs that occur due to opening the new facility at a particular site but also the capacity acquisition costs that vary with the size of the new facility are location specific. In a recent review however, Verter and Dincer [142] pointed out that the facility location and the capacity acquisition problems have been dealt with separately in the literature. That is the capacity acquisition costs are not incorporated in the facility location models which implies an implicit assumption that they would be the same at all sites. Therefore, the information provided by a facilty location model regarding the size of a new facility might be far from optimal when the above assumption is not valid. Whereas, the capacity expansion models dwell on a given set of existing plants which may not necessarily contain the optimal site to locate the new facility. Thus, separate treatment of the facility location and capacity acquisition decisions could be justified only under quite stringent assumptions.

The aim of this chapter therefore, is to present an integrated approach for the problem of simultaneously deciding the optimal location and size of each new facility to be established. Thus, the remainder of this chapter is organized as follows: Section 4.1 provides the problem definition and a model formulation. The relevant literature is reviewed in Section 4.2. Analytical properties of the model for the uncapacitated version of the problem are explored in Section 4.3 which constitute the foundations of the algorithm presented in Section 4.4. Computational results obtained via the implementation of this algorithm are reported in Section 4.5. Section 4.6 justifies the applicability of the same algorithm (with a minor adjustment) for also solving the capacitated version of the problem. Finally, some concluding remarks are provided which suggest directions for further research.

4.1 The facility location and capacity acquisition problem

Given a set of alternative facility locations and a set of markets to be served, the *facility location and capacity acquisition problem* involves simultaneously locating an undetermined number of new facilities, and deciding their size to minimize the total cost of serving the clients. For each alternative location the cost items are:

- Fixed setup cost of establishing a new facility at that site,

- Variable cost of capacity acquisition associated with the size of the new facility, and

- Variable costs of operation and transportation for serving the markets.

Fixed setup costs such as the acquisition of land and the construction of infrastructure will be incurred only if a new facility is opened. Capacity acquisition costs would normally represent economies of scale, and hence would be monotone increasing concave functions of the capacity to be built-in at each new facility. Although it is also possible that the operation and transportation costs represent economies of scale, we presume that this would not have a considerable effect on the strategic location and sizing decisions. Therefore, variable costs of operation and transportation are assumed to be linear.

The facility location and capacity acquisition problem is by definition concerned with a single commodity. Furthermore, the problem is deterministic, static, and has no transshipment points. Note that the problem boils down to the uncapacitated facility location problem (UFLP) when the capacity acquisition costs are ignored. UFLP is shown to be NP-complete by Krarup and Pruzan [88] which in consequence means that the facility location and capacity acquisition problem also belongs to the NP-complete class of problems.

Let n denote the number of markets (indexed by j) and m denote the number of alternative facility locations (indexed by i). The problem can be modeled as follows:

$$\text{Minimize} \quad z = \textstyle\sum_{i \in I} [F_i Y_i + f_i(\sum_{j \in J} X_{ij}) + \sum_{j \in J} c_{ij} X_{ij}], \tag{4.1}$$

$$\text{subject to} \quad \textstyle\sum_{i \in I} X_{ij} = D_j, \quad \forall j, \tag{4.2}$$

$$0 \leq X_{ij} \leq Y_i D_j, \quad \forall i, j, \tag{4.3}$$

$$Y_i \in \{0, 1\}, \quad \forall i, \tag{4.4}$$

where

I, J = the sets of alternative facility locations and markets respectively,

F_i = the fixed setup cost of opening facility i,

$f_i(.)$ = the total capacity acquisition cost at facility i,

c_{ij} = the unit cost of producing and shipping from facility i to market j,

D_j = the demand of market j,

and the decision variables are

X_{ij} = the quantity shipped from facility i to market j,

Y_i = 1 if facility i is opened, 0 otherwise.

It should be emphasized that F_i excludes any costs associated with the capacity of facility i, and obviously will depend on whether the new facility is established at an existing plant or it requires construction of a new plant. Thus, the total cost that is incurred due to the location and sizing of the new facilities as well as the facility-market allocations is minimized, while constraints (4.2) guarantee that each market's demand will be fully satisfied, and constraints (4.3) ensure that markets receive shipments only from open facilities.

The above mathematical program models the problem where there are no upper bounds on the capacity acquired at the new facilities, which we call the uncapacitated facility location and capacity acquisition problem (UFL&CAP). If the size of each new facility however, is constrained due to a variety of reasons e.g. availability of land, then the following constraints are appended to the model:

$$\sum_{j \in J} X_{ij} \leq CAP_i \qquad i = 1, .., m \tag{4.5}$$

where, CAP_i is the maximum capacity that can be built-in at facility i. This version of the problem is called the capacitated facility location and capacity acquisition problem (CFL&CAP). It is evident that CFL&CAP boils down to the capacitated facility location problem (CFLP) when the capacity acquisition costs are ignored. Note that, it is possible to interpret CFLP as the problem of locating an undetermined number of new facilities where the capacity of each alternative facility is given, and hence capacity acquisition costs are incorporated in the fixed setup costs. It should be emphasized that however, for a new facility, such a predetermined size might be far from optimal.

4.2 Review of the relevant literature

In this section the relevant literature is reviewed in order to provide the reader with further insight about the problem we address here. Note that, the mathematical program presented in Section 4.1 is also suitable for modeling the concave cost facility location problem. It is possible to show this by redefining $f_i(.)$ as the total cost of operating facility i, and c_{ij} as the unit cost of transport from facility i to market j. If the parameters are defined as above then (4.1)-(4.5) constitutes the concave cost capacitated facility location model. Therefore, the techniques available for solving the concave cost facility location problem are also suitable for solving the facility location and capacity acquisition problem.

The literature on concave cost facility location however, is rather sparse. In their seminal work on UFLP, Efroymson and Ray [28] suggested that if the cost functions are piecewise linear then the concave cost facility location problem can be formulated as an UFLP by associating a separate "facility" with each segment. Khumawala and Kelly [81] suggested a heuristic approach to the uncapacitated case where operating costs are represented via power functions. The earliest algorithm that guarantees an optimal solution with no further assumption regarding the form of the concave cost functions is due to Soland [125]. He devised a branch-and-bound algorithm, where the nodal problems can be solved by inspection in the uncapacitated case. They are however, in the form of the standard transportation problem when there are capacity constraints on the volume of production. At each node, linear underestimates (chords) are used to approximate the concave operating costs (including the fixed costs), and hence a lower bound on the problem solution is obtained by solving the associated linear program (LP). Branching involves partitioning the constraint space by the aid of the LP solution, and hence narrowing the relevant range of the concave cost functions in the subsequent nodal problems. Thus, the chord inscribed in a facility's operating cost curve is replaced with two adjacent chords which results in a better approximation. Therefore, the algorithm generates progressively better lower bounds. Khumawala and Kelly [81] however, observed the efficiency of tangent line approximation in assigning the facilities to markets for a given set of open facilities. Whereas, in the presence of fixed setup costs of opening new facilities, Kelly and Khumawala [78] had to resort to a combination of the tangent line and chord approximations. Their algorithm for the capacitated problem seems to have less memory requirements than that of Soland [125] since only the previous solution needs to be retained at each iteration.

It is also possible to cast the facility location and capacity acquisition problem as a minimum concave cost network flow problem (MCNFP). Figure 4.1 depicts a network flow representation of the UFL&CAP. Here, facilities acquire the necessary capacity from a single source by paying the associated costs, to be able to produce and ship the market demand. CFL&CAP can also be represented by the same network by imposing upper bounds on the flows from the capacity source to the facilities. Therefore, the techniques available for solving MCNFP are also suitable for solving our problem.

Guisewite and Pardalos [54] provided an extensive review of the solution techniques for MCNFP. There are a variety of algorithms based on branch-and-bound, dynamic programming, and extreme point ranking. Falk and Soland [34] presented a branch-and-bound algorithm for minimizing a separable nonconvex function over a linear polyhedron, e.g. MCNFP. At each node, a linear underestimate of the nonconvex function is minimized over the associated partition of the constraint space. Note that, Soland [125] involves minimization of the associated linear underestimate over the entire constraint space at each node, and hence constitutes a simplified version of Falk and Soland [34]. Florian and Robillard [42] however, suggested transforming the original network to an equivalent uncapacitated bipartite network using Wagner's [143] transformation. Thus, their branching involves forcing flow either on

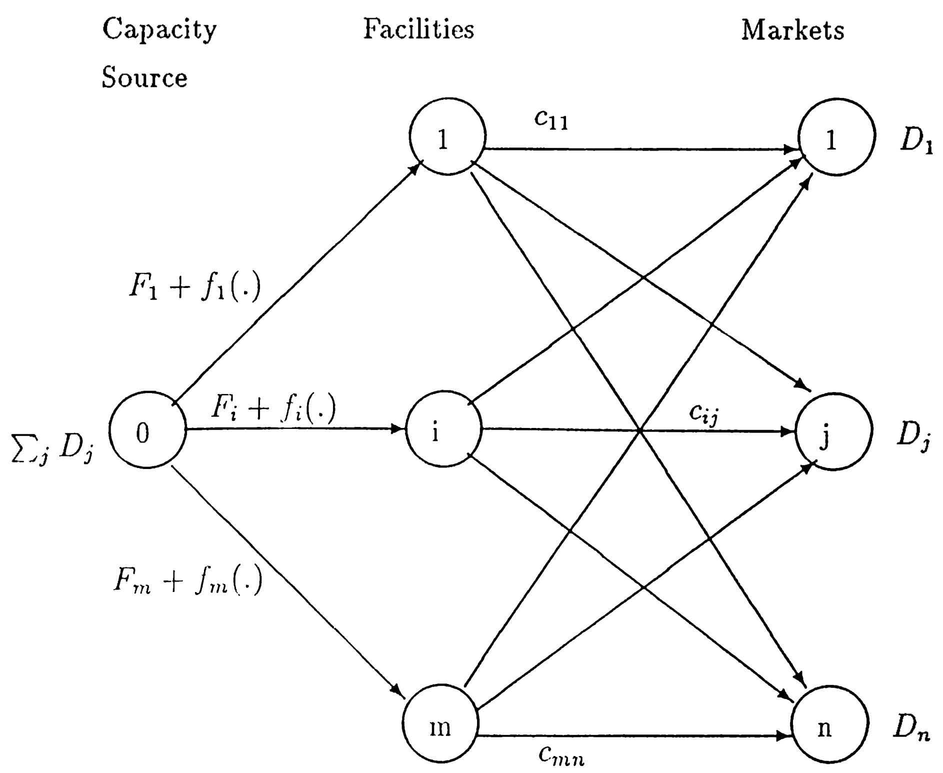

Figure 4.1: Network flow representation of UFL&CAP

an arc in the original network, or on a "slack" arc. Nevertheless, their algorithm requires implicit enumeration of quite large branch-and-bound trees for modest problems, since the number of arcs and the number of nodes increase considerably due to the transformation.

Erickson, Monma and Veinott [31] provided a dynamic programming approach for the single-source uncapacitated version of MCNFP that is called the send-and-split method. The algorithm involves recursively solving subproblems $l \rightarrow L$, where l denotes a node which is assumed to have a preflow that is sufficient for serving demand of the nodes in set L, in order to obtain a minimum cost solution to the original problem $0 \rightarrow J$. At any node l, *sending* corresponds to shipping all the demand of L to another node l' which is accessible from l, whereas *splitting* corresponds to the decision to serve two complementary subsets of L via separate descendents. The complexity of this method arises from the splitting operation. Nevertheless, this technique is shown to be polynomial in the number of (transshipment) nodes, and arcs, but exponential in the number of demand nodes.

Evidently, a local optimum is not necessarily a global optimum for MCNFP, due to concavity of the objective function. It is also well known however that if a finite optimum solution exists then there exists an extreme flow i.e. an extreme point of the polyhedron defined by the set of linear constraints, that is optimal. Extreme point ranking methods dwell on this property in searching for a local optimum. That is, based on an initial extreme solution, at each iteration, the adjacent vertices are enumerated for moving (if possible) to the best adjacent vertex. Guisewite and Pardalos [55] provided a computational comparison of the various local search algorithms for the single source uncapacitated MCNFP.

The review of the relevant literature reveals that although there exist a variety of techniques applicable for solving the facility location and capacity acquisition problem, the ones that exploit the problem structure are not that many. Furthermore, since Soland's [125] computational experiments were confined to the fixed-charge cost structure, and Kelly and Khumawala [78] provided only a numerical example, the computational performance of the existing algorihms that recognize the problem structure remains to be investigated for problems of the type commonly encountered in practice.

4.3 Analytical properties of the UFL&CAP

Given that each market is accessible by at least one alternative new facility, there always exists a feasible solution to the UFL&CAP since there are no constraints on the capability of the new facilities to serve the market demand. Further, since the associated MCNFP does not contain any negative cost cycles, the UFL&CAP always has a finite optimum solution.

Efroymson and Ray [28] observed that for any given set of open facilities, the optimal allocation decisions for UFLP can be obtained by allowing each market to be supplied from the "closest" facility. Such a *dominant* facility has the least unit variable cost of serving the market among the open facilities.

Existence of a dominant facility for each market leads to a significant increase in the computational efficiency of their branch-and-bound procedure. This is because dominance enables decomposition of a nodal problem into n easily solved subproblems. Note that, each market's dominant facility among the set of open facilities is decided independent of the quantity demanded. Linearity of the variable supply costs is a sufficient condition for this property to be present which is called *consistent dominance.*

It is possible to show that a different version of the dominance property holds for UFL&CAP where the effective variable costs of serving the markets are no longer linear due to the presence of concave capacity acquisition costs. That is, for a given set of open facilities, the optimal sizing and allocation decisions for UFL&CAP can still be obtained by allowing each market to be served by its dominant facility. In this case however, "closeness" of a facility to a market depends on the demand to be served in addition to the unit variable costs of production and transportation. Thus, the dominant facilities and hence the optimal facility-market allocations might differ due to variations in market demand while costs remain the same. We call this *conditional dominance.*

To formalize the conditional dominance property, let $\{1, \ 2\}$ be the set of *open* facilities to serve market j with demand $D_j = D$. Further, let

$$g_i(X) = f_i(X) + c_{ij}X, \qquad i = 1,2 \tag{4.6}$$

represent the total cost of providing X units of the commodity to market j from facility i. Note that, $g_i(.)$ are monotone increasing concave functions when $f_i(.)$ and c_{ij} are defined as in Section 4.1.

Proposition 4.1: Market j will be served by *either* facility 1 *or* facility 2, depending on D.

Proof : It suffices to show that

$$min\{g_1(D), \ g_2(D)\} \leq g_1(X) + g_2(D-X), \qquad X \in [0, \ D]. \tag{4.7}$$

Let $g_1(Y) = g_2(Y)$ such that $Y > 0$. Note that $Y = \infty$ constitutes the case where consistent dominance is present. Therefore first, examine the case where the intersection is at $Y \geq D$.

Assume $g_1(Z) < g_2(Z), \quad Z \in (0, \ Y)$:

Case 0 Since $g_1(.)$ is concave,

$$g_1(D) \leq g_1(X) + g_1(D - X) \tag{4.8}$$

By substituting $g_1(D-X)$ in (4.8) with $g_2(D-X)$ which is larger, (4.7) holds. It can be shown in a similar manner that (4.7) holds when $g_2(.)$ constitutes the lower envelope of the two functions between 0 and D.

Thus, assume $Y < D$ and $g_1(D) < g_2(D)$. Then, there are four (nontrivial) cases in terms of the values of X and $D - X$:

Case 1 $g_1(X) < g_2(X)$, and $g_1(D-X) < g_2(D-X)$. The proof is as in Case 0.

Case 2 $g_2(X) < g_1(X)$, and $g_1(D-X) < g_2(D-X)$. The proof is as in Case 0.

Case 3 $g_1(X) < g_2(X)$, and $g_2(D - X) < g_1(D - X)$. This is the case where $X \in (Y, \ D)$ and $D-X \in (0, \ Y)$. Thus, both $g_1(X)$ and $g_2(D-X)$ are on the lower envelope of the two functions. Since, the lower envelope is a monotone increasing concave function, its slope is non-increasing. Hence for $\Delta > 0$

$g_2(D - X) - g_2(D - X - \Delta) \geq g_1(X + \Delta) - g_1(X)$.

Let, $\Delta = D - X$. (4.7) holds since $g_2(0) = 0$.

Case 4 $g_2(X) < g_1(X)$, and $g_2(D - X) < g_1(D - X)$. In this case,

$g_1(D) < g_2(D) \leq g_2(X) + g_2(D - X) < g_1(X) + g_2(D - X)$,and hence (4.7) holds.

Note that the cases where $X = Y$, $D - X = Y$, and Y is not unique are amenable to proof by the same strategy. It can be shown in a similar manner that (4.7) holds for $Y < D$ and $g_2(D) < g_1(D)$. □

The above proposition means that market j will be fully served by the facility that has the minimum total cost of providing D_j among $\{1, \ 2\}$. This can easily be generalized to the case where there are more than two open facilities to serve a market. For the ease of exposition, Figure 4.2 depicts the presence of conditional dominance for fixed-charge costs in the three-facility case. Although, facility 3 happens to be the dominant facility for serving market j when $D_j = D$, it should be realized that first, facility 2 and then facility 1 become dominant as D_j decreases.

Theorem 4.1: *Conditional dominance* in the UFL&CAP:

At the optimum solution of the UFL&CAP containing a set of *open* facilities

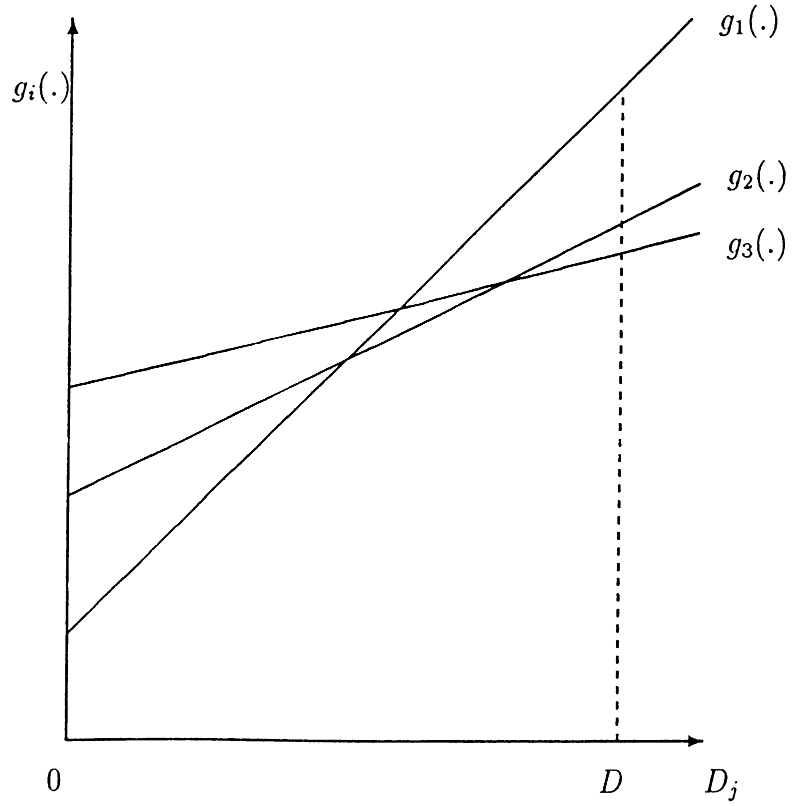

Figure 4.2: Conditional dominance for fixed-charge costs

$\{1, 2, .., m'\}$, any market j will be fully served by a dominant facility that varies with D_j, all other parameters remain the same.

Proof: The proof constitutes making use of Proposition 4.1 in pairwise comparisons of all possible pairs of the m' open facilities. Let $m' = 3$ as in Figure 4.2,

For $\{1, 2\}$ as the set of open facilities, facility 2 will be dominant at $D_j = D$, due to Proposition 4.1. Facility 3 will be dominant at $D_j = D$, for both $\{1, 3\}$ and $\{2, 3\}$ again due to Proposition 4.1. Thus, for $\{1, 2, 3\}$, facility 3 is the dominant facility for serving market j at $D_j = D$, for this instance of the UFL&CAP.

Obviously, the proof for $m' > 3$ would require more effort but is the same in spirit. □

It has to be emphasized that for a given instance of the cost items, each market's dominant facility actually depends on the total demand to be served rather than the demand of that market, due to the economies of scale in capacity acquisition costs.

The presence of conditional dominance is very useful in the characterization of the set of alternative sizes for a facility in the UFL&CAP. Since each market will be fully served by *one* facility at the optimum solution, each facility can fully serve all possible combinations of the markets. Therefore, there are at most 2^n alternative sizes for any facility i, despite the fact that the acquired capacity is represented by a continuous variable (i.e. $\sum_{j \in J} X_{ij}$) in the mathematical model. Thus, any feasible solution to the UFL&CAP that contains more than one facility serving a market qualifies to be nonoptimal irrespective of the costs incurred. Note that, this result is in parallel with Zangwill [145] stating that an extreme flow of the single-source uncapacitated MCNFP, would include at most one arc (with a positive flow) entering each node.

4.4 An algorithm for solving the UFL&CAP

In the UFL&CAP, the total capacity acquisition cost is a separable concave function. This enables utilization of an underestimate that is also separable in terms of the facilities. Thus, the cost of providing capacity at each facility, i.e. sum of the fixed setup and the capacity acquisition costs, is approximated by a piecewise linear concave function. At each iteration of the algorithm, a *pseudo-facility* is associated with each segment of the current linear underestimate for each facility. Hence, the UFL&CAP is transformed to an equivalent UFLP on the basis of the piecewise linear approximation. Therefore, the algorithm devised for solving the UFL&CAP involves solving a sequence of UFLPs. Optimum solution of an UFLP however, corresponds to an extreme flow of the network underlying the UFL&CAP (see Figure 4.1). This is because in an extreme flow of the network, there will be one facility serving each market, which is in parallel with the dominance property as discussed in the previous section. At each iteration, the underestimate is improved by the aid of the optimum solution to the associated UFLP, and hence progressively better lower bounds are provided. The algorithm finds a global optimum of the UFL&CAP in a finite number of iterations since the number of the extreme flows of the underlying network is finite.

At an iteration of the algorithm, let m_i denote the number of pseudo-facilities (indexed by k) associated with facility i. Further let,

F_{ik} = the fixed setup cost of opening pseudo-facility k of facility i,

c_{ik} = the unit cost of capacity acquisition at pseudo-facility k of facility i,

R_{ik}, R_{ik+1} = the lower and upper bounds on the size of pseudo-facility k of facility i respectively.

Thus, m_i represents the number of linear segments in the current approximation of the cost of providing capacity at facility i. Observe that the pseudo-facilities represent size ranges for a facility, and hence at most one pseudo-facility associated with the facility must be open in a feasible solution to the UFL&CAP. For pseudo-facility k of facility i, F_{ik} is the intercept obtained by extending the associated linear segment back to the y-axis whereas, R_{ik} and R_{ik+1} are the endpoints of the associated partition of the x-axis, and c_{ik} is the slope of the linear segment. On the basis of the current approximation the UFL&CAP can be modeled by the following mathematical program:

$$\text{Minimize } z_L = \sum_{i\in I}\sum_{k\in K_i}[F_{ik}Y_{ik} + \sum_{j\in J} c_{ijk}X_{ijk}], \tag{4.9}$$

subject to

$$\sum_{i\in I}\sum_{k\in K_i} X_{ijk} = D_j, \qquad j = 1,..,n, \tag{4.10}$$

$$0 \le X_{ijk} \le Y_{ik}D_j, \qquad j = 1,..,n,\ i = 1,..,m,\ k = 1,..,m_i, \tag{4.11}$$

$$Y_{ik} \in \{0,1\}, \qquad i = 1,..,m,\ \ k = 1,..,m_i, \tag{4.12}$$

$$Y_{ik}R_{ik} \le \sum_{j\in J} X_{ijk} \le Y_{ik}R_{ik+1}, \quad i = 1,..,m,\ \ k = 1,..,m_i, \tag{4.13}$$

$$\sum_{k\in K_i} Y_{ik} \le 1, \qquad i = 1,..,m, \tag{4.14}$$

where

K_i = the set of pseudo-facilities associated with facility i,

c_{ijk} = the unit cost of serving market j from pseudo-facility k of facility i i.e. $c_{ijk} = c_{ik} + c_{ij}$,

and the decision variables are

X_{ijk} = the quantity shipped from pseudo-facility k of facility i to market j,

Y_{ik} = 1 if pseudo-facility k of facility i is opened, 0 otherwise.

The optimal value of z_L constitutes a lower bound on the optimal solution value of the UFL&CAP. Constraints (4.10) ensure that each market's demand will be fully satisfied, constraints (4.11) guarantee that markets receive shipments only from open pseudo-facilities. Whereas, constraints (4.13) ensure that the total production of each open pseudo-facility is between its lower and upper bounds, and constraints (4.14) specify that at most one pseudo-facility can be open associated with each facility. Due to the concavity of the piecewise linear underestimates however, the constraints (4.13) and (4.14) are redundant in the above formulation. That is for each facility, cost minimization will automatically select the correct pseudo-facility which corresponds to the size range that contains the optimal size of the facility. Evidently, the remaining integer program constitutes a classical model for an UFLP with $\sum_{i=1}^{m} m_i$ "facilities" and n markets. As pointed out by Verter and Dincer [142] however, there are very efficient techniques available for solving the UFLP such as the dual-based optimization procedure of Erlenkotter [33].

The Algorithm

Step 0: Initialize

Input: *For* $i \in I$, $j \in J$, get F_i, $f_i(.)$, c_{ij}, D_j.
Set total demand, $TD = \sum_{j \in J} D_j$.
Initialize the arrays:
For $i \in I$, set

$m_i = 1,\ R_{i1} = 0,\ R_{i2} = TD,\ F_{i1} = F_i,$

$c_{i1} = (f_i(TD) - f_i(0))/TD,$

$For\ \ j \in J$, set $c_{ij1} = c_{i1} + c_{ij}$.

Label the current pseudo-facility as pseudo-facility 1 of facility i.

Step 1: Solve the UFLP

$For\ \ i \in I,\ j \in J,\ k \in K_i$, obtain $X^*_{ijk},\ Y^*_i$, and the associated value of z^*_L that constitute the optimum solution of the UFLP corresponding to the current approximation.

$For\ i \in I,\ j \in J$, set $X^*_{ij} = \sum_{k=1}^{m_i} X^*_{ijk}$.

Calculate the implied size for each facility:

$For\ i \in I$, set $SZ_i = \sum_{j=1}^{n} X^*_{ij}$.

Step 2: Improve the approximation

$For\ \ i \in I,\ For\ \ k \in K_i,$

$if\ \ SZ_i \in (R_{ik},\ R_{ik+1}),$

then partition this size range to generate two new pseudo-facilities k' and k'' to replace the pseudo-facility k. Set

$R_{ik'} = R_{ik},\ \ R_{ik'+1} = R_{ik''} = SZ_i,\ \ R_{ik''+1} = R_{ik+1},$

$c_{ik'} = (f_i(SZ_i) - f_i(R_{ik}))/(SZ_i - R_{ik}),$

$c_{ik''} = (f_i(R_{ik+1}) - f_i(SZ_i))/(R_{ik+1} - SZ_i),$

$F_{ik'} = F_i + f_i(R_{ik}) - c_{ik'}R_{ik},$

$F_{ik''} = F_i + f_i(SZ_i) - c_{ik''}SZ_i,$

set $m_i = m_i + 1$,

Relabel the pseudo-facility k' as k, k'' as $k+1$, $k+1$ as $k+2$ and so forth. Rearrange the arrays accordingly.

Step 3: Terminate

if no new pseudo-facility is generated

then $For\ i \in I,\ j \in J,$

output $X^*_{ij},\ Y^*_i,\ z^*_L$ as the global optimum of the UFL&CAP,

Terminate.

else $For\ \ i \in I,\ For\ \ k \in K_i$, set $c_{ijk} = c_{ik} + c_{ij},$

Go to Step 1.

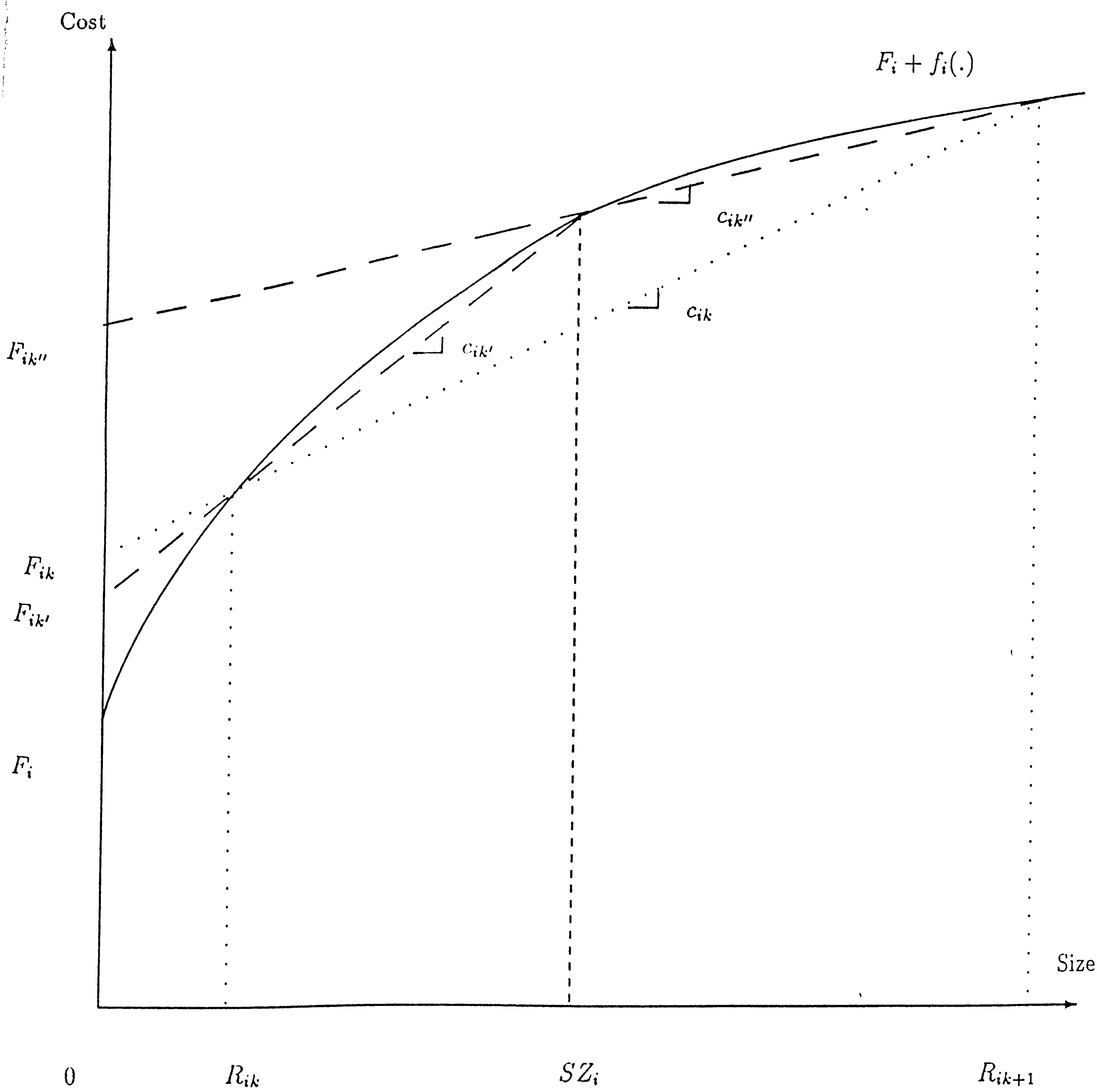

Figure 4.3: Step 2 of the algorithm for facility i

Figure 4.3 depicts an iteration of Step 2 for facility i. If at any iteration SZ_i equals to one of the interval endpoints (i.e. $R_{ik}, \ k = 1, ..., m_i$) then the cost of providing capacity at facility i is exactly represented by the underestimate, and hence no new pseudo-facilities are generated. At each iteration, the value of the original objective function z^* for $X^*_{ij}, \ Y^*_i$ constitutes an upper bound on the optimal solution value of the UFL&CAP. The gap between the lower and upper bounds provides an indication of the quality of the solution at each iteration. Thus, the algorithm can also be used as a heuristic for solving the UFL&CAP. Let ϵ denote the maximum acceptable gap between the lower and upper bounds. Due to the separability of both the original objective function and its underestimate let

$$\epsilon = \sum_{i \in I} \epsilon_i, \quad z^* = \sum_{i \in I} z^*_{Ui}, \quad z^*_L = \sum_{i \in I} z^*_{Li}. \tag{4.15}$$

In a heuristic implementation, no new pseudo-facilities associated with facility i will be generated at Step 2 of the algorithm: *if* $(z^*_{Ui} - z^*_{Li})/z^*_{Ui} \leq \epsilon_i$.

4.5 Computational results

The algorithm devised for solving the UFL&CAP was programmed in FORTRAN and run on Sun Microsystems on a number of test problems generated on the basis of the test problems drawn from the literature. It should be noted that none of the nonstandard features of the Sun FORTRAN have been used to enhance the computational performance of the algorithm. The current implementation contains the DUALOC code of Erlenkotter [33] for solving the UFLPs formulated during the operation of the algorithm. The demand, fixed setup cost, and variable operation and transportation cost data used in the computational experiments originates from the standard test problems of Kuehn and Hamburger [89] which are available via electronic mail from the OR-Library (see Beasley [6]). Although the algorithm is valid for general monotone increasing concave functions, the computational experiments were confined to the power functions in modeling the capacity acquisition costs. This stems from the empirical evidence regarding the validity of these functions in modeling industrial problems, and hence their common use in the literature on capacity acquisition as pointed out by Luss [99]. Verter and Dincer [142] stated that the fixed charge cost function and the piecewise linear concave cost function are also popular in modeling the capacity acquisition costs. Observe that the former constitutes a trivial case which can be solved in a single iteration by the algorithm. Whereas, in the latter case an equivalent UFLP can be formulated as described in the previous section that again can be solved in one iteration. Thus, the computational experiments presented in this section focus on the most general form of the capacity acquisition costs reported in the literature.

In the UFL&CAP the major trade off is between the cost of providing capacity and the operation and transportation costs at each facility. The UFLP named *cap71* in the OR-Library will be used as a basis for an illustrative example. The problem contains 16 alternative facility locations and 50 markets. The fixed setup costs of opening a facility at any location is given as \$7,500 except the already existing facility 11, i.e. $F_{11} = 0$. Further, let the capacity acquisition

α	Total Cost ($)	# of open facilities	change in the set of open fac.	# of pseudo-fac.	# of iter.	Total Sun time (sec)
1.00	1515295.6	11		16	1	0.23
0.95	1308133.6	11		33	3	1.01
0.90	1174586.9	10	{12}	38	4	1.21
0.80	1033678.7	10		34	4	1.10
0.75	998100.6	11	[12]	33	3	0.76
0.70	975050.5	11		31	3	0.58
0.60	950495.0	11		29	3	0.53
0.50	940183.4	11		27	2	0.45
0.40	935833.4	11		27	2	0.40
0.00	932615.8	11		16	1	0.21

Table 4.1: Computational results based on *cap*71 for $\beta = 10$

costs have the following form:

$$f_i(\sum_{j\in J} X_{ij}) = \beta_i(\sum_{j\in J} X_{ij})^{\alpha_i}, \quad i = 1, ..., m, \tag{4.16}$$

where $\alpha_i \in [0, \ 1]$ represents the economies of scale in capacity acquisition at facility i whereas, β_i is a positive scalar for scaling the capacity acquisition cost with respect to the fixed setup cost at that facility. Without loss of generality it will be assumed that $\alpha_i = \alpha, \quad \beta_i = \beta, \quad$ for, $\ i = 1, ..., m$ in investigating the impact of scale economies on the location and sizing decisions. This assumption ensures that the location and sizing decisions are not biased toward establishment of a larger facility at a certain location. For $\beta = 10, \quad \alpha = 1$ the optimum solution to the *cap71* constitutes opening facilities 1,2,3,4,6,7,8,9,11,12, and 13 for serving the 50 markets. When there is economies of scale in capacity acquisition and hence $\beta = 10, \quad \alpha = 0.8$ however, facility 12 is closed in the optimum solution while its markets are allocated to facilities 4,7, and 11. Although, the total operation and transportation cost of serving facility 12's markets by facilities 4,7, and 11 is higher, this is more than compensated by the economies achieved by increasing the size of each of the three facilities.

Table 4.1 presents the effects of varying the degree of scale economies in the

α	Total Cost ($)	# of open facilities	change in the set of open fac.	# of pseudo-fac.	# of iter.	Total Sun time (sec)
1.00	2097975.8	11		16	1	0.23
0.95	1682095.1	9	{12,9}	46	5	1.97
0.90	1411790.1	6	{1,4,6}	49	7	2.39
0.85	1242238.4	9	[1,4,6]	52	8	4.29
0.80	1132823.2	9		47	6	2.07
0.75	1062582.4	10	[9]	42	4	1.20
0.70	1016944.7	10		36	4	1.15
0.65	987540.7	10		34	4	1.11
0.60	968374.6	11	[12]	31	3	0.59

Table 4.2: Computational results based on *cap*71 for $\beta = 20$

cap71 for $\beta = 10$. Evidently, the total cost decreases as the economies of scale in capacity acquisition increases. Note that $\alpha = 1$ constitutes the case where the marginal cost of capacity acquisition is (a positive) constant whereas, $\alpha = 0$ constitutes the unrealistic case where the marginal cost is zero. The fourth column in the table depicts the changes in the set of open facilities as α decreases. {...} denotes the set of facilities that are closed due to a decrease in α whereas, [...] denotes the set of facilities that are opened for the same reason. The total Sun time (including the input and output) relates to the total number of pseudo-facilities generated during the operation of the algorithm as well as the number of iterations in finding the optimum solution.

Table 4.2, and Table 4.3 present the effects of increasing the weight of capacity acquisition costs with respect to the fixed setup costs in *cap71*. Note that $\beta = 30$ is a sufficiently large factor since for example facility 3 incurres a $ 87,319 capacity acquisition cost (for acquiring 21,379 units of capacity to serve % 37 of the total market demand for 58,268 units) compared to the $7,500 fixed setup cost in the optimal solution for $\alpha = 0.8$. As the capacity acquisition costs increase due to the increase in the scaling factor β, the effects of scale economies are magnified. This leads to drastic changes in facility sizes. Note that as scale economies increases at an equal rate at all facilities, its effect in decreasing the

α	Total Cost ($)	# of open facilities	change in the set of open fac.	# of pseudo-fac.	# of iter.	Total Sun time (sec)
1.00	2680655.2	11		16	1	0.25
0.95	2046686.0	6	{12,9,1,4,6}	43	6	1.70
0.90	1633869.5	5	{2}	43	6	1.90
0.85	1380066.5	5		41	6	1.45
0.80	1223853.8	5		43	6	1.91
0.78	1179137.6	6	[2]	46	6	1.71
0.75	1125328.2	9	[1,4,6]	48	7	3.55
0.70	1058199.8	9		42	4	1.20
0.65	1014372.8	10	[9]	36	4	1.20
0.60	985928.7	10		34	4	1.00
0.55	967491.9	11	[12]	33	3	0.78

Table 4.3: Computational results based on *cap*71 for $\beta = 30$

Problem Name	F_i	Total Cost ($)	open fac.	change in the set of open fac.	# of pseudo-fac.	# of iter.	Total Sun time (sec)
cap71	7500	1682095.1	9	{12,9}	46	5	1.97
cap72	12500	1708123.6	5	{1,4,6,2}	37	5	1.35
cap73	17500	1727685.5	4	{7}	35	6	1.05
cap74	25000	1745875.9	3	{8}	24	4	0.66

Table 4.4: Computational results for increasing fixed setup costs for $\beta = 20, \quad \alpha = 0.95$

number of open facilities gradually vanishes. Increasing the fixed setup costs of opening facilities, results in larger economies of scale in capacity acquisition as depicted by Table 4.4. Apparently, the demand, and the operation and transportation cost data is the same for all the problems referred in Table 4.4.

There are two remarks to be made about the computational experiments: First, the computational performance of the algorithm is encouraging. All of the test problems mentioned above were solved in at most 8 iterations. Furthermore, for $\beta = 20, \quad \alpha = 0.95$, the 25 facility locations problem *cap101* was solved to optimality in 7 iterations generating 70 pseudo-facilities which took 6.44

seconds. Whereas, for the same values of α and β, finding an optimal solution to the 50 facility locations problem *cap131* required 9 iterations involving the generation of 104 pseudo-facilities in 7.99 seconds. Note that the number of markets is 50 in all the test problems which would require 2^{50} iterations in the worst case. Second, the computational experiments identified the existence of a sequence in closing (and then opening) facilities as the scale economies increases. For example, facilities 5,10,14,15, and 16 are closed in the optimum solution of *cap71*. Depending on the economies in building larger facilities, the following order can be observed in closing the facilities:

12,9,1,4,6,2,7,8.

Note that this example presumes the equality of scale economies at all the alternative facility locations. Nevertheless, such an analysis is also possible without the equality assumption and would provide the decision maker with valuable information about the priorities of the alternative facility locations. This is especially crucial when there is an upper bound on the number of facilities to be established due to a variety of reasons such as the scarcity of the financial resources or the strategic policies that discourage diversification of operations.

4.6 Analytical properties of the CFL&CAP

In the CFL&CAP there is an upper bound on the size of each new facility to be built at an alternative location. In terms of the underlying network (see Figure 4.1), these bounds impose constraints on the flows from the capacity source to the facilities. In consequence, the flow on each arc emanating from a facility is also constrained by the upper bound on the size of the facility. Thus, given that each market is accessible by at least one alternative new facility, the CFL&CAP has a feasible solution only if for each market, the set of facilities that have access to the market can acquire sufficient capacity for serving the demand. If a feasible solution to the problem exists however, then there exists a finite optimum solution.

The piecewise linear concave approximation to the total cost of providing capacity at the new facilities enables the transformation of the CFL&CAP to an equivalent CFLP. Therefore, the application of the ***progressive piecewise linear*** *undersetimation algorithm* described in Section 4.4 for solving the CFL&CAP involves solving a sequence of CFLPs. Evidently, the UFLP solver used at every iteration of Step 1 needs to be replaced by a CFLP solver. Beasley [5] presented an efficient algorihm for solving sufficiently large CFLPs whereas, the cross decomposition method of Van Roy [138] remains to be the most efficient technique for solving moderate size problems.

Observe that the dominance property does not hold for CFLP, since more than one facility might serve a market in the optimal solution, due to presence of the capacity constraints. Nevertheless, optimum solution of a CFLP corresponds to an extreme flow of the capacitated network underlying the CFL&CAP. In a capacitated network however, a flow is extremal only if at most one of the arcs entering each node has a flow that is strictly between its bounds. The implication of this for the CFLP, and hence for the CFL&CAP is that in the optimal solution although a market might be served by multiple facilities, all of these facilities except at most one will be fully utilizing their capacity in serving the market. Investigation of properties of the extreme flows of the underlying capacitated network provides further insight about the analytical properties of the CFL&CAP. Since the number of extreme flows is finite, the algorithm will find an optimum solution to the CFL&CAP in a finite number of iterations. The following definitions facilitate the analysis:

Definition 1: A facility that fully serves a market's demand is called a *full-server* of the market.

Definition 2: A facility that partially serves a market's demand at its capacity limit is called a *partial-server* of the market.

Definition 3: A facility that serves the remaining demand of a partially served market is called a *remainder-server* of the market.

In an extreme flow of the uncapacitated network associated with the UFLP, and hence the UFL&CAP, each market will have one full-server i.e. its dominant facility. This implies that each facility might be a full-server for all possible combinations of the markets. Thus, the acquired capacity at each facility can take 2^n distinct values. That is at a new facility the optimal size is essentially determined by making a "fully serve / do not serve" decision associated with each market. Note that the number of values that the acquired capacity can take constitutes a worst case bound on the number of iterations of the algorithm required for solving the UFL&CAP.

In an extreme flow of the capacitated network associated with the CFLP, and hence the UCL&CAP, each market will have one of the following:
- 1 full-server,
- 1 to $m-1$ partial-servers and 1 remainder-server,
- 2 to m partial-servers.

This implies that each facility might be one of the following:
- A full-server for some combination of the markets,
- A remainder-server for some combination of the markets,
- A full-server for some combination of the markets, and a remainder-server for a disjoint combination of the markets,
- A partial-server for one of the markets.

Facility i being a remainder-server for market j implies that market j is being partially served by a combination of the remaining $m-1$ facilities. Further, facility i being a full-server for market j is equivalent to facility i being a remainder-server of market j that is partially served by none of the remaining $m-1$ facilities. Thus, there are actually 2^{m-1} remainder values that a facility can serve. Hence the following can be stated:

Proposition 4.2: In the CFL&CAP the acquired capacity at a facility can take at most $(2^{m-1}+1)^n+1$ distinct values.

Proof: For each of the n markets, a facility will either be a remainder-server providing one of the 2^{m-1} remainder values or not serve the market. Alternatively, the facility will be a partial-server for one of the markets, and hence its size will be CAP_i. The former implies the first term whereas the latter implies the second term in the expression that constitutes an upper bound on the cardinality of the set of alternative sizes for a facility. □

Let p denote the number of alternative partial-servers for a market given that one of the facilities is qualified as a remainder-server, and t equal 1 if there are capacity constraints 0 otherwise. The following theorem enables the perception of the UFL&CAP as a special case of the CFL&CAP in terms of the set of alternative sizes for a facility:

Theorem 4.2: In the facility location and capacity acquisition problem, the acquired capacity at each facility can take at most $(2^p + 1)^n + t$ distinct values.

Proof: Observe that $t = 0$ implies $p = 0$ and $t = 1$ implies $p = m - 1$. □

Note that however, Proposition 4.2 provides a weak upper bound on the cardinality of the set of alternative sizes in the CFL&CAP. To show this, let ψ denote the actual number of alternative sizes for a facility. In the UFL&CAP $\psi \leq 2^n$. Note that, $\psi = 2^n$ only if D_j $j = 1, .., n$ are such that each possible combination of them sums up to a distinct number. There are two special cases worth to mention here: First, if $D_j = D$ $j = 1, .., n$ then $\psi = n$. Second, if the demand figures are integers then the demand of any combination of markets is also an integer number. In this case, ψ is bounded by the total market demand which would be much less than 2^n as n increases.

Proposition 4.3: In the CFL&CAP,

$$\psi < (2^{m-1} + 1)^n + 1 \qquad (4.17)$$

Proof: Let $R_j(S)$ denote the remainder of the demand of market j being partially served by the facilities in the set S. If facility i serves $R_j(S)$ and $R_{j'}(S')$ such that $j \neq j'$ then $S \cap S' = \Phi$ where Φ denotes the empty set. This is because if facility $i' \in S$, that is i' is a partial-server of market j, then i' *not* $\in S'$. Thus the strict inequality holds. □

It is possible to provide closed form expressions for ψ in the CFL&CAP when n is small. Let $p = m - 1$, for $n = 2$, $p \geq 1$,

$$\psi = 2(2^p + 1) + \sum_{i=1}^{p} \binom{p}{i} (2^{p-i} + 1) \qquad (4.18)$$

Whereas, for $n = 3$, $p \geq 2$,

$$\psi = 4(2^p+1)+2\sum_{i=1}^{p}\binom{p}{i}(2^{p-i}+1)+\sum_{k=1}^{p-1}\binom{p}{k}[2(2^{p-k}+1)+\sum_{i=1}^{p-k}\binom{p-k}{i}(2^{p-k-i}+1)]+4 \tag{4.19}$$

The above expressions constitute enumeration of the possible sizes of a facility based on the properties stated in the proof of Proposition 4.3. Evidently, as the number of markets in the CFL&CAP increases, it becomes quite cumbersome to provide a closed form expression for ψ. Thus, for example in a 4 alternative facility locations 3 markets CFL&CAP, the facilities can actually be of 170 different sizes compared to the upper bound of 729 provided by Proposition 4.2. As in the uncapacitated case ψ constitutes a worst case bound on the number of iterations of the algorithm required for solving CFL&CAP.

4.7 Concluding remarks

This chapter presents an integrated approach for the facility location and capacity acquisition decisions. The arising model requires global minimization of a concave function over the constraint space which constitutes the set of feasible solutions to the problem. When the facility size is unconstrained, the algorithm devised for solving the problem involves solving a sequence of UFLPs. It is shown that the dominance property present in the UFLP also holds for the UFL&CAP, although in a conditional sense. The dominance property however, is instrumental in the characterization of the set of alternative sizes for a facility in the UFL&CAP. Note that the cardinality of this set provides a worst case bound on the number of iterations of the algorithm, required for solving the problem. The computational performance of the algorithm in solving the UFL&CAP is satisfactory. In the capacitated case however, the algorithm involves solving a sequence of CFLPs. Although the dominance property does not hold for the CFLP, the set of alternative sizes for a facility can still be characterized. This provides a framework for the perception of the UFL&CAP as a special case of the CFL&CAP in terms of the alternative sizes of a facility. The computational performance of the algorithm in solving the

CFL&CAP is currently an open question.

The proposed algorithm can also be used as a heuristic for solving large size facility location and capacity acquisition problems, since both lower and upper bounds on the optimum solution value are available at each iteration. Further, if it is to be assumed that the capacity acquisition costs are piecewise linear concave functions (as assumed in Balakrishnan and Graves [4] for the arc flow costs in the MCNFP) then the set of alternative sizes provides valuable information for deciding the endpoints of the linear segments. Note that in this case, the problem can be solved in one iteration by the aid of an a priori transformation as described in Section 4.4. At this stage, it is possible to relax the linearity assumption regarding the variable operation costs which was stated in Section 4.1 for the ease of exposition. Thus, the economies of scale in operation costs can also be incorporated in the model by redefining $f_i(.)$ as the total capacity acquistion and operation cost at facility i, and c_{ij} as the unit cost of shipping from facility i to market j.

The present model is in need of two major extensions to enhance its capability in assisting the strategic decision-making process. First, the model should be generalized for also dealing with the facility relocation and capacity expansion decisions via incorporation of the dynamic nature of the cost and demand parameters. No need to say however, the arising dynamic model will be much more difficult to handle in terms of its computational complexity compared to the static model provided in this paper. Second, the model should be generalized for dealing with multiple commodities which will enable simultaneous optimization of the plant location and sizing decisions. Note that however, there would normally be a set of alternative technologies for producing each family of commodities. Thus, such an extension constitutes a primary step in improving the model to also provide the optimal technology selection decisions. The more general model should be able to provide the optimal location of the plants, including their facility configuration (implying their product-mix) as well as the amount of capacity acquired in terms of each technology at each open plant. Next chapter presents the incorporation of the technology selection decisions in the model presented in this chapter.

Chapter 5

Plant Location and Technology Acquisition

Location of production facilities, their size, and the manufacturing technology adopted to provide the required capacity at each facility constitute the primary structural decisions in designing the production-distribution system of a firm. These decisions are strategic in nature, that is they require large capital outlays which are usually irreversible in the short run. Thus, the location, sizing, and technology decisions not only contribute to the achievement of the manufacturing strategy goals but also constrain the short term performance of the manufacturing activity. Therefore, selection of the best sites for production facilities, and acquisition of the most appropriate technology in providing the optimal production capacity are crucial in terms of the competitive ability of the firm in all timeframes.

Globalization of product and factor markets fosters the interactions between the structural decisions. The facility location and capacity acquisition decisions are interdependent for global firms. This is due to the provision of subsidized financing and low tax rates by the national governments to attract establishment of new facilities for the creation of employment opportunities in their country. Further, the investment costs associated with manufacturing technology might differ from one location to another due to the necessity to import the state-of-the-art technology in some countries. Therefore, separate treatment of the facility location, capacity acquisition and technology selection decisions is bound to produce sub-optimal solutions within the international context. Global manufacturing strategy planning requires simultaneous optimization of the structural decisions.

The problem of simultaneously deciding the optimal location and size of each new facility to be estalished was analyzed in the previous chapter. The firm however, is to choose among a set of available manufacturing technologies to acquire the required capacity at each location. The aim of this chapter therefore, is to extend the model for facility location and capacity acquisition to also provide the technology selection decisions. Thus, the remainder of this chapter is organized as follows: The presence of alternative technologies for producing the commodity is incorporated in the model in Section 5.1. Section 5.2 provides the extension to the multicommodity problem where each commodity has its own set of alternative technologies to provide the required production capacity. In Section 5.3 availability of a flexible technology that is capable of producing all of the commodities is incorporated in the plant location and technology acquisition model. Finally, some concluding remarks are provided which suggest directions for future research.

5.1 The facility location and technology acquisition problem

The previous chapter presumed the availability of a single technology at each facility in providing the required production capacity. Hence, this section constitutes the extension of the single technology problem to the multitechnology setting. Given a set of alternative facility locations, a set of alternative manufacturing technologies, and a set of markets to be served, the *facility location and technology acquisition problem* involves simultaneously locating an undetermined number of new facilities, and deciding the amount of each type of technology acquired at each facility to minimize the total cost of serving the clients. Note that, the production capacity of a facility is determined by the total amount of technology acquired to manufacture the commodity. Hence, the optimal solution to the facility location and technology acquisition problem provides the optimal size of each facility in addition to its location and manufacturing technology content. The cost items at an alternative facility location are:

- Fixed setup cost of establishing a new facility at that site,
- For each alternative manufacturing technology;
  - Variable cost of technology investment associated with the amount of capacity acquired,
  - Variable cost of operation associated with the amount of commodity produced,
- Variable cost of transportation for serving the markets.

Fixed setup costs such as the acquisition of land and the construction of infrastructure will be incurred only if a new facility is opened. There exists scale economies in the acquisition of manufacturing technology. Thus, for each technology, the capacity acquisition cost would be a monotone increasing concave function of the amount to be acquired. Further, the operation costs also represent economies of scale. The degree of scale economies in both acquisition and operation costs might differ from one technology to another due to the differences in the levels of automation and integration. Note that however, it is these differences among alternative manufacturing technologies that constitute the primary trade off regarding the technology selection decision at a facility. Although the transportation costs might also represent scale economies, we presume that this would not have a considerable effect on the strategic location, sizing and technology decisions. Therefore, variable costs of transportation are assumed to be linear.

The facility location and technology acquisition problem is by definition concerned with a single commodity. Furthermore, the problem is deterministic, static, and has no transshipment points. Note that the problem boils down to the uncapacitated facility location problem (UFLP) when the technology acquisition and operation costs are ignored. UFLP is shown to be NP-complete by Krarup and Pruzan [88] which in consequence means that the facility location and technology acquisition problem also belongs to the NP-complete class of problems.

5.1.1 The model

Let n denote the number of markets (indexed by j), m denote the number of alternative facility locations (indexed by i), and s denote the number of alternative technologies (indexed by h). The problem can be modeled as follows:

$$\text{Minimize } z = \sum_{i \in I}[F_i Y_i + \sum_{h \in H} f_{hi}(\sum_{j \in J} X_{hij}) + \sum_{j \in J} c_{ij} \sum_{h \in H} X_{hij}], \tag{5.1}$$

$$\text{subject to } \sum_{i \in I} \sum_{h \in H} X_{hij} = D_j, \quad \forall j, \tag{5.2}$$

$$0 \leq X_{hij} \leq Y_i D_j, \quad \forall h, i, j, \tag{5.3}$$

$$Y_i \in \{0, 1\}, \quad \forall i, \tag{5.4}$$

where

H, I, J = the sets of alternative technologies, alternative facility locations, and markets respectively,

F_i = the fixed setup cost of opening facility i,

$f_{hi}(.)$ = the total acquisition and operation cost of technology h at facility i, i.e. $f_{hi}(.) = a_{hi}(.) + o_{hi}(.)$ where,

$a_{hi}(.)$ = the total acquisition cost of technology h at facility i,

$o_{hi}(.)$ = the total operation cost of technology h at facility i,

c_{ij} = the unit cost of shipping from facility i to market j,

D_j = the demand of market j,

and the decision variables are

X_{hij} = the quantity produced using technology h at facility i and shipped to market j,

Y_i = 1 if facility i is opened, 0 otherwise.

It should be emphasized that F_i excludes any costs associated with technology acquisition at facility i, and obviously will depend on whether the new facility is established at an existing plant or it requires construction of a new plant. The capacity acquired at each facility will be fully utilized in production due to the cost minimization objective and the single period structure of the problem. The total technology acquisition and operation cost $f_{hi}(.)$ is a monotone increasing concave function since both $a_{hi}(.)$ and $o_{hi}(.)$ are monotone increasing concave functions. It has to be ensured that the cost items in the above model are commensurate. For example, if D_j represents the annual demand then F_i and $a_{hi}(.)$ must represent the annuities associated with the investments. Thus, the total cost that is incurred due to the location, size, and technology content of the new facilities as well as the facility-market allocations is minimized, while constraints (5.2) guarantee that each market's demand will be fully satisfied, and constraints (5.3) ensure that markets receive shipments only from open facilities. The above mathematical program models the problem where there are no upper bounds on the amount and mix of technology acquired at the new facilities, which we call the uncapacitated facility location and technology acquisition problem (UFL&TAP). Note that the size of each new facility might be constrained due to a variety of reasons e.g. availability of land, and the limited availability of some technology types might impose further constraints on technology acquisition which would require the formulation and analysis of the *capacitated* version of the problem.

5.1.2 Analytical properties of the UFL&TAP

The facility location and technology acquisition problem can be perceived as a minimum concave cost network flow problem (MCNFP). Figure 5.1 depicts a network flow representation of the UFL&TAP. Here, facilities acquire the

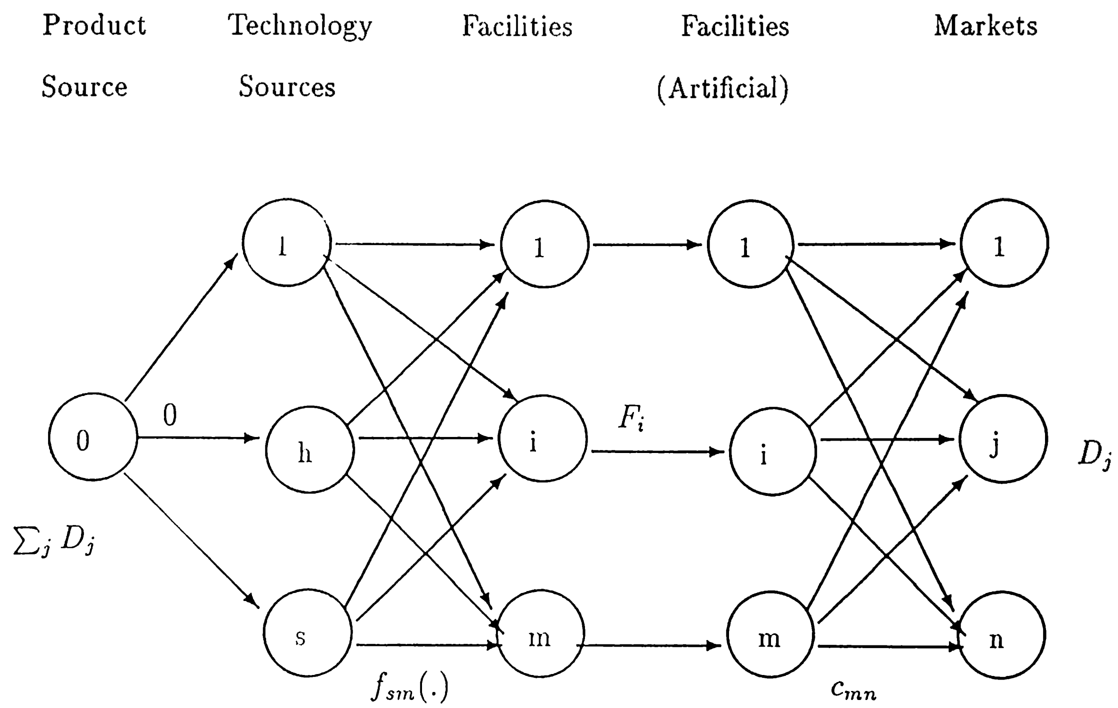

Figure 5.1: Network flow representation of UFL&TAP

necessary capacity from any combination of the technology sources by paying the associated costs, to be able to produce and ship the market demand. The artificial layer of facilities in the network ensures that the fixed setup costs are incurred at the open facilities. Therefore, the techniques available for solving MCNFP are also suitable for solving the UFL&TAP. The literature on MCNFP was reviewed in the previous chapter. It should be emphasized however that the variety of techniques applicable for solving MCNFP do not exploit the structure of the UFL&TAP.

Given that each market is accessible by at least one alternative new facility, there always exists a feasible solution to the UFL&TAP since there are no constraints on the capability of the new facilities to serve the market demand. This is due to the assumption that neither the size of a facility nor the availability of a manufacturing technology are limited. Further, since the associated MCNFP does not contain any negative cost cycles, the UFL&TAP always has a finite optimum solution.

It is possible to show that conditional dominance holds in the technology selection decisions in UFL&TAP. At the optimal solution, each open facility will acquire one type of technology depending on its size. To formalize the conditional dominance property, let $\{1, \ \ 2\}$ be the set of alternative technologies at an *open* facility i to serve the demand $D_i = \sum_{j \in J_i} D_j$ of a collection of markets $J_i \subseteq J$.

Proposition 5.1: Facility i will acquire *either* technology 1 *or* technology 2, depending on D_i.

Proof : It suffices to show that

$$min\{f_{1i}(D_i), \ \ f_{2i}(D_i)\} \leq f_{1i}(X) + f_{2i}(D_i - X), \qquad X \in [0, \ \ D_i]. \tag{5.5}$$

Since, both $f_{1i}(.)$ and $f_{2i}(.)$ are monotone increasing concave functions, remainder of the proof constitutes an analysis similar to that of Proposition 4.1, and hence will be omitted. □

The above proposition means that facility i will adopt the technology that has the minimum total cost of providing D_i among $\{1, \ \ 2\}$. This can easily be generalized to the case where there are more than two alternative manufacturing technologies at a facility.

Theorem 5.1: *Conditional dominance in technology selection* in the UFL&TAP:

At the optimum solution of the UFL&TAP, any *open* facility i will acquire a dominant technology that varies with D_i, all other parameters remain the same.

Proof: The proof constitutes making use of Proposition 5.1 in pairwise comparisons of all possible pairs of the s technologies. □

Theorem 5.1 enables characterization of the *effective* cost of capacity acquisition and operation at each facility in the UFL&TAP. At the optimum solution, each open facility will acquire the required capacity in terms of the dominant technology which has the minimum investment and operation cost. Thus, any facility i faces the lower envelope of the technology acquisition and operation costs $f_{1i}(.), f_{2i}(.), ..., f_{si}(.)$ as the effective cost of capacity acquisition and operation $f_i(.)$. That is

$$f_i(.) = min\{f_{hi}(.), \ \ h \in H\}, \quad \forall i. \tag{5.6}$$

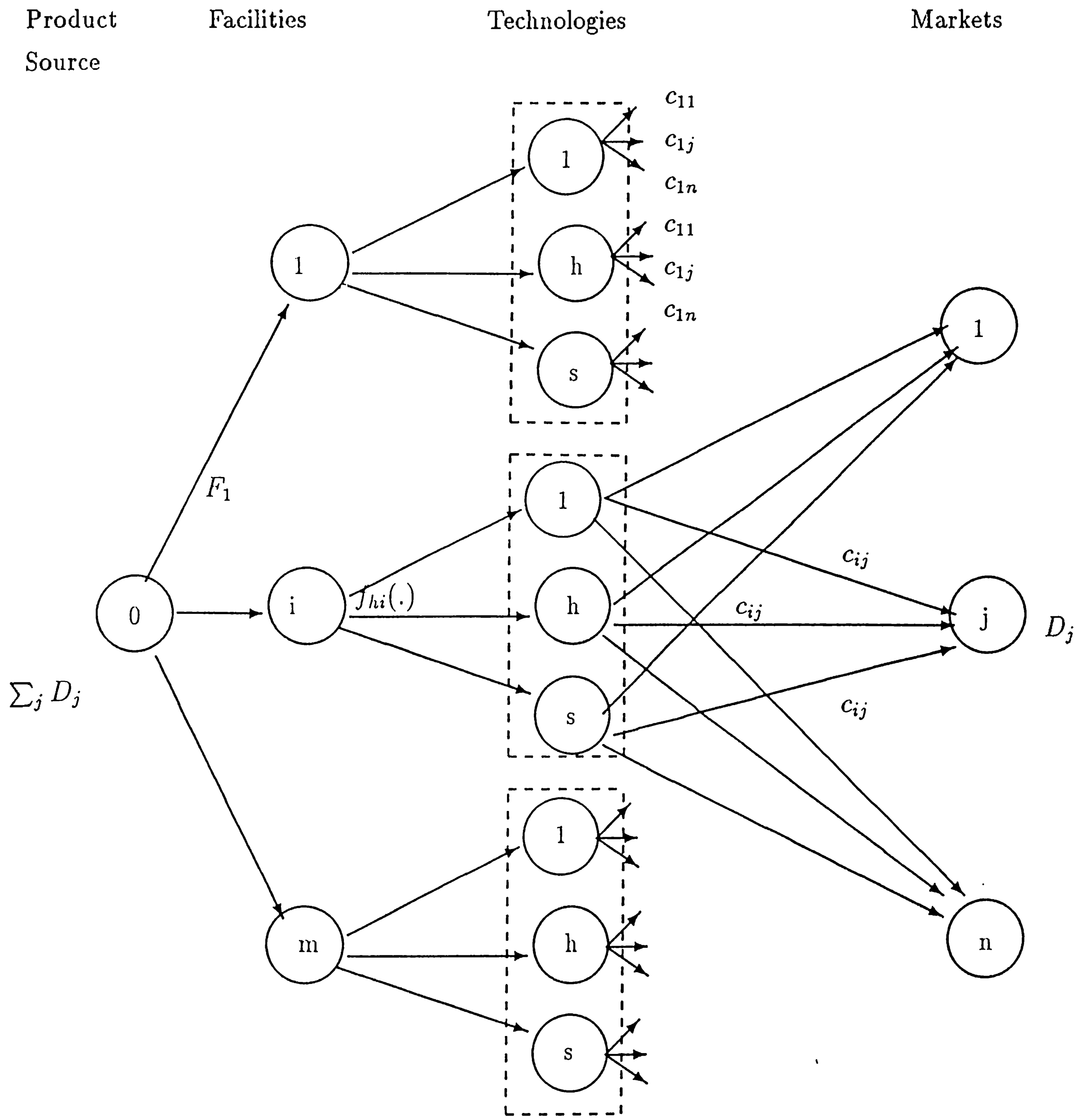

Figure 5.2: Network flow representation of UFL&TAP

Thus, at each facility all the relevant information regarding the technology selection decision can be represented by a single cost function.

Lemma 5.1: $f_i(.)$ is a monotone increasing concave function.

Proof: The proof is straighforward and will be omitted. □

Hence, the UFL&TAP boils down to the uncapacitated facility location and capacity acquisition problem (UFL&CAP) where $f_i(.)$ denote the capacity acquisition and operation costs.

Figure 5.2 depicts an alternative network flow representation of the UFL&TAP. Here, facilities pay the fixed setup costs for establishment, and the technology acquisition and operation costs for acquiring the required capacity in serving the market demand. The presence of conditional dominance in technology selection is evident from Figure 5.2. That is, an open facility will adopt the minimum cost technology to serve its clients since the transportation costs c_{ij} are technology independent. Existence of a dominant technology at each facility conditional to its optimal size, enables the reduction of the UFL&TAP to an equivalent UFL&CAP. As shown in the previous chapter however, there exists a dominant facility for each market in the optimum solution of the UFL&CAP. Note that, this result is in parallel with Zangwill's [145] characterization of an extreme flow of the associated MCNFP containing a unique path from the single source to each of the markets.

5.1.3 An algorithm for solving the UFL&TAP

Analytical properties of the UFL&TAP constitute the foundations of the following algorithm for solving the problem:

The Algorithm

Step 0: Initialize

Input: $For\ h \in H,\ i \in I,\ j \in J$, get $F_i,\ f_{hi}(.),\ c_{ij},\ D_j$.

Step 1: Construct the effective costs of capacity acquisition and operation

$For\ \ i \in I$, set $f_i(.) = min\{f_{hi}(.),\ \ h \in H\}$.

Step 2: Solve the UFL&CAP

$For\ i \in I,\ j \in J$, obtain $X_{ij}^*,\ Y_i^*$, and the associated value of z^* that constitute the optimum solution of the UFL&CAP. Calculate the implied size for each facility: $For\ \ i \in I$, set

$SZ_i = \sum_{j=1}^{n} X_{ij}^*$.

Step 3: Determine the dominant technologies

$For \;\; i \in I,$
$if \;\; Y_i = 1, \; then$ set $h^* = argmin\{f_{hi}(SZ_i), \;\; h \in H\},$
$else$ set $h^* = 0,$
$For \;\; j \in J, \; For \;\; h \in H,$
$if \;\; h = h^*, \; then$ set $X^*_{hij} = X^*_{ij},$
$else$ set $X^*_{hij} = 0.$

Step 4: Terminate

Output: *For* $h \in H$, $i \in I$, $j \in J$, output X^*_{hij}, Y_i^*, and z^* as the global optimum of the UFL&TAP.

The algorithm presented in the previous chapter is suitable for solving the UFL&CAP that arises in Step 2. Step 3 constitutes identification of the minimum cost technology for the optimum size of each new facility.

An alternative method could be suggested for solving the UFL&TAP. This is inspired by the network flow representation in Figure 5.2 in conjunction with the conditional dominance in technology selection. The method constitutes transforming the UFL&TAP to an equivalent UFL&CAP by defining a pseudo-facility for each facility-technology combination. The arising UFL&CAP however would have $s * m$ "facilities" (in general), and n markets. Thus, for the facility location and technology acquisition problems that are commonly encountered in practice, the alternative method would require solution of a much larger UFL&CAP than that of the proposed algorithm.

5.2 The plant location and technology acquisition problem

A plant refers to a collection of production facilities each producing a single commodity (or, at most a single family of commodities) in the same location. Thus, the problem presented in this section constitutes an extension of the single commodity problem analyzed in the previous section to the multicommodity setting. Given a set of alternative plant locations, a set of products, a set of alternative manufacturing technologies for each product, and a set of markets to be served, the *plant location and technology acquisition problem* involves simultaneously locating an undetermined number of new plants, and deciding the amount of each type of technology acquired at each plant to minimize the total cost of serving the clients. It is presumed that each technology is capable of producing a single product. Therefore, the amount and mix of technology acquisition at a plant determine its production capacity in terms of each commodity. The cost structure is similar to that of the single commodity problem except the variable costs of technology acquisition, operation, and transportation are product specific in the multicommodity version. The plant location and technology acquisition problem is deterministic, static, and has no transshipment points. This problem also belongs to the NP-complete class of problems since its single product version is NP-complete

5.2.1 The model

Let n denote the number of markets (indexed by j), m denote the number of alternative plant locations (indexed by i), l denote the number of products (indexed by p), and s_p denote the number of alternative technologies available for manufacturing product p (indexed by h_p). The problem can be modeled as follows:

$$\text{Minimize } z = \sum_{i\in I}\{F_iY_i + \sum_{p\in P}[\sum_{h_p\in H_p} f_{h_pi}(\sum_{j\in J} X_{h_pij}) + \sum_{j\in J} c_{ijp} \sum_{h_p\in H_p} X_{h_pij}]\}, \quad (5.7)$$

$$\text{subject to } \sum_{i\in I}\sum_{h_p\in H_p} X_{h_pij} = D_{jp}, \quad \forall j,p, \quad (5.8)$$

$$0 \le X_{h_pij} \le Y_iD_{jp}, \quad \forall p, h_p, i, j, \quad (5.9)$$

$$Y_i \in \{0,1\}, \quad \forall i, \quad (5.10)$$

where

P, I, J = the sets of products, alternative plant locations, and markets respectively,

H_p = the set of alternative technologies for product p,

F_i = the fixed setup cost of opening plant i,

$f_{h_p i}(.)$ = the total acquisition and operation cost of technology h_p at plant i, i.e. $f_{h_p i}(.) = a_{h_p i}(.) + o_{h_p i}(.)$ where,

$a_{h_p i}(.)$ = the total acquisition cost of technology h_p at plant i,

$o_{h_p i}(.)$ = the total operation cost of technology h_p at plant i,

c_{ijp} = the unit cost of shipping product p from plant i to market j,

D_{jp} = the demand of market j for product p,

and the decision variables are

$X_{h_p ij}$ = the amount of commodity p produced using technology h_p at plant i and shipped to market j,

Y_i = 1 if plant i is opened, 0 otherwise.

It should be emphasized that F_i excludes any costs associated with technology acquisition at plant i. Thus, the total cost that is incurred due to the location, size, and technology content of the new plants as well as the plant-market allocations is minimized, while constraints (5.8) guarantee that each market's demand will be fully satisfied, and constraints (5.9) ensure that markets receive shipments only from open plants. The above mathematical program models the problem where there are no upper bounds on the amount and mix of technology acquired at the new plants, which we call the uncapacitated plant location and technology acquisition problem (UPL&TAP).

5.2.2 Analytical properties of the UPL&TAP

The plant location and technology acquisition problem can also be cast as a MCNFP. Figure 5.3 depicts a network flow representation of the UPL&TAP

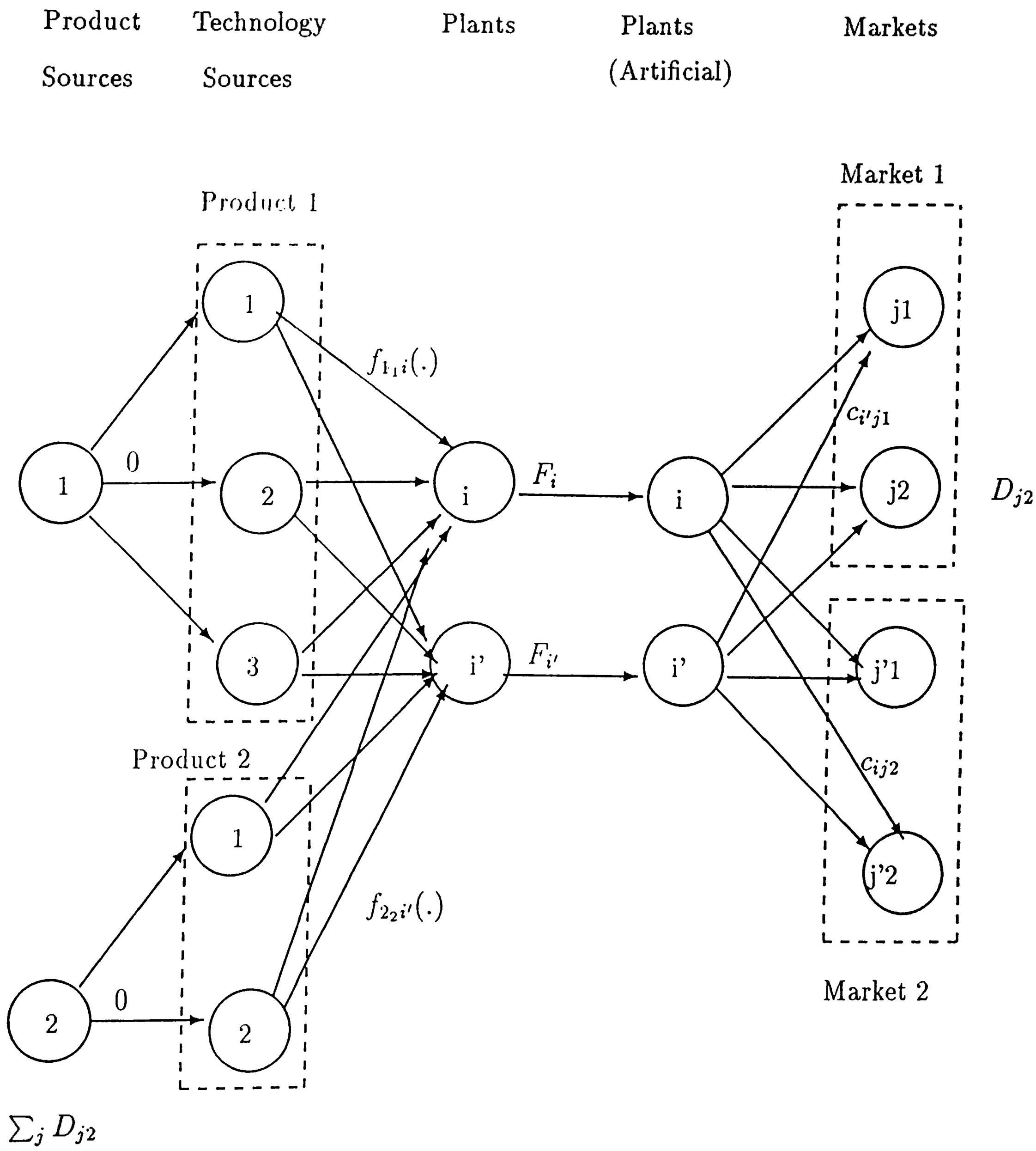

Figure 5.3: Network flow representation of UPL&TAP .

where $P = \{1, 2\}$, $I = \{i, i'\}$, $J = \{j, j'\}$, $H_1 = \{1, 2, 3\}$, $H_2 = \{1, 2\}$ for the ease of exposition.

Here, plants acquire the necessary capacity from the ***product-dedicated*** technology sources by paying the associated costs, to be able to produce and ship the market demand. The artificial layer of plants in the network ensures that the fixed setup costs are incurred at the open plants. Note that (i, i) and (i', i') are multicommodity arcs whereas all other arcs represent the flow of a single commodity. A market's demand for each commodity is represented by a distinct node in the network. It should be emphasized that the associated network has l sources in the UPL&TAP compared to that of the UFL&TAP having a single source. The variety of techniques applicable for solving the multisource MCNFP however do not exploit the structure of the UPL&TAP.

The UPL&TAP always has a finite optimum solution since the associated MCNFP does not contain any negative cost cycles. The above property presumes the accessibility of each market by at least one alternative new plant which is sufficient for the existence of a feasible solution when there are no constraints on plant size. An important special case of the UPL&TAP arises when the fixed setup cost at each plant can be fully attributed to the commodities produced at that site i.e. when

$$F_i = \sum_{p \in P} F_{ip}, \quad \forall i, \tag{5.11}$$

where

F_{ip} = the fixed setup cost of opening the facility that manufactures product p in plant i.

In this case, the objective function (5.7) becomes separable in terms of the commodities. Hence, the UPL&TAP decomposes into l single commodity problems each amenable to solution by the algorithm presented in the previous section for solving the UFL&TAP. The significance of this case is due to its suitability in modeling the plant loading problem which frequently arises in manufacturing strategy design. Given a set of *existing* plants, and the sets J, P, H_p, $p \in P$, the *plant loading problem* involves decisions regarding the product mix, production capacity and technology content of each plant to minimize the total cost of serving the clients. Here, F_{ip} denotes the fixed setup cost of loading product p to plant i which can also be perceived as the cost of complexity whereas the scale economies in technology acquisition are incorporated in the model via $f_{h_p i}(.)$. Recently, Cohen and Moon [23] presented a plant loading model which also incorporates the raw material sourcing decisions at each plant. Their model however, does not deal with the plant sizing and technology selection decisions. That is plant size is taken as a parameter and the availability of alternative manufacturing technologies is not incorporated.

It is possible to show that conditional dominance holds in the technology selection decisions in UPL&TAP. Since the technologies are assumed to be product-dedicated, the sets $H_p,\ p \in P$ are disjoint. Therefore, at an open plant, the technology selection decision for each product is independent of the technologies selected for manufacturing the other products. Hence, at the optimal solution, each open plant will adopt the technology that has the minimum total cost of providing the required production capacity for each product. Let $\{1,\ 2\}$ be the set of alternative technologies at an *open* plant i to serve the demand $D_{ip} = \sum_{j \in J_{ip}} D_{jp}$ of a collection of markets $J_{ip} \subseteq J$ for product p. The following statements are analogous to those of the previous section, and hence their proof will be omitted:

Proposition 5.2: Plant i will acquire *either* technology 1 *or* technology 2, depending on D_{ip}.

Theorem 5.2: *Conditional dominance in technology selection* in the UPL&TAP:

At the optimum solution of the UPL&TAP, any *open* plant i will acquire a dominant technology for each product p that varies with D_{ip}, all other parameters remain the same.

Thus, any plant i faces the lower envelope of the technology acquisition and operation costs $f_{1_{pi}}(.), f_{2_{pi}}(.), ..., f_{s_{pi}}(.)$ as the *effective* cost of capacity acquisition and operation for product p. That is

$$f_{ip}(.) = min\{f_{h_{pi}}(.),\ \ h_p \in H_p\}, \quad \forall i, p. \tag{5.12}$$

Thus, at each plant all the relevant information regarding the technology selection decision for each product can be represented by a single cost function.

Lemma 5.2: $f_{ip}(.)$ is a monotone increasing concave function.

Hence, the UPL&TAP model (5.7) - (5.10) reduces to the following mathematical program:

$$\text{Minimize } z = \sum_{i \in I} \{F_i Y_i + \sum_{p \in P} [f_{ip}(\sum_{j \in J} X_{ijp}) + \sum_{j \in J} c_{ijp} X_{ijp}]\}, \tag{5.13}$$

$$\text{subject to } \quad \textstyle\sum_{i \in I} X_{ijp} = D_{jp}, \quad \forall j, p, \tag{5.14}$$

$$0 \leq X_{ijp} \leq Y_i D_{jp}, \quad \forall i, j, p, \tag{5.15}$$

$$Y_i \in \{0, 1\}, \qquad \forall i, \tag{5.16}$$

where

X_{ijp} = amount of product p shipped from plant i to market j.

An alternative network flow representation of the UPL&TAP analogous to that of the UFL&TAP presented in Figure 5.2 is also possible. In such a network, plants constitute the upstream layer of nodes, and the technology layer contains a replica of the set of nodes representing the technology alternatives for each plant. Since the transportation costs c_{ijp} are technology independent, an open plant will adopt the minimum cost technology for each product in serving the market demand. Hence, this representation provides an alternative way to observe the presence of conditional dominance in technology selection in the UPL&TAP. Note that this result is in parallel with Klincewicz [82] stating that in the associated multisource uncapacitated MCNFP, it is never optimal to have positive flow on more than one path between a given source (product) and a destination (market) with relevant demand.

5.2.3 An algorithm for solving the UPL&TAP

The algorithm devised for solving the UPL&TAP adopts the *progressive piecewise linear underestimation technique* suggested in the previous chapter for solving the facility location and capacity acquisition problem. Thus, at each plant, the effective cost of capacity acquisition and operation for each product is approximated by a piecewise linear concave function. To facilitate the analysis, let production of commodity p in plant i take place in facility

ip. At each iteration of the algorithm, a *pseudo-facility* is associated with each segment of the current linear underestimate for $f_{ip}(.)$, $i \in I$, $p \in P$. Let m_{ip} denote the number of pseudo-facilities (indexed by k) associated with facility ip. Further let,

F_{ipk} = the fixed setup cost of opening pseudo-facility k of facility ip,

c_{ipk} = the unit cost of capacity acquisition and operation at pseudo-facility k of facility ip,

R_{ipk}, R_{ipk+1} = the lower and upper bounds on the size of pseudo-facility k of facility ip respectively.

Observe that the pseudo-facilities represent size ranges for a facility, and hence at most one pseudo-facility associated with the facility must be open in a feasible solution to the UPL&TAP. For pseudo-facility k of facility ip, F_{ipk} is the intercept obtained by extending the associated linear segment back to the y-axis whereas, R_{ipk} and R_{ipk+1} are the endpoints of the associated partition of the x-axis, and c_{ipk} is the slope of the linear segment. Thus, at an iteration of the algorithm, the current approximation enables modeling the UPL&TAP by the following mathematical program:

$$\text{Minimize } z_L = \sum_{i \in I} \{F_i Y_i + \sum_{p \in P} \sum_{k \in K_{ip}} [F_{ipk} Y_{ipk} + \sum_{j \in J} c_{ipjk} X_{ipjk}]\}, \tag{5.17}$$

subject to

$$\textstyle\sum_{i \in I} \sum_{k \in K_{ip}} X_{ipjk} = D_{jp}, \qquad j = 1,..,n,\ p = 1,..,l, \tag{5.18}$$

$$0 \leq X_{ipjk} \leq Y_{ipk} D_{jp}, \qquad j = 1,..,n,\ i = 1,..,m,\ p = 1,..,l,\ k = 1,..,m_{ip}, \tag{5.19}$$

$$Y_{ipk} \leq Y_i, \qquad i = 1,..,m,\ p = 1,..,l,\ k = 1,..,m_{ip}, \tag{5.20}$$

$$Y_{ipk} \in \{0,1\}, \qquad i = 1,..,m,\ p = 1,..,l,\ k = 1,..,m_{ip}, \tag{5.21}$$

$$Y_i \in \{0,1\}, \qquad i = 1,..,m, \tag{5.22}$$

$$Y_{ipk}R_{ipk} \leq \sum_{j\in J} X_{ipjk} \leq Y_{ipk}R_{ipk+1}, \quad i = 1,..,m, \; p = 1,..,l, \quad k = 1,..,m_{ip}, \tag{5.23}$$

$$\sum_{k\in K_{ip}} Y_{ipk} \leq 1, \qquad i = 1,..,m, \; p = 1,..,l, \tag{5.24}$$

where

K_{ip} = the set of pseudo-facilities associated with facility ip,

c_{ipjk} = the unit cost of serving market j from pseudo-facility k of facility ip i.e. $c_{ipjk} = c_{ipk} + c_{ijp}$,

and the decision variables are

X_{ipjk} = the quantity shipped from pseudo-facility k of facility ip to market j,

Y_{ipk} = 1 if pseudo-facility k of facility ip is opened, 0 otherwise,

Y_i = 1 if plant i is opened, 0 otherwise.

The optimal value of z_L constitutes a lower bound on the optimal solution value of the UPL&TAP. Constraints (5.18) ensure that each market's demand will be fully satisfied, constraints (5.19) guarantee that markets receive shipments only from open pseudo-facilities. Whereas, constraints (5.20) force that the pseudo-facilities are established in the open plants. Constraints (5.23) ensure that the total production of each open pseudo-facility is between its lower and upper bounds, and constraints (5.24) specify that at most one pseudo-facility can be open associated with each facility. Due to the concavity of the piecewise linear underestimates however, the constraints (5.23) and (5.24) are redundant in the above formulation. That is for each facility, cost minimization will automatically select the correct pseudo-facility which corresponds to the size range that contains the optimal size of the facility.

The remaining integer program (5.17) - (5.22) constitutes a model for the multicommodity uncapacitated plant location problem (MUPLP) with m

plant locations, $\sum_{p=1}^{l} m_{ip}$ "products" that can be produced at plant i, and n markets. The MUPLP constitues a generalization of the UFLP where multiple products are required by the clients, and an additional fixed cost is incurred if an open plant is equipped to manufacture a particular product. For the ease of exposition, Figure 5.4 depicts the network flow representation of a MUPLP with two plants, two products, and two markets. Given a set of open plants, and the product mix to be provided by each open plant, the optimal allocation decisions for MUPLP can be obtained by allowing each market to be supplied from the closest plant for each product. That is consistent dominance holds in the MUPLP since the variable costs of serving the markets are linear. Klincewicz, Luss and Rosenberg [84] provided an optimal and various heuristic branch-and-bound procedures for solving the MUPLP. They suggested decomposition of the nodal problems into separate UFLPs each associated with a product, for the calculation of the lower bounds. Akinc [2] presented a branch-and-bound algorithm for the capacitated version of the problem which constitutes an extension of the Akinc and Khumawala [3] algorithm for the CFLP to the multicommodity setting.

Klincewicz and Luss [83] developed a dual-based algorithm for solving the MUPLP. Their algorithm is inspired by the dual-based approach of Erlenkotter [33] for the UFLP. Erlenkotter's dual ascent and dual adjustment procedures are extended to generate a good feasible solution to the dual of the linear programming relaxation of MUPLP. This solution provides a lower bound on the value of the optimal solution to MUPLP. Further, based on the dual solution, a feasible primal solution is constructed using the complementary slackness conditions. As in Erlenkotter [33] these procedures are incorporated in a branch-and-bound algorithm for providing an optimal solution to the MUPLP. Klincewicz and Luss [83] reported solving extensions of the 25 plant locations 50 markets Kuehn and Hamburger [89] problem as well as a set of random MUPLP's. The computational performance of their algorithm is encouraging since the set of sixteen MUPLPs (based on the Kuehn and Hamburger problem) consisting of 3, 5, and 10 product problems, required only 18.42 seconds on the average on an Amdahl 470/V8 computer.

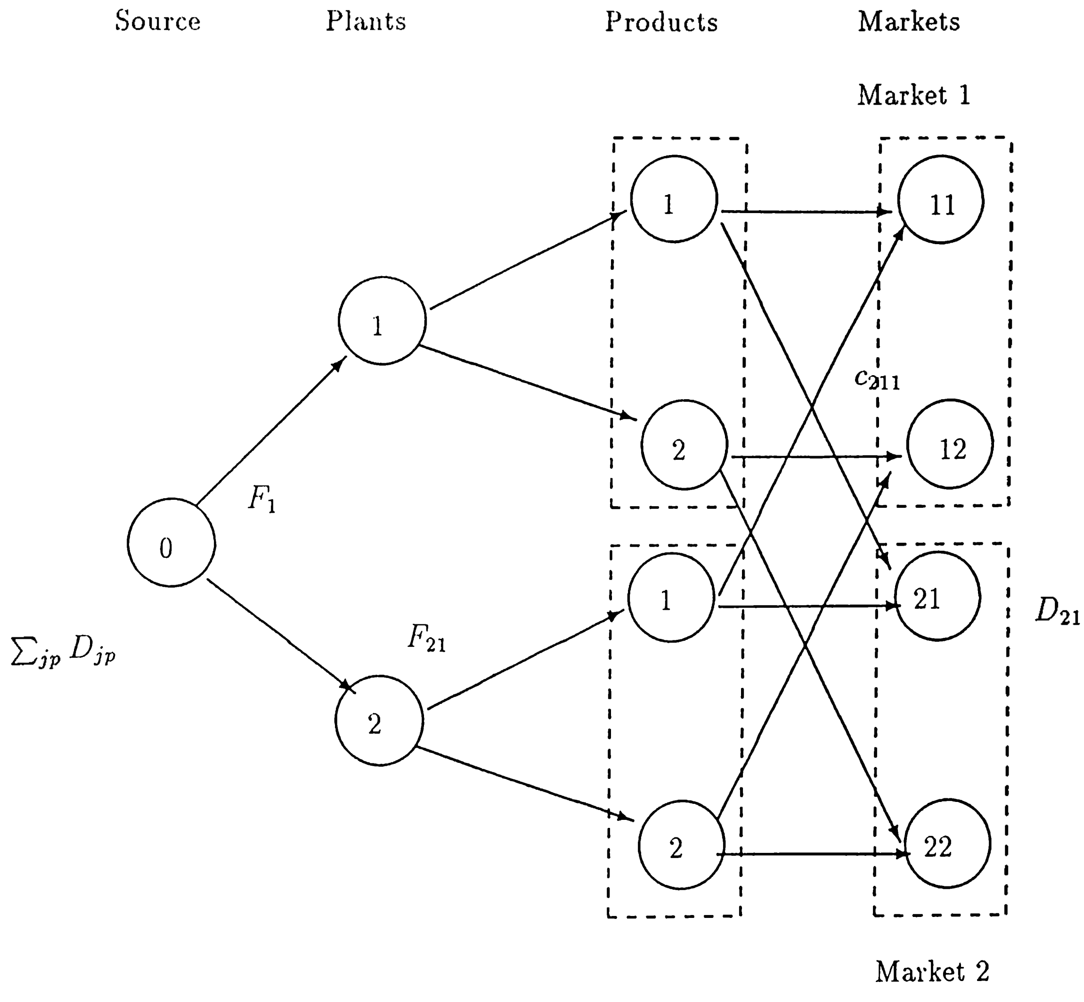

Figure 5.4: Network flow representation of MUPLP

Hence, the algorithm devised for solving the UPL&TAP involves solving a sequence of MUPLPs. Optimum solution of a MUPLP however, corresponds to an extreme flow of the network underlying the UPL&TAP model (5.13) - (5.16). Thus, the algorithm finds a global optimum of the UPL&TAP in a finite number of iterations since the number of the extreme flows of the underlying network is finite. The technicalities associated with the following algorithm have already been presented in the previous section and in the previous chapter, and hence will be omitted.

The Algorithm

Step 0: Input an instance of the UPL&TAP.

Step 1: Construct the effective cost of capacity acquisition and operation for each product at each plant, using (5.12).

Step 2: Solve the arising problem using progressive piecewise linear underestimation:

- Step 2a: Initialize by generating the first pseudo-facility at each "facility" (plant-product combination) using the total demand for the associated product.
- Step 2b: Solve the arising MUPLP and determine the implied size for each "facility".
- Step 2c: Improve the approximation by generating two new pseudo-facilities at a "facility" when its size is strictly between the size range of a pseudo-facility that is to be discarded.
- Step 2d: If no new pseudo-facility is generated terminate Step 2, else Go to Step 2b.

Step 3: Determine the dominant technology for each product at each plant.

Step 4: Terminate providing the global optimum solution to the UPL&TAP.

The dual-based algorithm of Erlenkotter [33] was used in solving the UFLPs that arise during the operation of the algorithm presented in the previous chapter for solving the UFL&CAP. Since, the dual-based approach has proved to be so succesful, we suggest utilization of the Klincewicz and Luss [83] procedure for solving the MUPLPs arising in Step 2b of the algorithm suggested for solving the UPL&TAP.

5.3 The plant location and flexible technology acquisition problem

In the previous section, it was presumed that the firm chooses among a set of product-dedicated technologies in providing the required production capacity for each commodity. The current trend in manufacturing technology however, is toward the development of *product-flexible* technologies that can process a variety of products with small changeover costs. Thus, the problem presented in this section constitutes an extension of the problem analyzed in the previous section that incorporates the availability of flexible technology alternatives. Given a set of alternative flexible technologies in addition to the sets regarding plant locations, products, product-dedicated technologies, and markets the *plant location and flexible technology acquisition problem* involves simultaneously locating an undetermined number of new plants, and deciding the amount of each type of technology acquired at each plant to minimize the total cost of serving the clients. It is presumed that the flexible technologies are capable of producing all of the commodities. Evidently, this problem is deterministic, static, has no transshipment points, and belongs to the NP-complete class of problems.

The economies of scale present in the acquisition and operation of dedicated technology means that firms benefit from operating on a larger scale for each product. That is, unit cost of each product decreases as its production increases. Hence, the total cost of providing product-dedicated capacity is represented by a monotone increasing concave function of the amount to be acquired. Flexible manufacturing technologies provide an alternative way of achieving economies in production that is called *economies of scope.* This stems from the capability of a flexible technology to process more than one product. Hence, the acquired flexible capacity can be allocated to manufacture the most appropriate quantity for each product. This enables the firm to benefit from the scope of operations while the production of each commodity remains small scale. Note that however, it is not possible to achieve similar benefits from the small scale manufacture of a variety of products with the use of dedicated technology. Although, the qualitative aspects of scope economies have been substantially discussed since the seminal paper of Goldhar and Jelinek [52], the issues related to its quantitative representation have not received much attention.

It is possible to conceive flexible technology as a generalization of the dedicated technology since the former can also be used in a product-dedicated manner. This leads to the observation that economies of scope is an extension of the single commodity economies of scale concept to the multicommodity setting. Thus, we suggest that the total cost of acquisition and operation of flexible technology would be a monotone increasing concave function of the amount to be acquired when there is economies of scope. Note that, this allows for the fact that a "unit" produced by the flexible technology might be any of the commodities. Although not explicitly stated, a similar representation of the economies of scope is utilized in Li and Tirupati [98]. Hence, in the plant location and flexible technology acquisition problem, the primary trade off regarding technology selection is between the economies of scale provided by the dedicated technology and the economies of scope provided by the flexible technology.

5.3.1 The model

In this section, a mathematical model for the uncapacitated plant location and flexible technology acquisition problem (UPL&FTAP) is presented. It is presumed that there are no constraints on the amount and mix of technology acquired at a new plant. Let $H = \{1, 2, ..., s\}$ denote the set of alternative product-flexible technologies each capable of processing the set of products $P = \{1, 2, ..., l\}$, and $H_p = \{1, 2, ..., s_p\}$ denote the set of alternative dedicated technologies for product $p \in P$. Further, let $f_{hi}(.)$ denote the total acquisition and operation cost of flexible technology $h \in H$, and $f_{h_pi}(.)$ denote the total acquisition and operation cost of dedicated technology $h_p \in H_p$ at plant i. The following Corrolaries which simplify model development result from the analyses presented in the previous sections:

Corrolary 5.1: At the optimum solution of the UPL&FTAP, an open plant will acquire at most one product-dedicated technology for each product. The dominant technology varies with the amount of dedicated capacity to be acquired, all other parameters remain the same.

Proof: Let $\{1, 2\} \in H_p$ and D_{ip} denote the amount of product p that is to be manufactured by a product-dedicated technology in plant i. If $D_{ip} > 0$ at the optimum solution then plant i will acquire either technology 1 or technology 2 due to Proposition 5.2. Making use of the above observation for all possible pairs of the s_p technologies completes the proof. □

Corrolary 5.2: At the optimum solution of the UPL&FTAP, an open plant will acquire at most one product-flexible technology that varies with the amount of flexible capacity to be acquired, all other parameters remain the same.

Proof: Let $\{1, 2\} \in H$ and D_i denote the amount of product-flexible technology that is to be acquired in plant i. If $D_i > 0$ at the optimum solution then plant i will acquire either technology 1 or technology 2 due to Proposition 5.1. Making use of the above observation for all possible pairs of the s technologies completes the proof. □

Corrolaries 5.1 and 5.2 enable us to model the case where $s = 1$ and $s_p = 1, p \in P$ without loss of generality. Note that, if there are more than one technology in the sets H and $H_p, p \in P$ then the problem can be reduced to this case via calculation of the effective cost of capacity acquisition and operation for each technology. Thus, the following model presumes the availability of a single product-dedicated technology for each product, and a single flexible technology capable of producing all of the products. This simplifies the analysis of the major trade off in flexible technology acquisition i.e. the scale economies provided by the dedicated technology versus the scope economies provided by the flexible technology.

On the basis of our previous notation regarding the sets I and J, the problem can be modeled as follows:

$$\text{Minimize } z = \sum_{i\in I}\{F_iY_i + \sum_{p\in P} f_{ip}(\sum_{j\in J} X^D_{ijp}) + f_i(\sum_{p\in P}\sum_{j\in J} X^F_{ijp}) + \sum_{p\in P}\sum_{j\in J} c_{ijp}[X^D_{ijp} + X^F_{ijp}]\}, \tag{5.25}$$

$$\text{subject to } \textstyle\sum_{i\in I}[X^D_{ijp} + X^F_{ijp}] = D_{jp}, \quad \forall j,p, \tag{5.26}$$

$$0 \le X^D_{ijp} \le Y_iD_{jp}, \quad \forall i,j,p, \tag{5.27}$$

$$0 \le X^F_{ijp} \le Y_iD_{jp}, \quad \forall i,j,p, \tag{5.28}$$

$$Y_i \in \{0,1\}, \quad \forall i, \tag{5.29}$$

where F_i, c_{ijp}, and D_{jp} are defined as in the previous section, and

$f_{ip}(.)$ = the total acquisition and operation cost of the dedicated technology for product p at plant i,

$f_i(.)$ = the total acquisition and operation cost of the flexible technology at plant i,

and the decision variables are

X^D_{ijp} = amount of product p manufactured by the dedicated technology in plant i and shipped to market j,

X^F_{ijp} = amount of product p manufactured by the flexible technology in plant i and shipped to market j,

Y_i = 1 if plant i is opened, 0 otherwise.

The total cost that is incurred due to the location, size, and technology content of the new plants as well as the plant-market allocations is minimized, while constraints (5.26) guarantee that each market's demand will be fully satisfied, and constraints (5.27) and (5.28) ensure that markets receive shipments only from open plants.

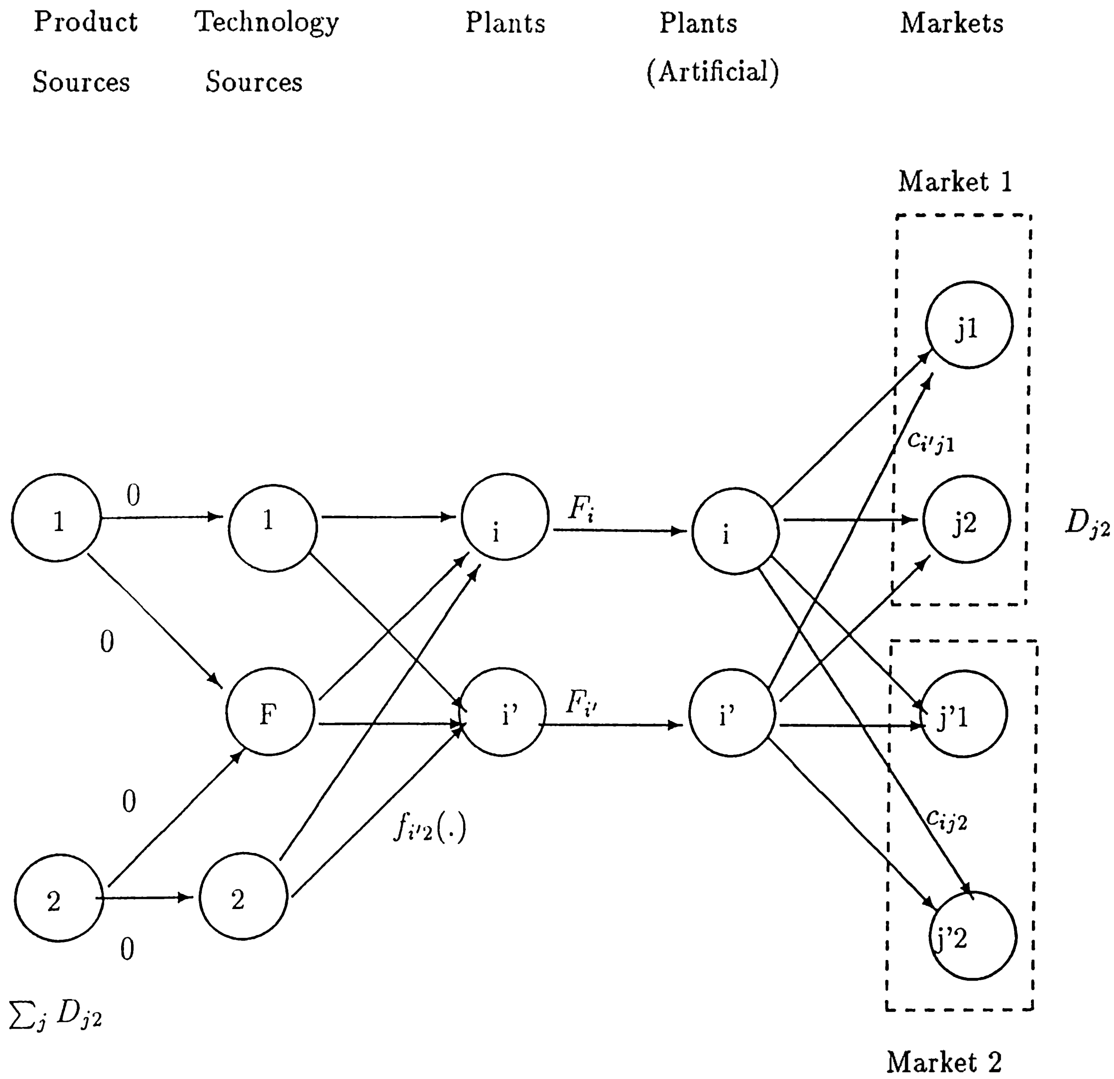

Figure 5.5: Network flow representation of UPL&FTAP

5.3.2 Analytical properties of the UPL&FTAP

The plant location and flexible technology acquisition problem can also be cast as a MCNFP. Figure 5.5 depicts a network flow representation of the UPL&FTAP where $P = \{1,\ 2\}$, $I = \{i,\ i'\}$, $J = \{j,\ j'\}$, $H_1 = \{1\}$, $H_2 = \{2\}$ and $H = \{F\}$ for the ease of exposition.

Although there is one dedicated technology for each product, Figure 5.5 constitutes an extension of the Figure 5.3 due to the additional node F representing flexible technology. Note that $(F,\ i)$ and $(F,\ i')$ are multicommodity arcs whereas $(1,\ F)$ and $(2,\ F)$ represent the flow of the associated commodity. The variety of techniques applicable for solving the multisource MCNFP however do not exploit the structure of the UPL&FTAP. Given that each market is accessible by at least one alternative new plant, the UPL&FTAP always has a finite optimum solution since the associated MCNFP does not contain any negative cost cycles.

It is possible to show that conditional dominance holds in the technology selection decisions in UPL&FTAP. That is, it is never optimal to produce a commodity using both dedicated and flexible technologies at an open plant. In the UPL&FTAP, the technology selection decision for a product is dependent to that of the other products due to the presence of scope economies in flexible technology acquisition and operation. Let D_i^p denote the demand for product p to be served by plant i, and D_i^F denote the amount to be produced by the flexible technology in plant i to serve the demand for the other products. That is,

$$D_i^p = \sum_{j \in J} (X_{ijp}^D + X_{ijp}^F), \quad \forall i, p, \tag{5.30}$$

$$D_i^F = \sum_{q \in P \setminus p} \sum_{j \in J} (X_{ijq}^F), \quad \forall i. \tag{5.31}$$

Theorem 5.3: *Conditional dominance in technology selection* in the UPL&FTAP:

At the optimum solution of the UPL&FTAP, any *open* plant i will acquire either the dedicated or the flexible technology for providing D_i^p. The dominant technology varies with D_i^p as well as D_i^F, all other parameters remain the same.

Proof : For the ease of exposition the subscript i will be dropped. It suffices to show that

$$min\{f_p(D^p)+f(D^F), \ \ f(D^F+D^p)\} \leq f_p(X)+f(D^F+D^p-X), \ \ X \in [0, \ \ D^p]. \tag{5.32}$$

Observe that the above ineqality reduces to that of Proposition 5.1 i.e. (5.7) when $D^F = 0$. Let $f_p(Y) + f(D^F) = f(D^F + Y)$ such that $Y > 0$. Note that $Y = \infty$ constitutes the case where consistent dominance is present. Therefore first, examine the case where the intersection is at $Y \geq D^p$.

Assume $f_p(Z) + f(D^F) < f(D^F + Z), \quad Z \in (0, \ \ Y)$:

<u>Case 0</u> Since $f_p(.) + f(D^F)$ is concave,

$f_p(D^p) + f(D^F) \leq f_p(X) + f_p(D^p - X) + f(D^F)$

Since $f_p(D^p - X) + f(D^F) < f(D^F + D^p - X)$ (5.32) holds.

It can be shown in a similar manner that (5.32) holds when $f(D^F + .)$ constitutes the lower envelope of the two functions between 0 and D^p.

Thus, assume $Y < D^p$ and $f_p(D^p) + f(D^F) < f(D^F + D^p)$ Then, there are four (nontrivial) cases in terms of the values of X and $D^p - X$:

<u>Case 1</u> $f_p(X)+f(D^F) < f(D^F+X)$ and $f_p(D^p-X)+f(D^F) < f(D^F+D^p-X)$

The proof is as in Case 0.

<u>Case 2</u> $f_p(X)+f(D^F) > f(D^F+X)$ and $f_p(D^p-X)+f(D^F) < f(D^F+D^p-X)$

The proof is as in Case 0.

<u>Case 3</u> $f_p(X)+f(D^F) < f(D^F+X)$ and $f_p(D^p-X)+f(D^F) > f(D^F+D^p-X)$

This is the case where $X \in (Y, \ D^p)$ and $D^p - X \in (0, \ Y)$. Thus, both $f_p(X) + f(D^F)$ and $f(D^F + D^p - X)$ are on the lower envelope of the two functions. Note that slope of the lower envelope is non-increasing, and $f_p(.)$ and $f_p(.) + f(D^F)$ have the same slope. Hence for $\Delta > 0$

$f(D^F + D^p - X) - f(D^F + D^p - X - \Delta) \geq f_p(X + \Delta) - f_p(X)$

Let, $\Delta = D^p - X$. (5.32) holds.

<u>Case 4</u> $f_p(X)+f(D^F) > f(D^F+X)$ and $f_p(D^p-X)+f(D^F) > f(D^F+D^p-X)$

This is the case where $X, \ D^p - X \in (0, \ Y)$. When $X > D^p - X$ slope of $f_p(X) + f(D^F)$ is less than that of $f(D^F + D^p - X)$, and hence the proof of Case 3 applies. Note that the difference between the two functions decreases as X approaches to Y. Thus,

$f(D^F + X) - f_p(X) > f(D^F + D^p - X) - f_p(D^p - X)$

$f(D^F + X) + f_p(D^p - X) > f_p(X) + f(D^F + D^p - X)$

Therefore, proving the case where $X > D^p - X$ is sufficient to show that (5.32) holds.

Note that the cases where $X = Y$, $D^p - X = Y$, and Y is not unique are amenable to proof by the same strategy. It can be shown in a similar manner that (5.32) holds for $Y < D^p$ and $f_p(D^p) + f(D^F) > f(D^F + D^p)$.□

This result is in parallel with the before mentioned property of an extreme flow of the associated multisource MCNFP: An extreme flow contains at most one path (with positive flow) between any source-destination pair. Presence of conditional dominance in technology selection in the UPL&FTAP provides useful insights regarding the acquisition and operation of flexible technology. Theorem 5.3 implies possible optimality of acquisition of the flexible technology for manufacturing a subset of P. This corresponds to a partially-flexible utilization of the product-flexible technology. Hence, the UPL&FTAP model facilitates determination of the *optimal degree* of flexibility needed, which is a major strategic issue in technology selection as also suggested by Gupta, Gerchak and Buzacott [57]. At the extreme, Theorem 5.3 allows for the possible optimality of utilization of a flexible technology for processing a single product. This is in parallel with a similar result due to Fine and Li [41].

5.3.3 An algorithm for solving the UPL&FTAP

The algorithm devised for solving the UPL&FTAP extends the procedure for UPL&TAP to capture the availability of flexible technology. Hence, facility ip refers to the dedicated technology adopted at plant i to manufacture product p. The parameters m_{ip}, F_{ipk}, c_{ipk}, and R_{ipk} associated with $f_{ip}(.)$ are defined as in the previous section. Whereas, the flexible-cell i refers to the product-flexible technology acquired at plant i. At each iteration of the algorithm, a *pseudo-flexible-cell* is associated with each segment of the current linear underestimate for $f_i(.)$, $i \in I$. Let m_i denote the number of pseudo-flexible-cells (indexed by k) associated with flexible-cell i. Further let,

F_{ik} = the fixed setup cost of opening pseudo-flexible-cell k of flexible-cell i,

c_{ik} = the unit cost of capacity acquisition and operation at pseudo-flexible-cell k of flexible-cell i,

R_{ik}, R_{ik+1} = the lower and upper bounds on the size of pseudo-flexible-cell k of flexible-cell i respectively.

Observe that the pseudo-flexible-cells associated with a piecewise linear underestimate of $f_i(.)$ are analogous to the psedo-facilities associated with that of $f_{ip}(.)$. Thus, at an iteration of the algorithm, the current approximation enables us to model the UPL&FTAP by the following mathematical program:

$$\text{Minimize } z_L = \sum_{i\in I}\{F_iY_i + \sum_{p\in P}\sum_{k\in K_{ip}}[F_{ipk}Y_{ipk} + \sum_{j\in J} c_{ipjk}X^D_{ipjk}] + \sum_{k\in K_i}[F_{ik}Y_{ik} + \sum_{p\in P}\sum_{j\in J} c^F_{ipjk}X^F_{ipjk}]\}, \tag{5.33}$$

subject to

$$\sum_{i\in I}[\sum_{k\in K_{ip}} X^D_{ipjk} + \sum_{k\in K_i} X^F_{ipjk}] = D_{jp}, \quad j = 1,..,n,\ p = 1,..,l, \tag{5.34}$$

$$0 \le X^D_{ipjk} \le Y_{ipk}D_{jp}, \quad j = 1,..,n,\ i = 1,..,m,\ p = 1,..,l,\ k = 1,..,m_{ip}, \tag{5.35}$$

$$0 \le X^F_{ipjk} \le Y_{ik}D_{jp}, \quad j = 1,..,n,\ i = 1,..,m,\ p = 1,..,l,\ k = 1,..,m_i, \tag{5.36}$$

$$Y_{ipk} \le Y_i, \quad i = 1,..,m,\ p = 1,..,l,\ k = 1,..,m_{ip}, \tag{5.37}$$

$$Y_{ik} \le Y_i, \quad i = 1,..,m,\ p = 1,..,l,\ k = 1,..,m_i, \tag{5.38}$$

$$Y_{ipk} \in \{0,1\}, \quad i = 1,..,m,\ p = 1,..,l,\ k = 1,..,m_{ip}, \tag{5.39}$$

$$Y_{ik} \in \{0,1\}, \quad i = 1,..,m,\ p = 1,..,l,\ k = 1,..,m_i, \tag{5.40}$$

$$Y_i \in \{0,1\}, \quad i = 1,..,m, \tag{5.41}$$

where K_{ip} and c_{ipjk} are defined as in the previous section, and

K_i = the set of pseudo-flexible-cells associated with flexible-cell i,

c^F_{ipjk} = the unit cost of serving the demand of market j for product p from pseudo-flexible-cell k of flexible-cell i i.e. $c^F_{ipjk} = c_{ik} + c_{ijp}$.

The decision variables Y_i and Y_{ipk} are defined as in the previous section, and

X^D_{ipjk} = the quantity shipped from pseudo-facility k of facility ip to market j,

X^F_{ipjk} = the amount of product p shipped from pseudo-flexible-cell k of flexible-cell i to market j,

Y_{ik} = 1 if pseudo-flexible-cell k of flexible-cell i is opened, 0 otherwise.

The optimal value of z_L constitutes a lower bound on the optimal solution value of the UPL&FTAP. Constraints (5.34) ensure that each market's demand will be fully satisfied, constraints (5.35) and (5.36) guarantee that markets receive shipments only from open pseudo-facilities and open pseudo-flexible-cells respectively. Whereas, constraints (5.37) and (5.38) force that the pseudo-facilities and the pseudo-flexible-cells are established in the open plants. The constraints to ensure that the total production of each open pseudo-facility/pseudo-flexible-cell is between its lower and upper bounds, and to guarantee that at most one pseudo-facility/pseudo-flexible-cell can be open associated with each facility/flexible-cell are not included in the model. This is in order not to further complicate the exposition. As mentioned before however, they are redundant due to the concavity of the piecewise linear underestimates.

The integer program (5.33) - (5.41) constitues a model for the two-echelon uncapacitated facility location problem (TUFLP). The TUFLP is a generalization of the UFLP where the commodity passes through two echelons of facilities before being served to the clients. The upstream layer of facilities is called echelon-1 whereas, the downstream layer represents the echelon-2 facilities. Typically, echelon-1 and echelon-2 correspond to production facilities and distribution centers respectively. Note that however, the TUFLP can be stated in terms of any two consecutive echelons of a production-distribution system that might include intermediate product plants, finished product plants, distribution centers, and warehouses. Thus, the TUFLP involves decisions regarding the number and location of the facilities in each echelon as well as the echelon-1-echelon-2 and echelon-2-market allocations so as to minimize the total cost of serving the clients. There are m echelon-1 facility locations, $\sum_{i=1}^{m}\sum_{p=1}^{l} m_{ip} + \sum_{i=1}^{m} m_i$ echelon-2 facility locations, and $n * l$ markets in the TUFLP modeled by (5.33) - (5.41). For the ease of exposition, Figure 5.6 depicts the network flow representation of the TUFLP that arises in solving a

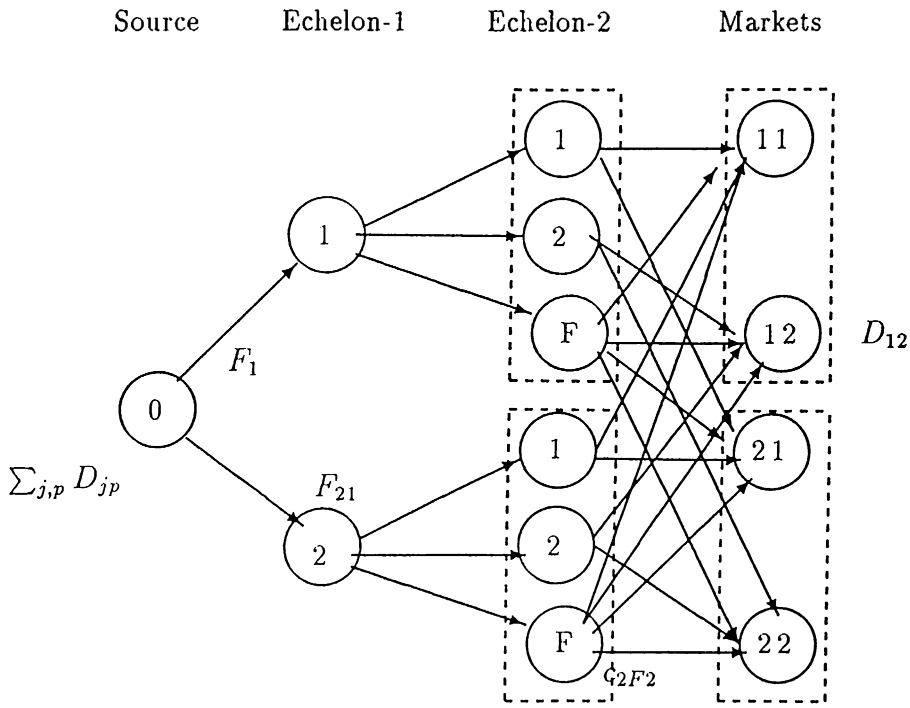

Figure 5.6: Network flow representation of TUFLP

UPL&FTAP with two plants, two products, and two markets. Since variable costs of serving the markets are linear, consistent dominance holds in TUFLP. A comparison of Figure 5.6 with Figure 5.4 reveals that the MUPLP is a special case of the TUFLP. This is due to the presence of additional nodes in TUFLP that represent the flexible technology at each plant, which is capable of serving all of the $n * l$ "markets". Ro and Tcha [120] provided a branch-and-bound procedure for solving the TUFLP with some side constraints. Their work extends the Efroymson and Ray [28] and Khumawala [80] algorithms to the TUFLP. Tcha and Lee [135] suggested a branch-and-bound approach for the multiechelon UFLP in which the dual ascent procedure of Erlenkotter [33] is utilized. Their computational experiments however, focus on the TUFLP.

Gao and Robinson [47] devised a dual-based optimization procedure for solving the TUFLP. Erlenkotter's [33] dual ascent and dual adjustment procedures are extended to generate a good feasible solution to the dual of the linear programming relaxation of TUFLP. This solution provides a lower bound on the value of the optimal solution to TUFLP. Further, based on the dual solution, a feasible primal solution is constructed using the complementary slackness conditions. As in Erlenkotter [33] these procedures are incorporated in a branch-and-bound algorithm for providing an optimal solution to the TUFLP. Gao and Robinson [47] reported solving TUFLPs with 25 facility locations at each echelon and 35 markets in 2.4 seconds on a CDC Cyber 170/855 computer.

Hence, the algorithm devised for solving the UPL&FTAP involves solving a sequence of TUFLPs. Optimum solution of a TUFLP however, corresponds to an extreme flow of the network underlying the UPL&FTAP. Thus, the algorithm finds a global optimum of the UPL&FTAP in a finite number of iterations since the number of extreme flows of the underlying network is finite. Here, we will relax the assumption that $s = 1$ and $s_p = 1$, $p \in P$, and present the algorithm for solving the general UPL&FTAP. This is to emphasize that the algorithm devised for solving the UPL&FTAP constitutes a generalization of the algorithm for solving the UPL&TAP.

The Algorithm

Step 0: Input an instance of the UPL&FTAP.

Step 1: At each plant, construct the effective cost of acquisition and operation of

- dedicated capacity for each product,
- flexible capacity.

Step 2: Solve the arising problem using progressive piecewise linear underestimation:

Step 2a: Initialize

- Generate the first pseudo-facility at each facility (plant-product combination) using the total demand for the associated product.
- Generate the first pseudo-flexible-cell at each flexible-cell (plant) using the aggregate market demand.

Step 2b: Solve the arising TUFLP and determine the implied size for each facility and each flexible-cell.

Step 2c: Improve the approximation

- Generate two new pseudo-facilities at a facility when its size is strictly between the size range of a pseudo-facility that is to be discarded.

- Generate two new pseudo-flexible-cells at a flexible-cell when its size is strictly between the size range of a pseudo-flexible-cell that is to be discarded.

Step 2d: If no new pseudo-facility or pseudo-flexible-cell is generated terminate Step 2, else Go to Step 2b.

Step 3: Determine the dominant technologies among the dedicated and flexible technology alternatives at each plant.

Step 4: Terminate providing the global optimum solution to the UPL&FTAP.

We suggest utilization of the Gao and Robinson [47] procedure for solving the TUFLPs arising in Step 2b of the algorithm.

5.4 Concluding remarks

This chapter presents an integrated approach for the plant location, capacity acquisition, and technology selection decisions. The facility location and capacity acquisition model of Chapter 5 is extended to incorporate the availability of technology alternatives in capacity acquisition. When there are no constraints on the amount of technology acquired, it is shown that conditional dominance holds in the technology selection decisions. This significantly simplifies the solution procedures devised for the problems presented in this chapter. The progressive piecewise linear underestimation technique devised for solving the facility location and capacity acquisition problem is shown to be also suitable for solving the plant location and technology acquisition problems. It is worth to mention that the approximate problems formulated during the operation of the algorithms in all three sections are amenable to solution with facility location techniques. Due to the conditional dominance property, the single commodity problem boils down to the facility location and capacity acquisition problem for which the suggested algorithm is computationally efficient. The computational performance of the algorithms for the multicommodity problems need to be investigated. It should be noted however that the dual based approach proved to be succesful for the location problems that arise in solving the multicommodity problems. Further, the progressive piecewise linear underestimation is shown to be effective in dealing with the concavity of the objective function. Hence, the computational performance for multicommodity problems is expected to be satisfactory. The proposed algorithms can also be used as heuristic procedures for solving the plant location and technology acquisition problems since both lower and upper bounds on the optimum solution value are available at each iteration.

The present plant location and flexible technology acquisition model is in need of the following extensions to enhance its capability in assisting the strategic decision-making process: First, the availability of partially-flexible technology alternatives should be incorporated in the model. Since the current model dwells on the cost of acquisition and operation of fully-flexible technology, the required degree of flexibility provided by the model might be far from optimal when the costs associated with partially-flexible technology are significantly different. Second, the current model presumes that the commodities processed by the flexible technology are quite similar, and hence the production costs of flexible technology are product independent. It is necessary however to define a "weighted unit" to be manufactured by the flexible technology to incorporate the commodities with different production costs in the model. Third, the current trend in flexible technology is toward the development of modular systems which would allow phased implementation of the technology. Thus, the present model should be extended to incorporate the availability of modular systems as technology alternatives. Note that the cost of acquisition of a modular system would be a step function of the amount of capacity to be acquired. This requires revision of the solution procedure since the model objective function is not concave in this case. The former extensions however, do not seem to require significant changes in the solution procedure, although they would inevitably complicate the model.

Chapter 6

Contributions and Future Research

This chapter provides an account of the contributions of this dissertation research and discusses the directions for future research. The primary concern of this study was to contribute to the global manufacturing strategy planning process. This stems from the fact that globalization leads to drastic changes in the nature of the problems associated with manufacturing, and hence constitutes a current theme in both industry and academia. Not only a variety of challenging problems arise when a firm starts operating globally but also the domestic firms have to compete with their multinational rivals due to the globalization of markets. Manufacturing strategy planning is one of the crucial means for a firm to achieve and sustain competitiveness within the international context. The global firm is perceived as an international value chain which can be represented by a production-distribution network. Thus, the major task in achieving the research objective was development of analytical methods to aid the design of international production-distribution sytems.

The following is a list of the contributions made in the process of conducting this dissertation research:

- A review of the state-of-the-art in production-distribution system design is provided. This reveals that the analytical methods devised for designing international networks are lacking the capability to produce manufacturing strategy options. The prevailing strategy generation models however, focus on domestic networks and provide only the locational decisions.

- It is shown that the facility location, capacity acquisition, and technology selection decisions have been dealt with separately in the literature. Whereas, global manufacturing strategy planning requires simultaneous optimization of these structural decisions.

- In the process of the development of an integrated model for the location, sizing, and technology decisions four new problems are defined, and a solution algorithm is devised for each problem based on its analytical properties. These problems are:

    - The facility location and capacity acquisition problem,
    - The facility location and technology acquisition problem,
    - The plant location and technology acquisition problem,
    - The plant location and flexible technology acquisition problem,

- Given that future is known with certainty, and the demand and cost parameters do not change with time; it is shown that there exists conditional dominance in technology selection as well as in facility/plant-market allocation when the dedicated and flexible technology alternatives represent scale and scope economies respectively. This is an important analytical property of the above mentioned problems that aids the characterization of the alternative sizes for a facility/plant, and also significantly simplifies the solution procedures.

- A novel method that is called the progressive piecewise linear underestimation technique is developed and implemented for solving the concave minimzation problems that arose in this study. This technique provides an effective way in dealing with the concavity of the objective function for the class of problems presented here.

Apart from the specific issues discussed at the end of each chapter this dissertation research should be extended in the following directions:

- The current models incorporate only a single echelon of production facilities/plants. Thus, it is necessary to extend the models presented here to facilitate the design of multiechelon production-distribution networks.
- The time dependent variations in the cost and demand parameters need to be incorporated in the models.
- The models should be extended in order to assist manufacturing strategy planning under demand, price and exchange rate uncertainties that are the prominent features global markets.
- Although, quality, delivery performance, and flexibility as well as cost are the common criteria to express the strategy goals for manufacturing, the present models focus on the cost minimization objective. The presence of a multiplicity of objectives in strategy design should be incorporated in the models.
- The proposed methodology for manufacturing strategy planning should be tested via real life applications. This will inevitably lead to a betterment of the normative framework.
- The applicability of the progressive piecewise linear underestimation technique in solving other global minimization problems should be investigated.

Evidently, this dissertation research will serve as a basis for further improving our capability in assisting the global manufacturing strategy design process.

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