

Invited Review

An integrated evaluation of facility location, capacity acquisition, and technology selection for designing global manufacturing strategies

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Abstract: Emergence of global markets enhanced the emergence of global firms which have plants in different countries and implement an integrated management style. Due to the intensive competition in global markets, manufacturing performance is conceived as an important strategic weapon. Facility location, capacity acquisition and technology selection decisions constitute means to implement manufacturing strategies. We review the literature in order to contribute to a better understanding of global manufacturing strategies. As a result we observe that an integrated analysis of the location, capacity and technology decisions is vital for the design of effective global manufacturing strategies.

Keywords: Global manufacturing strategy; facility location; capacity acquisition; technology selection

1. Introduction

Emergence of global markets is one of the phenomena that characterizes 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.

In this paper 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, the paper is organized as follows. In Section 2 we review the literature on facility location. In order to better capture the dynamics of the international environment, the international plant location problem is presented in a separate subsection. Section 3 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 2 and 3, 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 4. In the final section we provide some comments on the existing literature and suggest an avenue for future research.

2. 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 (1985). *Macroeconomic* location theories on the other hand, analyze the distribution of industries, economic sectors or urban areas in space. Ponsard (1983) 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. (1983) 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. (1983a, 1983b) 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 (1985) 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, capaci-

tated, multi-echelon versions. A recent book edited by Mirchandani and Francis (1990) 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. (1983) 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, Brandaue and Chiu (1989) 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.

2.1. 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 (1983) 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:

$$\text{Minimize } z = \sum_{i \in I} \sum_{j \in J} C_{ij} x_{ij} + \sum_{i \in I} F_i Y_i \quad (1)$$

subject to

$$\sum_{i \in I} x_{ij} = 1, \quad j = 1, \dots, n, \quad (2)$$

$$0 \leq x_{ij} \leq Y_i, \quad i = 1, \dots, m, \quad j = 1, \dots, n, \quad (3)$$

$$Y_i \in \{0, 1\}, \quad i = 1, \dots, m, \quad (4)$$

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 (2) guarantee that each market's demand will be fully satisfied, and constraints (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 (1963). 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 (1985). Our review however, is confined to the exact methods since very efficient algorithms which guarantee optimal solutions for SPLP are available. Efraymson and Ray (1966) adopted the branch and bound technique to solve SPLP. Actually, they worked on a different formulation which replaces the constraints (3) with the following:

$$0 \leq \sum_{j \in J} x_{ij} \leq n Y_i, \quad i = 1, \dots, m. \quad (5)$$

This is a compact formulation having a set of (integer) solutions identical to that of (2)–(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 (1972) 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* (1)–(4) yields tight lower bounds which are often (integer) solutions to SPLP. Erlenkotter (1978) took advantage of this to devise 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.

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:

$$\sum_{j \in J} D_j x_{ij} \leq S_i, \quad i = 1, \dots, m, \quad (6)$$

where

D_j = the demand of market j ,

S_i = the capacity of plant i .

Van Roy (1980) 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 within 1 second (except the last two which needs at most 3.08 seconds) on the IBM 3033. This outperforms the algorithms by Guignard and Spielberg (1979) and Akinc and Khumawala (1977). Recently, Beasley (1988) de-

vised an efficient algorithm for CPLP. He reported solving problems involving up to 500 potential locations and 1000 customers on a Cray-1S.

Van Roy and Erlenkotter (1982) 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.

2.2. 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 controllable 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 (1)–(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:

$$\text{Maximize } \pi = \sum_{i \in I} \sum_{j \in J} (P_j - c_{ij}) X_{ij} - \sum_{i \in I} F_i Y_i \quad (7)$$

subject to

$$\sum_{i \in I} X_{ij} \leq D_j \quad j = 1, \dots, n, \quad (8)$$

$$0 \leq X_{ij} \leq Y_i D_j, \quad i = 1, \dots, m, \quad j = 1, \dots, n, \quad (9)$$

$$Y_i \in \{0, 1\}, \quad i = 1, \dots, m. \quad (10)$$

Presuming the firm can predict the future cost structure relatively easily, Jucker and Carlson (1976) addressed different control strategies for dealing with price and demand uncertainty. Their classification is based on exogenous versus controllable 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 (1985a) 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 (1976) proposed a mean-variance framework which has long been in use for optimal portfolio selection (see Markowitz (1987)). 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 $V = E(\pi) - \lambda \text{var}(\pi)$. Then, SPLPU can be stated as follows:

$$\text{Maximize } V = \sum_{i \in I} \sum_{j \in J} E(P_j - c_{ij}) X_{ij} - \sum_{i \in I} F_i Y_i - \lambda \text{var} \left(\sum_{i \in I} \sum_{j \in J} P_j X_{ij} \right) \quad (11)$$

subject to (8)–(10).

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

$$V = \sum_{i \in I} \sum_{j \in J} E(P_j) X_{ij} - \lambda \text{var} \left(\sum_{i \in I} \sum_{j \in J} P_j X_{ij} \right) - z. \quad (12)$$

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 (1971) provided a good account of techniques for the assessment 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 (1984) suggested adoption of the financial market approaches to model SPLPU. He utilized the Capital Asset Pricing Model of Sharpe (1964) for illustration purposes. In this case the model takes the form

$$\text{Maximize } V_M = E(\pi) - \lambda_M \text{cov}(\pi, R_M) \quad (13)$$

subject to (8)–(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 (13) is a linear objective function compared to the quadratic structure of (11). For a detailed comparison of

the above models within an international context see Dincer and Hodder (1989).

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 (1976) assumed the random variables are independent. That is,

$$P_j = v_j - w_j \sum_{i \in I} X_{ij} + \varepsilon_j, \quad (14)$$

$$\varepsilon_j \sim N(0, \sigma_j^2), \quad \text{cov}(\varepsilon_j, \varepsilon_k) = 0 \quad \forall j, \forall k \neq j. \quad (15)$$

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 (1985a) allowed for correlated prices;

$$P_j = b_j(P_0 + \varepsilon_j). \quad (16)$$

Here, b_j is a (positive) market adjustment parameter for the common random factor P_0 with mean \bar{P} and variance σ^2 . Hodder and Dincer (1986) adopted a multifactor price generating mechanism where random prices are expressed as a linear combination of orthogonal factors.

Froymsen and Ray (1966) 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 (1976) 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 (1985a) 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 (1987) for a generalization of that algorithm.

2.3. 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 (1976) 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 (1982). That model however, is restricted to a deterministic setting. Hodder and Jucker (1985b) 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:

$$P_j e_{1j} = b_j(P_1 + \varepsilon_j) \quad (17)$$

where

P_1 = the random price in the home country with mean \bar{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 is incorporated, is rather implicit.

Hodder and Dincer (1986) 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. At this stage, IPLP can adequately be considered as one of the building blocks of our major problem: designing global manufacturing strategies.

3. 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 (1982).

3.1. *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 pre-specified time horizon. Objective is to minimize the discounted costs associated with the expansion process.

The pioneering work on capacity expansion is due to Manne (1961). 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 (1967) 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, 1982), 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 fu-

ture 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:

Minimize

$$C = \sum_{t=1}^T \sum_{i=1}^m \left[f_{it}(s_{it}) + \sum_{\substack{k \in I \\ k \neq i}} g_{ikt}(w_{ikt}) + h_{it}(E_{it}) \right] \quad (18)$$

subject to

$$E_{it} = E_{i,t-1} + s_{it} + \sum_{\substack{k \in I \\ k \neq i}} (w_{kit} - w_{ikt}) - D_{it},$$

$$i = 1, \dots, m, \quad t = 1, \dots, T, \quad (19)$$

$$E_{i0} = E_{iT} = 0, \quad i = 1, \dots, m, \quad (20)$$

$$E_{it} \geq 0, \quad s_{it} \geq 0, \quad w_{ikt} \geq 0, \\ i = 1, \dots, m, \quad t = 1, \dots, T, \quad k = 1, \dots, m, \\ k \neq i, \quad (21)$$

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 ,

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

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

$h_{it}(\cdot)$ = 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 (1968) 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 (1975) for the Minimum Annual Cost algorithm or Fong and Srinivasan (1981a, 1981b) for their capacity exchange heuristic. Recently, Lee and Luss (1987) provided some results about computational complexities of various multifacility-type CEPs.

3.2. Capacity expansion under uncertainty

In his seminal paper Manne (1961) 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 (1970) 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 (1961) 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 (1975) where he presented a theory of monopoly pricing and capacity choice under uncertainty.

Jucker, Carlson and Kropp (1982) 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 (1987).

Eppen, Martin and Schrage (1989) developed a model and software to analyze the multiprod-

uct, 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

$$\begin{aligned} \hat{\pi} &= \text{target profit,} \\ d_{\hat{\pi}}(\pi) &= \text{downside risk of profit } \pi \text{ for target } \hat{\pi} \\ \text{where } d_{\hat{\pi}}(\pi) &= \max\{\hat{\pi} - \pi, 0\} \text{ for } \pi \in \mathbb{R}^1 \text{ and} \\ \Phi(\pi) &= \text{probability mass function of profit } \pi. \end{aligned}$$

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

$$\text{EDR}[\hat{\pi}] = E[d_{\hat{\pi}}(\pi)] = \sum_{\pi \in \mathbb{R}^1} \Phi(\pi) d_{\hat{\pi}}(\pi). \quad (22)$$

First, the model is solved without any risk constraint and then successive constraints on the $\text{EDR}[0]$ 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% of the optimum) a problem with 160 binary variables in 1.3 CPU hours on a VAX 8650.

Bird (1987) 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 (1989) 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 multistage 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.

4. 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 (1991) 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 (1990) 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 (1986) and Kusiak (1986).

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 (1986) 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 (1990) 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 perfor-

mance evaluation models are not in the scope of this review. The interested reader is referred to Buzacott and Yao (1986). 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 (1991) provided an excellent review of the economic evaluation models including the literature on multiple firm models.

4.1. *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. (1987) 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 (1986) 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 (1984) 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 (1979a) 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 (1979b) 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 (1988) 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 (1988) 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 (1986), 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 (1973) 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 alternatives.

4.2. 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 (1978) 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 (1988) 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 perfor-

mance 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. (1984) 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.

Production flexibility: the universe of part types that can be produced.

Carter (1986) 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 that are less sensitive and highly stable with respect to the changes influencing their performance. Recently, Suresh (1990a) provided a more operational definition: Flexibility is the capability of a system as well as the ease to accommodate 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 (1990) presumed that the variable operation costs are linear functions of volume and ignored them to simplify their model. Fine and Li (1988) and Fine and Freund (1990) 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 (1982) and Gupta et al. (1990) suggested that FMSs have higher variable 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 (1982) 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 (1988) 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 produc-

ing a single item using flexible technology at some stages of the product and process life cycles. Li and Tirupati (1990) 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 (1990) 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 (1990) 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:

$$\begin{aligned} \text{Maximize } V_F = & -f_F(s^F) - \sum_{i=1}^m f_i(s_i) \\ & + \sum_{k=1}^K p_k \sum_{i=1}^m [R_{ik}(X_{ik}^F + X_{ik}) \\ & - C_F(X_{ik}^F) - C_i(X_{ik})], \quad (23) \end{aligned}$$

subject to

$$X_{ik} \leq s_i, \quad i = 1, \dots, m, \quad k = 1, \dots, K, \quad (24)$$

$$\sum_{i=1}^m X_{ik}^F \leq s^F, \quad k = 1, \dots, K, \quad (25)$$

$$s^F \geq 0, \quad s_i \geq 0, \quad i = 1, \dots, m, \quad (26)$$

$$X_{ik}^F \geq 0, \quad X_{ik} \geq 0, \quad i = 1, \dots, m, \quad k = 1, \dots, K, \quad (27)$$

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 ,

$f(\cdot)$ = capacity acquisition cost function,

$C(\cdot)$ = variable production cost function,

$R_{ik}(\cdot)$ = 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 (1990) 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. (1990) 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. (1990) 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 (1990) 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 (1990) suggested the usage of the multi-attribute decision methods whereas, Stam and Kuula (1989) and Kuula and Stam (1989) 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 paper in order not to lose the focus of our presentation. However, we believe that the convex programming model of Burstein (1986) which incorporates production and technology selection decisions, the stochastic dynamic program of Kulatilaka (1988) 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 (1990) which uses the contingent claims pricing methodology to value FMS investments, the works of Suresh (1989, 1990b) and Suresh and Sarkis (1989) on the phased implementation of FMSs, and the model of Park and Son (1988) (see also Son and Park (1987) and Son and Park (1990)) 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.

5. 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 (1989) 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. Structural similarities between problems such as the dynamic location problem and the multifacility capacity expansion problem could be explored in order to come up with a possible synthesis. The authors are currently working on the development of an integrated model for facility location, capacity acquisition and technology selection which will presumably aid the design of global manufacturing strategies.

References

- Aikens, C.H. (1985), "Facility location models for distribution planning", *European Journal of Operational Research* 22, 263–279.
- Akinc, U., and Khumawala, B.M. (1977), "An efficient branch and bound algorithm for the capacitated warehouse location problem", *Management Science* 23, 585–594.
- Beasley, J.E. (1988), "An algorithm for solving large capacitated warehouse location problems", *European Journal of Operational Research* 33, 314–325.
- Bird, C.G. (1987), "A stochastic programming with recourse approach to capacity planning", Technical Report, General Motors Research Lab.
- Brandea, M.L., and Chiu, S.S., (1989), "An overview of representative problems in location research", *Management Science* 35, 645–674.
- Browne, J., Dubois, D., Rathmull, K., Sethi, S.P. and Stecke, K.E. (1984), "Classification of flexible manufacturing systems", *The FMS Magazine* 2 114–117.
- Burstein, M.C. (1986), "Finding the economical mix of rigid and flexible automation for manufacturing systems", in: K.E. Stecke and R. Suri (eds.), *Second ORSA/TIMS Conference on Flexible Manufacturing Systems*, Elsevier, Amsterdam, 43–54.
- Buzacott, J.A., and Yao, D.D. (1986), "Flexible manufacturing systems: A review of analytical models", *Management Science* 32, 890–905.
- Carlson, R., Hodder, J., and Jucker, J. (1987), "Simple solution procedures for nonlinear programming problems that are derivative decomposable", *European Journal of Operational Research* 31, 118–126.
- Carter, M.F. (1986), "Designing flexibility into automated manufacturing systems", in: K.E. Stecke and R. Suri (eds.), *Second ORSA/TIMS conf. on Flexible Manufacturing Systems*, Elsevier, Amsterdam, 107–118.
- Caulkins, J.P., and Fine, C.H. (1990), "Seasonal inventories and the use of product-flexible manufacturing technology", Technical Report, Sloan School of Management, MIT.
- Cohen, M.A. and Halperin, R.M. (1986), "Optimal technology choice in a dynamic-stochastic environment", *Journal of Operations Management* 6, 317–331.
- Dantzig, G.B., and Glynn, P.W. (1989), "Parallel processors for planning under uncertainty", Technical Report, SOL, Stanford Univ.
- Dincer, M.C. and Hodder, J.E. (1989), "A comparison of mean-variance based models for plant location under uncertainty", Technical Report, Bilkent Univ.
- Efroymsen, M.A., and Ray, T.L. (1966), "A branch-bound algorithm for plant location", *Operations Research* 14, 361–368.
- Eppen, G., Martin, K., and Schrage, L. (1989), "A scenario approach to capacity planning", *Operations Research* 37, 517–527.
- Erlenkotter, D. (1975), "Capacity planning for large multilocation systems: Approximate and incomplete dynamic programming approach", *Management Science* 22, 274–285.
- Erlenkotter, D. (1978), "A dual based procedure for uncapacitated facility location", *Operations Research* 26, 992–1009.
- Falkner, C.H., and Benhajla, S. (1990), "Multi-attribute decision models in the justification of CIM systems", *The Engineering Economist* 35, 91–114.
- Fine, C.H. (1990), "New manufacturing technologies", in: P.E. Moody (ed.), *Strategic Manufacturing: Dynamic Directions for the 1990s*, Dow-Jones Irwin, Homewood, IL., 257–273.
- Fine, C.H. (1991), "Developments in manufacturing technology and economic evaluation models", in: S.C. Graves, A. Rinnooy Kan, and P. Zipkin (eds.), *Logistics of Production and Inventory*, North Holland Series in OR and Management Science, North-Holland, Amsterdam (to appear).
- Fine, C.H., and Freund, R.M. (1990), "Optimal investment in product-flexible manufacturing capacity", *Management Science* 36, 449–466.
- Fine, C.H., and Li, L. (1988), "Technology choice, product life cycles and flexible automation", *Journal of Manufacturing and Operations Management* 1, 372–399.
- Fong, C.O., and Srinivasan, (1981a), "The multiregion dynamic capacity expansion problem, part I", *Operations Research* 29, 787–799.
- Fong, C.O., and Srinivasan, V. (1981b) "The multiregion capacity expansion problem, part II", *Operations Research* 29, 800–816.
- Francis, R., McGinnis, L., and White, J. (1983), "Locational analysis", *European Journal of Operational Research* 12, 220–252.
- Giglio, R.J., (1970), "Stochastic capacity models", *Management Science* 17, 174–184.
- Guignard, M., and Spielberg, K. (1979), "A direct dual method

- for the mixed plant location problem with some side constraints", *Mathematical Programming* 17, 198–228.
- Gupta, D., and Buzacott, J.A. (1988), "A framework for understanding flexibility of manufacturing systems", Technical Report, Univ. of Waterloo.
- Gupta, D., Gerchak, Y., and Buzacott, J. (1990), "The optimal mix of flexible and dedicated manuf. capacities: Hedging against demand uncertainty", Technical Report, McMaster University.
- Hayes, R.H., and Wheelwright, S.C. (1979a), "Link manufacturing process and product life cycles", *Harvard Business Review* Jan–Feb., 133–140.
- Hayes, R.H., and Wheelwright, S.C. (1979b), "The dynamics of process-product life cycles", *Harvard Business Review* May–Apr., 127–136.
- Hodder, J.E. (1984), "Financial market approaches to facility location under uncertainty", *Operations Research* 32, 1374–1380.
- Hodder, J.E., and Dincer, M.C. (1986), "A multifactor model for international plant location and financing under uncertainty", *Computers & Operation Research* 13, 601–609.
- Hodder, J.E., and Jucker, J.V. (1982), "Plant location modeling for the multinational firm", *1982 AIB Asia-Pacific Conference*, 248–258.
- Hodder, J.E., and Jucker, J.V. (1985a), "A simple plant-location model for quantity-setting firms subject to price uncertainty", *European Journal of Operational Research* 21, 39–46.
- Hodder, J.E., and Jucker, J.V. (1985b), "International plant location under price and exchange rate uncertainty", in: R. Grubbström and H. Hinterhuber (eds.), *Production Economics – Trends and Issues*, Elsevier, Amsterdam, 225–230.
- Howard, R.A. (1971), "Proximal decision analysis", *Management Science* 17, 507–541.
- Huang, P.Y., and Chen, C.S. (1986), "Flexible manufacturing systems: An overview and bibliography", *Production and Inventory Management* 27, 80–90, 1986.
- Hurter, A.P., and Martinich, J.S. (1989), *Facility Location and the Theory of Production*, Kluwer Academic Publishers, Dordrecht.
- Hutchinson, G.K., and Holland, J.R., (1982), "The economic value of flexible automation", *Journal of Manufacturing Systems* 1, 215–228.
- Jaikumar, R. (1986), "Postindustrial manufacturing", *Harvard Business Review* Nov.–Dec., 69–76.
- Jucker, J.V., and Carlson, R.C. (1976), "The simple plant location problem under uncertainty", *Operations Research* 24, 1045–1055.
- Jucker, J., Carlson, R., and Kropp, D. (1982), "Determination of plant and leased warehouse capacities for a firm facing uncertain demand", *IIE Transactions* 14, 99–108.
- Kalotay, A.J. (1973), "Capacity expansion and specialization", *Management Science* 20, 50–64.
- Kaplan, R.S. (1986), "Must CIM be justified by faith alone", *Harvard Business Review* Mar.–Apr., 239–247.
- Khumawala, B.M. (1972), "An efficient branch and bound algorithm for the warehouse location problem", *Management Science* 18, B718–731.
- Krarup, J., and Pruzan, P.M. (1983), "The simple plant location problem: Survey and synthesis", *European Journal of Operational Research* 12, 36–81.
- Kuehn, A.A., and Hamburger, M.J. (1963), "A heuristic program for locating warehouses", *Management Science* 9, 643–666.
- Kulatilaka, N. (1984), "Financial, economic and strategic issues concerning the decision to invest in advanced automation", *International Journal of Production Research* 22, 949–968.
- Kulatilaka, N. (1988), "Valuing the flexibility of flexible manufacturing systems", *IEEE Transactions on Engineering and Management* 35, 250–257.
- Kusiak, A. (1986), "Application of operational research models and techniques in flexible manufacturing systems", *European Journal of Operational Research* 24, 336–345.
- Kuula, M., and Stam, A. (1989), "A nonlinear multi-criteria model for strategic FMS selection decisions", Technical Report, IIASA.
- Lee, S., and Luss, H. (1987), "Multifacility-type capacity expansion planning: Algorithms and complexities", *Operations Research* 35, 249–253.
- Li, S., and Tirupati, D. (1990), "Dynamic capacity expansion problem with multiple products: Technology selection, timing of capacity additions", Technical Report, Sc. of Business, Univ. of Texas, Austin.
- Luss, H. (1982), "Operations research and capacity expansion problems: A survey", *Operations Research* 30, 907–947.
- Mandelbaum, M. (1978), *Flexibility in Decision Making: An Exploration and Unification*, Ph.D. Thesis, Univ. of Toronto.
- Manne, A.S. (1961), "Capacity expansion and probabilistic growth", *Econometrica* 29, 632–649.
- Manne, A.S. (ed.), (1967), *Investments for Capacity Expansion: Size, Location and Time-Phasing*, George Allen and Unwin, London.
- Markowitz, H.M. (1987), *Mean-Variance Analysis in Portfolio Choice and Capital Markets*, Basil Blackwell, Oxford.
- Meyer, R.A. (1975), "Monopoly pricing and capacity choice under uncertainty", *The American Economic Review* 65, 326–337.
- Mirchandani, P., and Francis, R. (eds.), (1990), *Discrete Location Theory*, John Wiley & Sons, New York.
- Park, C.S., and Son, Y.K. (1988), "An economic evaluation model for advanced manufacturing systems", *The Engineering Economist* 34, 1–25.
- Pomper, C.L. (1976), *International Investment Planning: An Integrated Approach*, North-Holland, Amsterdam.
- Ponsard, C. (1983), *History of Spatial Economic Theory*, Springer-Verlag, Berlin.
- Sethi, A.K., and Sethi, S.P. (1990), "Flexibility in manufacturing: A survey", *The International Journal of Flexible Manufacturing Systems* 2, 289–328.
- Sharpe, W.F. (1964), "Capital asset prices: A theory of market equilibrium under conditions of risk", *Journal of Finance* 19, 425–442.
- Singhal, K., Fine, C.H., Meredith, J.R., and Suri, R. (1987), "Research and models for automated manufacturing", *Interfaces* 17/6, 5–14.

- Son, Y.K., and Park, C.S. (1987), "Economic measure of productivity, quality and flexibility in advanced manufacturing systems", *Journal of Manufacturing Systems* 6, 193–207.
- Son, Y.K., and Park, C.S. (1990), "Quantifying opportunity costs associated with adding manufacturing flexibility", *International Journal of Production Research* 28, 1183–1194.
- Stam A., and Kuula, M. (1989), "Selecting a flexible manufacturing system using multiple criteria analysis", Technical Report, IIASA.
- Suresh, N.C. (1989), "A generalized multimachine replacement model for flexible automation investments", Technical Report, State Univ. of NY at Buffalo.
- Suresh, N.C. (1990a), "A multi-objective multi-period replacement model for flexible automation systems", Technical Report, State Univ. of NY at Buffalo.
- Suresh, N.C. (1990b), "Towards an integrated evaluation of flexible automation investments", *International Journal of Production Research* 28, 1657–1672.
- Suresh, N.C., and Sarkis, J. (1989), "A MIP formulation for the phased implementation of FMS modules", in: K.E. Stecke and R. Suri (eds.), *Third ORSA / TIMS Conference on Flexible Manufacturing Systems*, Elsevier, Amsterdam, 41–46.
- Tansel, B., Francis, R., and Lowe, T. (1983a), "Location on networks: A survey, part I: The p -center and p -median problems", *Management Science* 29, 482–497.
- Tansel, B., Francis, R., and Lowe, T. (1983b), "Location on networks: A survey, part II: Exploiting the tree network structure", *Management Science* 29, 498–511.
- Thizy, J., Van Wassenhove, L.N., and Khumawala, B.M. (1985), "Comparison of exact and approximate methods of solving the uncapacitated plant location problem", *Journal of Operational Management* 6, 23–33.
- Triantis, A.J., and Hodder, J.E. (1990), "Valuing flexibility as a complex option", *The Journal of Finance* 45, 549–565.
- Van Roy, T.J. (1980), "A cross decomposition algorithm for capacitated facility location", Technical Report, Katholieke Univ.
- Van Roy, T.J., and Erlenkotter, D. (1982), "A dual based procedure for dynamic facility location", *Management Science* 28, 1091–1105.
- Zangwill, W.I. (1968), "Minimum concave cost flows in certain networks", *Management Science* 14, 429–450.