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STRATEGIC PLANNING FOR THE OPTIMAL ACQUISITION OF FLEXIBLE MANUFACTURING SYSTEMS TECHNOLOGY

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STRATEGIC PLANNING FOR THE OPTIMAL ACQUISITION OF FLEXIBLE MANUFACTURING SYSTEMS TECHNOLOGY

DISSERTATION

Presented in Partial Fulfillment of the Requirement for
the Degree Doctor of Philosóphy in the Graduate
School of the Ohio State University

By

Aleda V. Roth, B.S., M.S.P.H.

* * * * *

The Ohio State University
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To my husband Doug and
children Brian and Lauren

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CHAPTER 1

INTRODUCTION

1.1 RESEARCH OVERVIEW

This dissertation represents research related to the acquisition of programmable, automated manufacturing technology such as flexible manufacturing systems (FMS). More specifically, "a flexible manufacturing systems is an integrated computer controlled complex of automated material handling devices and numerically controlled machine tools that can simultaneously process medium-sized volumes of a variety of parts" (Browne et al. 1984). Since the flexible systems technology offers manufacturing improvements by achieving a continuous material flow as well as considerably reducing machine setup times, cycle times, and space requirements, FMS technology has been designed to bridge the gap between high production transfer lines and low production numerically controlled machines. Therefore, FMS improve productivity in mid-volume, mid-variety, discrete parts manufacturing environments. The practitioner literature supports the assertion that these manufacturing environments are deemed to have the largest payoff for conversion to new technological alternatives, and in particular, programmable automation strategies such as FMS.

For these reasons, it is assumed the adoption of flexible technology is more than the simple replacement of old machines with new ones. FMS technology has more far-reaching strategic potential to define the firm's competitive position by placing boundaries on its production capabilities. Furthermore, it is assumed that FMS technology is acquired in modules, continuously over time and that each modular acquisition offers progressively greater benefits as more sectors of the plant are integrated. In effect, value is added from linking new technology modules with one another over time.

The purpose of this research is threefold. First, a conceptual framework is presented depicting linkages among corporate, business unit, and manufacturing strategy from which the potential contribution of flexible manufacturing systems technology is further elucidated. Second, two normative, dynamic decision models are introduced to assist firms in strategic planning activities concerning the development of a manufacturing process technology strategy. These models capture salient features corresponding to the firm's competitive position over time and the relative impact of flexible automation on goal attainment. Third, through systematic variation of exogenous input parameters, each model's dynamic behavior can be assessed under different environmental scenarios. Given a set of likely input parameter values over time, sensitivity analysis illustrates the prospective utility of each model to provide strategic policy alternatives. Policy guidance for the selection and timing of new manufacturing process technology may be obtained from the analysis of key environmental scenarios.

The types of decisions that are identified with the design, justification, and operation of an FMS are typically made according to the level of management involved and the length of planning horizon. The first level of decision making which a firm may encounter is strategic analysis and economic consideration of flexible manufacturing systems technology as a competitive weapon and as a source of productive capacity. At this level, the decision to implement an FMS must be concerned with the aggregate notion of automation and not with the details concerning the specific types and layouts. It is this first level or strategic level of decision making that is the focus of this dissertation research.

Strategic planning is essential since there are (a) significant amounts of capital to be committed; (b) a high degree of risk involved due to uncertainty arising from such sources as the general conditions of the economy, the cost of capital, and volume of future sales; and (c) long lead times to install and implement an FMS. For these reasons the adoption of a new manufacturing process technology such as flexible automation is a strategic decision which impacts on the long-run survival of the firm.

1.2 CONCEPTUAL BACKGROUND

In Chapter 2, the relevant literature is reviewed in terms of the conceptual genesis of the research. First, the research is motivated by the presentation of an overview of strategic planning from a decision making perspective. Strategic management decision tasks tend to be more long-range, unstructured, and dynamic in nature.

Second, strategy is defined and characterized by scope and level. In particular, the notion of a manufacturing strategy is illustrated in terms of capacity and process technology decisions. Linkages are highlighted among corporate, business unit and manufacturing strategies. It is illustrated that such factors as innovativeness, quality, responsiveness to demand, dependability, flexibility and low production costs provide firms with competitive advantages in the market.

Third, the potential contribution of a properly implemented, fully automated computer integrated FMS as a manufacturing process strategy is to capture through the production process those factors supportive of the firm's competitive strategy. The decision to adopt an FMS as a firm's manufacturing process strategy assumes benefits of the technology due to economies of scope and production process efficiencies outweigh the costs over time. Moreover, consideration is given to an evolutionary integration strategy wherein individual flexible automation modules are acquired continuously over the planning horizon.

Fourth, Chapter 2 is concluded with a discussion of the appropriateness of optimal control theory methodology as a dynamic modeling tool for broad scale policy formation. Related modeling research concerned with the optimal introduction of new technology is summarized. Particular attention is focused on related research employing optimal control theory as a methodological tool.

1.3 THE MODELS

The strategic planning conceptual framework which evolves out of the management and engineering literature as well as other related research using modern control theory as a decision support tool provides the impetus for the development of two dynamic decision models presented in Chapters 3 and 4. Both models have been formulated to assist firms in the broad scale, strategic planning activities concerned with the acquisition of new flexible technology as a source of productive capacity over time and as a competitive weapon. In each model, the timing and sizing of technology purchases are decision variables. Other decision variables are model specific. In both models it is assumed (a) sales equals demand; (b) all demand is satisfied in the period requested and, therefore, no backlogging/backordering of demand occurs; and (c) the decision variables are measured in units of aggregate output.

In order to portray the kinds of managerial insight which might be gleaned from each of the decision models, sensitivity analyses are performed. Illustrative results are included in Chapters 3 and 4, respectively. Through sensitivity analysis, the relative importance of the selected input parameters is evaluated. Sensitivity analysis affords managers the opportunity to delineate certain tradeoffs in goals over the planning horizon and to ascertain those technological process policies which are consistent with corporate and business unit goals. Because of the dynamic nature of the model formulation and solution technique, a distinct advantage of optimal control theory as a normative modeling approach is the capability to examine the optimal time paths for the decision variables that are part of a particular solution. These solutions can often be counterintuitive, and therefore, unlikely to be chosen as an alternative without such a decision aiding tool.

In the model detailed in Chapter 3, the general tradeoffs between the adoption of a programmable, fully automated FMS technology and the more conventional, semiautomatic, manually operated technology is explored. The model's objective is to derive the optimal, dynamic mix of productive capacity, i.e., the rates output over time from both flexible systems technology and conventional, semiautomatic process technology.

Within the context of the model, the multicriterion objective function is defined to maximize the long-term effectiveness of the firm in supporting planned, business unit goals minus relevant costs incurred over the planning horizon. Long-term effectiveness is modeled as the terminal time value of market share and capacity held by the firm minus the total penalty costs arising from deviations between actual and planned market share levels over time. Other relevant costs subtracted from the maximizing objective over the planning horizon include those related to production plus in-process inventory, purchases of flexible technology and changes in the levels of conventional technology.

In this model it is assumed that all demand is satisfied with available productive capacity at time $t \in [0,T]$ where T represents the length of an appropriate managerially determined planning horizon. In order to satisfy the latter assumption, the formulation explicitly includes a constraint requiring that over the planning horizon the level of productive capacity comprised of both flexible and conventional capacity be greater than or equal to the level of production. Both capacity and production levels are measured in units of output at an instant of time. No scrapping of flexible technology is permitted for the duration of the planning horizon.

In Chapter 4, a related model is introduced which differs from that of Chapter 3 in several fundamental ways. First, the model formulated in Chapter 4 addresses the issue of organizational learning (technological progress). It is assumed that increases in both the levels of demand and productive capacity beyond the time of initial acquisition occur as a result of cumulative experience with the flexible automation. Subsequently, technological progress is an important factor to be considered in the strategic aggregate modeling of the production environment. Second, this model allows for the scrapping of existing productive capacity including vintage flexible technology. Acquisitions of new flexible automation either augment capacity currently in place or substitute for vintage existing capacity. Acquisitions of conventional technology are not permitted so that dynamic adjustments in the level of operating capacity are made through purchases of new flexible systems technology and/or reductions in existing productive capacity. Third, in contrast to the model of Chapter 3, demand in excess of the available operating capacity may be met through the use of short-term capacity expansion measures of the usual type (e.g., overtime, reduction in planned maintenance schedules and expansion to another shift).

1.4 OVERVIEW OF FUTURE RESEARCH

Models are subject to limitations corresponding to both the assumptions and descriptions regarding the decision environment. In Chapter 5, the explicit assumptions embodied in the models of Chapters 3 and 4 are delineated. Furthermore, Chapter 5 suggests areas for future research. Future research streams run in two directions. First, possible extensions to the dissertation models of Chapters 3 and 4 are outlined. Second, empirical research validating (a) the relationships among the variables, (b) the exogenous input data and (c) the utility of this approach for strategic decision support is recommended.

1.5 RESEARCH CONTRIBUTIONS

The ultimate contribution of this research to the field of operations management is premised upon the hypothesis that the composition of productive capacity to meet demand is fundamental to the firm's strategic planning process. The objective is to define a set of control policies which support manufacturing process strategies and which are consistent with the firm's overall goals. Therefore, to be included in the firm's strategic plan are recommendations for the introduction of new manufacturing process technology under alternate environmental scenarios. Obtaining a "satisficing" way of overlapping new flexible technology onto the existing production environment, is a key consideration to the firm. Having agreed upon the direction of the technology change; i.e., flexible automation, the more challenging task is to determine how best to manage the introduction and application of the new technology as well as the orderly and economic transition from old to new.

The value of the decision models formulated in this study are twofold. First, they address the normative issue of the appropriate timing and sizing of acquisitions of flexible technology for a given set of input parameters. Hence, they support first level decisions which must be made with respect to the adoption of the new process technology. It is assumed that this modeling effort provides a framework for comparing alternative courses of action with respect to those manufacturing process strategies which may be most attractive for the long-run survival of the firm.

Once these first level decisions have been made, the infrastructure of the firm can be managed to permit (a) the build-up of a trained workforce, (b) appropriate management structure and (c) other necessary factors requisite for the orderly introduction of the technology. The importance of a global top-down strategy cannot be overstated. All too often companies have tried to respond to competition by simultaneously leapfrogging into new technology, and thereby, increasing the rapidity of incremental improvement in their business without concern for the appropriate infrastructure changes (Graham 1985a,b). These firms fail to realize such strategies require an enormous amount of organizational support. An overall schema for the feasible integration of technology can provide a useful interface for a well-conceived comprehensive plan.

The second important contribution of this research is to provide a structured framework for comparing alternative choices of manufacturing process technologies over time. Due to relative uncertainty of future events, strategic planning activities tend to be more difficult to grasp. They are generally considered to be more nonroutine and less well-structured. However, as one type of decision support tool, the models developed in this research yield a systematic basis for future planning and making current decisions with regard to the acquisition of manufacturing technology.

Further, the particular objectives of a firm tend to be multiple, of different measures, and to vary over time. The models afford the relative advantage of assessing the new flexible automation in terms of economic factors such as acquisition costs, maintenance costs, and production plus in-process inventory costs as well as the weighted importance of meeting goal levels of market share (demand) and capacity. They take into consideration the dynamic interaction among strategic and cost factors over the entire planning horizon. In fact, in both models the multicriterion objective function specifically maximizes measures of the effectiveness or strength of the firm over the planning horizon minus the discounted costs incurred of (a) changing the mix of productive capacity and (b) maintaining the operating capacity. Effectiveness and strength are measured by relative values ascribed to the firm's market share holdings, capacity, and level of organizational learning at the terminal time minus penalty costs between deviations of actual and planned market share levels over the planning horizon. Further, sensitivity analysis on the models is illustrated by varying exogenous input variables. This analysis provides managers with a decision support tool to evaluate the relative impact of the exogenous input parameter changes on the optimal timing and sizing of new technological purchases of the firm over time.

CHAPTER 2

LITERATURE REVIEW

2.1 STRATEGIC PLANNING FRAMEWORK

One major objective of this study is to provide top management with two normative decision models to assist in strategic planning for the acquisition of manufacturing process technology. In order to motivate the formulation of these models for the problems addressed in the study, an overview of strategic planning from a decision making perspective is now presented. While there exists a multiplicity of definitions for strategic planning in the literature, a few examples should suffice to illustrate the models' potential utility in this context.

The classic taxonomy of management planning activities proposed by Anthony (1965) remains useful today. Much of the current literature in management decision support systems stems from Anthony's taxonomy. According to Anthony, management decisions can be divided into three classes: namely, strategic planning, management control and operational control.

Strategic planning decisions encompass "the process of deciding upon objectives of the organization, on changes in those objectives, on the resources used to attain these objectives, and the policies that are to govern the acquisition, use and disposition of the resources" (Anthony 1965). It is noted that

Anthony does not equate long-range planning with strategic planning which is an important, but subtle distinction. In fact, long-range planning is deemed to more likely resemble decisions related to the second level of decision making, management control.

Management control is the process by which managers assure that the firm's resources are used wisely in the accomplishment of the organization's objectives over time. Therefore, long-range planning may be considered a tool or benchmark in the strategic planning process. In contrast to strategic planning and management control activities, operational control refers to the class of decisions which assure that specific tasks are carried out in an efficient manner and in accordance with the stated objectives.

Planning at each level of management is decision making toward the anticipated design of a desired future state for the firm. The difficulty of planning at any level is a function of the rate and magnitude of change, the degree of uncertainty faced, and the potential impact of the decisions on the firm (Boulden 1975). The higher the level of decision making, the greater the difficulty in formulating plans. In particular, strategic planning decisions are construed as being more complex since they have a more pervasive long-term impact on the firm overall. Indeed, the result of strategic planning efforts are plans and policies that determine or change the character and direction of the firm.

Strategic planning focuses upon more effectiveness-oriented performance criteria in a more unstructured decision setting. For this reason, strategic planning is portrayed in Figure 1 as the apex of all planning activities. As described in Section 2.1.1 below, effectiveness implies that decision support models for

Figure 1. Organizational Planning Levels

strategic planning should consider only major conceptual aspects related to the firm's objectives and resource acquisition and deployment. Furthermore, strategic plans should be open-ended, allowing for alternative courses of action due to environmental uncertainty and the ramifications of strategic decisions on the firm over time.

2.1.1 Strategic Decision making

The effectiveness performance criteria for strategic decision making represent the degrees to which the organizational objectives are met. Therefore, organizations must explicitly specify in quantitative terms desired goal levels at stated times. The degree to which the actual goal levels meet the desired levels is a measure of the relative effectiveness of the firm. Unfortunately, for most firms, objectives are multiple and more often than not, competing not only across top level management but also among the functional areas. Therefore, in strategic planning the choice of appropriate objectives, the relative value or weight ascribed to each, and their desired timing are the critical factors in obtaining the ultimate effectiveness measure which is long-term survival.

Note at the operational control level, performance criteria tend to be more efficiency-oriented. (See Figure 1.) Efficiency measures the consumption of resources relative to the output. It must be noted, however, that even at the operational level where efficiency performance criteria are necessary and may dominate, they are still not sufficient. Efficiency-oriented criteria should coincide with the pre-established effectiveness measures. The relative tradeoffs between efficiency and effectiveness must be analyzed along the entire continuum of planning levels. The decision support models depicted in Chapters 3 and 4 incorporate effectiveness-oriented and efficiency-oriented criteria so that the relative tradeoffs can be scrutinized over the planning horizon.

Next the issue of the degree of structure and level of decision making is treated as illustrated in Figure 1. A continuum of structured through unstructured types of problems permeate each level of management. Following Simon (1965) as extended by Gory and Scott-Morton (1978), a structured or programmed problem solving activity is assumed to be well-defined and repetitive in nature. Usually programmed decisions can be made with a rule or algorithm. On the other hand, an unstructured problem area involves decisions which are ill-defined and vague. They are more nonroutine due to situational novelty. Unstructuredness exacerbates the complexity of strategic planning activities. Therefore, to the extent that the decision tools presented in this research assist in identifying appropriate policy, objectives, and resources, more structure can be imposed on an otherwise ambiguous situation. More structure implies more modeling capability to support the decision maker's judgment and intuition.

It is also useful to note that the data base for strategic planning is usually comprised of summary (aggregated) data obtained from a variety of sources. The scope of the information required is broad and the accuracy level is bound to be relatively low (Alter 1980, Craig et al. 1975). Due to the unpredictable and variable nature of strategic decision making activities, much "hard", factual type data cannot be collected at all, or if collectable, not on a regular basis (Keen and Scott-Morton 1978).

Thus, appropriate decision support models for strategic planning might well be those which in some way incorporate the decision maker's judgment and intuition with whatever hard data may be available. For example, in the formulations presented in Chapters 3 and 4, it is possible to incorporate subjective assessment of functional relationships among variables over time and to provide the decision maker with the opportunity to postulate "what-if" type questions under different but plausible scenarios. This is particularly important since there exists a dearth of hard data when considering the acquisition of new technology. The very notion of being "strategic" embodies the notion that managers have reviewed different scenarios about the future and have considered alternative policies in light of a changing and uncertain environment.

The relationship between the firm and its environment requires the strategic plan be comprised of a set of corporate objectives and conditional action steps or policies to reach the objectives. In this regard, the strategic plan must be viewed as highly conditional and subject to continuous adjustments (Katz 1970). It is a "broad, ever-changing program of corporate emphasis and resource deployment which responds to and initiates upon the competitive environment in which the company operates...(it) has a limited time perspective...(and) it is a matter of continually balancing the requirements for satisfactory performance today with the anticipated requirements for assuring satisfactory performance in the future." Clearly, strategic planning is a dynamic concept for addressing evolving organizational goals and objectives rather than a static approach to one time problem solving. The methodology described in Section 2.4.1 is particularly suited for dynamic analysis.

Katz (1970) further indicates that strategic issues for the firm incorporate characteristics of the product, service, and the customers. Katz distinguishes strategic and operating variables. Strategic variables include the broad product policy, customer policy, competitive emphasis, pricing, financing policy and investment policy. To evaluate strategic activities, various effectiveness measures such as growth rate, market share, return on investment, lifespan should be considered. Operating variables include the level of output, degree of customer satisfaction, degree of learning, and level of costs. It is likely that operating criteria may not be totally congruent with strategic performance objectives. In this dissertation research, the strategic policy variables relate to capacity and production process investment policies which are evaluated based upon a market share performance criteria and operating variables concerning the levels of output, learning, and costs.

In summary, Figure 2 depicts a broad view of the firm and the characteristic management decision tasks. The purpose of this conceptual formulation is to show the macro interrelationships among the decision tasks characteristics at each management level and for the firm as a whole that should be addressed by strategic decision models. Therefore, one way of illustrating a particular model's relevance is by considering the important elements of strategic planning in terms of the firm in gestalt as well as in terms of nature of the individual decision tasks. Within this

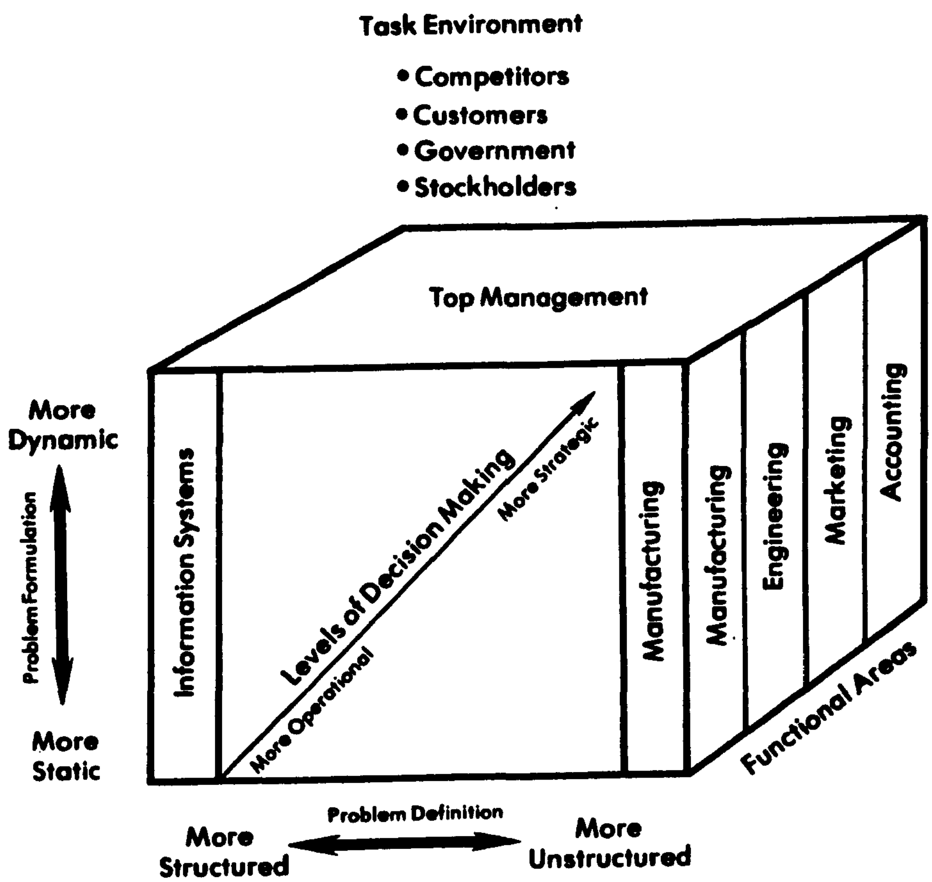

Figure 2. Integrated Model for Strategic Planning and Control

context, the organization is defined as a system of regularly interacting and interdependent groups of individual functional areas forming the whole. Demarcation of the functional areas should coincide with the actual organizational structure of the firm. Levels of management decision making are portrayed as diagonal slices permeating all functional areas.

Due to the interdependencies of the components, all planning activities should be viewed from a systems perspective. Boulden (1975) describes a strategic plan as a set of interdependent decisions of which each decision (a) is conditioned by both preceding and succeeding decisions and (b) imposes constraints on the stream of succeeding decisions with which it must be compatible and (c) is measured by the achievement of organizational goals. Steiner (1979) reports that strategic planning should link major types of planning activities: strategic, medium-range programs, short-range budgets and operating plans.

In Figure 2, it is also noted that management decision tasks may be characterized by both the degree of problem structure and the time focus of the problem formulation. Interpretation of the characteristics of the decision tasks is straightforward. At the lower end of the management activity continuum is operational control. At this level there are many predefined tasks which help insure that resources are used wisely. Since the tasks, goals and resources for operational control have been preestablished, much less judgment is usually required in their execution. Decision making is said to be more structured. Decisions are usually more myopic and narrowly defined to a specific problem area. These decisions tend to be more static in focus. They incorporate a high amount of detailed, accurate and current data and use more cross-sectional analysis, i.e., a wide variety of detailed data at a single period.

On the other hand, strategic decision making is characterized as being more unstructured and more dynamic. The unstructured decision areas are either those which are less amenable to structure or those which have not yet been scrutinized in depth to reveal an underlying pattern. For these reasons, managers will often structure subproblems which are known or manageable parts of the total problem in order to provide insight into the gestalt. (Buzacott and Yao 1983, Mintzberg et al. 1976). Furthermore, strategic decision making requires analysis of the time varying dynamics among the organizational goals, the decision variables and exogenous factors. Therefore, a more dynamic focus, is required in strategic decision making.

2.1.2 Strategy

The notion of strategy as a grand or broad scale schema for achieving the organization's goals and objectives is explored in this section. A strategy is a statement of important actions to be taken to improve the firm's relative performance by the allocation of limited resources to activities. A strategy is reflective of the firm's understanding of the impinging principal economic forces, the external changes requiring action and the role to be played by the firm and its competitors (Sherman 1982).

Competitive Strategy

Since competition is at the core of business success or failure, firms adopt a competitive strategy as a response to perceived opportunities and threats. A competitive strategy (a) requires the search for a favorable position in the industry and (b) aims to establish profitability and sustained market position against the forces that determine industry competition (Porter 1985).

Development of a competitive strategy mandates the firm assess the relative position of the competition as well as their own unique characteristics (Porter 1980, 1985). Taking stock of their relative position, a firm scrutinizes general business factors such as market share, revenue growth rate, market opportunity, industry maturity, and potential for improved profitability in the product line. In addition, the firm determines important business attractiveness measures including sales potential, competitor analysis, risk distribution and opportunities for restructuring the industry.

In order to ascertain its own distinct competitive advantage, the firm considers the company's strength factors. Strength factors include the technology base, in-house capabilities and resources, the availability of needed capital and raw materials, and the management skills (Wheelwright 1984). The firm's distinctive competence grows out of the "value" the firm is able to create relative to the costs. Value is defined as what the customer is willing to pay for the products and services offered and is a function over time of key relationships among the basic competitive forces in the industry, growth/market share holdings, the experience curve and the value-added at various stages of the overall production processes (Buffa 1984).

Out of value analysis three primary forms of strategy emerge whereby firms may achieve a competitive advantage: cost leadership, differentiation, and focus (Porter 1985). First, a cost leader strategy is followed by a firm which can offer lower prices than the competition. Cost leadership is predicated upon taking advantage of cost reduction sources including new technology, economies of scale and learning. Second, the differentiation strategy is pursued by firms seeking to be unique in some way such as offering higher quality or better service. Third, a focus strategy is undertaken by a firm which targets on a narrow market and meets the needs of this sector in a special way.

Linking these competitive strategic concepts to the choice of a manufacturing process technology is an essential ingredient of a strategic plan. For example, firms adopting a low cost posture will tend to choose production methods using specialized equipment that maximize production efficiency. Differentiation or focus strategies generally call for more general purpose equipment which does not offer the same production efficiencies as specialized equipment. Other firms may capitalize on new forms of process technology enabling competition on more than one strategic dimension simultaneously. In order to assist firms in choosing a manufacturing process technology strategy supportive of the firm's competitive advantage, the models of Chapters 3 and 4 incorporate a market responsiveness factor.

Scope of Strategy

Strategy is distinguished from tactics which are more specific and operational maneuvers. The crux of strategy is that it corresponds to the totality of the organization. It maps out how the organization intends to achieve its established objectives and goals. Underlying strategies should be sweeping enough to provide a lasting sense of direction for the company over the time frame of the strategic plan, yet specific enough to supply real operational guidelines (Ryans and Shanklin 1985).

In order to distinguish between strategy and tactics, it is useful to describe strategy by its characteristics. According to Wheelwright (1984) strategy may be characterized by activities (a) with a more long-term time horizon, (b) having a continuing impact on the firm after elapsed time intervals, (c) concerning a concentration of effort in terms of resources and focus, (d) showing a pattern of decisions across subareas of the firm and (e) which are pervasive in that they embrace a wide breadth of resource allocation.

The resultant strategic plan sets forth the firm's generic strategy which is comprised of four sets of decisions: (a) the mission and role of the business, (b) the definition of the business in terms of market and scope, (c) the interface with functional areas and (d) budgeting (Abell and Hammond 1979). These decision areas mesh with the three primary levels of strategy as elucidated by Wheelwright (1984): corporate strategy, business strategy, and functional strategy. Long-term effectiveness in goal attainment requires the alignment of the strategic priorities of each level to the total system (Judson 1984).

2.1.3 Levels of Strategy

In this section the three levels of strategy are defined. Figure 3 illustrates a conceptual framework depicting the relationships among the three levels of strategy which is the basis for this research. In particular, the dissertation research links the three levels of strategy in the following ways. First, corporate strategy is manifested in the effectiveness-oriented objective function which is maximized over the planning horizon. Second, the SBU strategy is reflected in a market responsiveness function. Third, the functional strategy is captured in the choice of manufacturing process technology which supports corporate and business unit strategy. The dynamic timing and sizing of new technology as a source of productive capacity is one part of the total manufacturing strategy. Acquisition of new manufacturing technology over the planning horizon is treated as a "challenger" to the existing (incumbent) productive capacity held by the firm.

Corporate Strategy

Embodied within the corporate strategy are the definition of the business in which the firm will participate, the acquisition of corporate resources, and the dominant business orientation. The dominant business orientation defines the business in terms of materials, markets and technologies to be used by the firm. The acquisition of corporate resources is normally concerned with acquiring financial capital and its allocation through capital budgeting procedures.

Since not all performance measures can be achieved simultaneously, corporate strategy involves making explicit tradeoffs among potentially conflicting objectives. Corporate

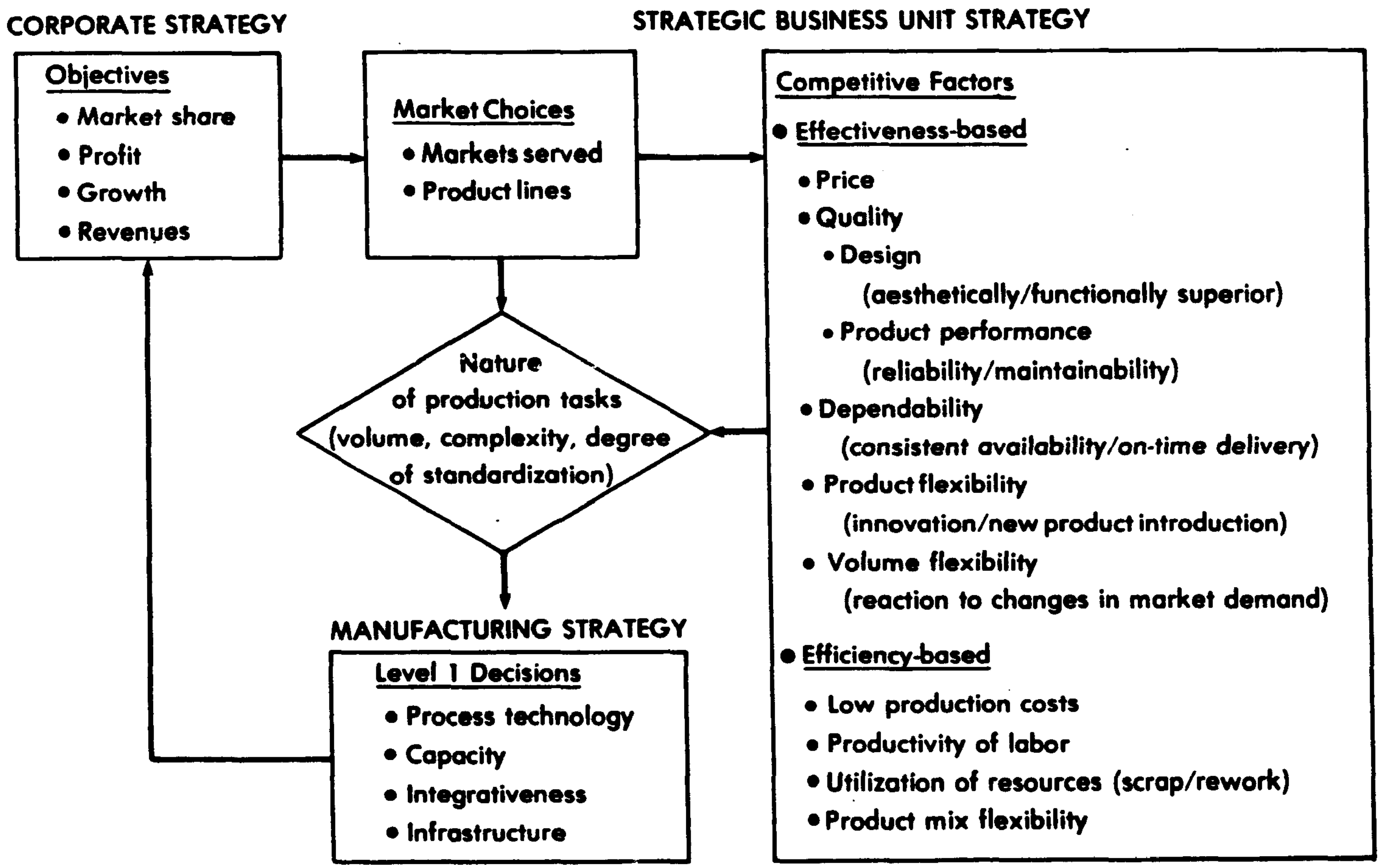

Figure 3. Manufacturing Strategy Framework

objectives are generally specified to reflect the overall financial well-being of the firm and are expressed by a limited number of key performance indicators such as market share, sales growth, return on investment and total revenues (Hax and Majlif 1984). Thus, the essence of corporate strategy is to achieve long-term sustainable advantages over the firm's competitors (Fine and Hax 1984).

Strategic Business Unit Strategy

Since the role of planning is so pervasive, it is increasingly important that strategy be formulated at the business unit or planning unit level. Business units or planning units are organizational entities which may differ in roles and objectives (Abell and Hammond 1979). They are usually regarded by corporate management as reasonably autonomous profit centers which may encompass several program units and/or functional departments (e.g., manufacturing, marketing and research and development). Program units may correspond to product lines, geographic market segments or units defined on the basis of some other strategic segmentation, dimension, or scope of activity.

The business unit strategy specifies the scope or boundaries of each strategic business unit (SBU) or strategic planning unit (SPU) in such a manner that it operationally links up with the corporate strategy. Corresponding to the product and market scope, the business strategy clarifies the customers to be served, the customer needs to be satisfied, and the technologies to be employed. Furthermore, the SBU/SPU strategy specifies the basis in which the unit will distinguish itself from its competitors. In other words, it determines how the business unit will achieve and maintain its competitive advantage. Examples of competitive strategies which a SBU may adopt are "low cost/high volume," "product innovation," and "customization" (Porter 1980).

Functional Strategy

A functional strategy is pursued in support of the competitive advantage delineated by the business unit strategy. It specifies how the functional areas will support the more global business strategy and how the area will complement the other functional units. The detailed functional area strategy requires that both an initial corporate strategy and a SBU/SPU strategy have been formulated.

Development of an effective functional strategy is an iterative process since the definition and mission of the business require assumptions about the functional strategy and the costs and benefits of various alternatives. Through each iteration, the tradeoffs among the competitive priorities and the competitive advantages sought should be evaluated in terms of the feasibility of functional area support.

Hobb and Heany (1977) report the necessity for all functional areas of the business unit to move in concert with the others and to be coupled with the strategic plans of the business unit and corporate level. The integration of the functional strategies with higher level planning represents an advanced phase in the evolution of formal strategic planning. In this advanced evolutionary phase of planning, all resources of the organization are orchestrated to create competitive advantages. Through a comprehensively chosen planning framework, a flexible planning process and a supportive systems climate are fostered (Gluck, et al. 1980).

2.2 MANUFACTURING STRATEGY

An effective manufacturing operation is more than one that promises maximum efficiency. Indeed, it is one that fits the needs of the business and one that strives for consistency between its internal capabilities and the business unit's competitive position.

As early as 1966, Skinner warns that manufacturing managers must react to external pressures due to new trends in the market place, increased competition, and new marketing pressures. In 1969, Skinner depicted the manufacturing function as either a competitive weapon or a corporate milestone wherein he describes the relationship between the firm's manufacturing function and the corporate need for survival, growth and profit. Manufacturing management should recognize the compromises or tradeoffs to be made with respect to variables such as cost, quality, delivery, technological constraints and customer satisfaction in the determination of plant and equipment decisions. Skinner advocated a top-down approach to manufacturing policy decision making which starts with the company and its competitive strategy.

Decision categories which constitute a manufacturing strategy are (a) capacity (amount, timing and type); (b) facilities (size, location, and focus); (c) product and process technology (equipment, automation, and degree of interconnectedness); (d) vertical integration (direction, extent and balance); (e) workforce and job design (skill, pay and reward system); (f) quality control (defect prevention, monitoring and intervention); (g) production planning and control operating decisions (computerization, decentralization and decision rules); and (h) organization (structure and reporting levels) (Wheelwright 1984, Buffa 1984, Wheelwright and Hayes 1985).

Items (a)-(d) above are generally considered structural or strategic because of their long-term impact on the firm, the difficulty in reversing the decisions, and amount of capital expenditures required. Hayes and Schmenner (1978) reported that production run decisions are small compared with decisions on process technology and capacity. To a large extent capacity, facility, process technology and vertical integration decisions must be in place in order to implement (e)-(h) above. It is also noted that these decision categories are generally interrelated with each other and with product and process design decisions. Therefore, it is not only necessary that the pattern of manufacturing policies be congruent with the capabilities required for an effective business strategy, and as natural extension to the corporate strategy, but also they should be consistent with each other over time (Hayes and Schmenner 1978). (See Figure 3.) In particular, two critical strategy decisions interrelated in this research are capacity decisions and production process technology decisions.

2.2.1 Capacity Expansion Decisions

Capacity expansion decisions primarily consist of determining the future expansion times, sizes and locations as well as types of production facilities. The typical objective function for a capacity planning problem is to minimize the discounted costs associated with the expansion process for a given pattern of demand over time. Typical costs considered in capacity planning are those due to expansion, idle capacity (underutilization), shortages for demand in excess of capacity, maintenance, and inventory. Constraints often associated with the capacity decisions include budgetary constraints and restrictions on the expansion size, and amount of excess capacity or capacity shortages permitted. Since production capacity requires substantial investment, careful planning of an expansion policy is of vital importance to the firm. In fact, poor capacity expansion decisions can severely affect the future viability of the firm (Buffa 1984).

A thorough survey of the capacity expansion literature which provides a useful framework of the subject from an operations research perspective is given in Luss (1982). In Luss's presentation three major issues in the capacity are addressed. First, the question of the relevant expansion size is treated. Expansion size may be assumed to be a continuous variable (i.e., the expansion size may take on any value) or it may be assumed to be of discrete sizes (chunks). In this research a continuous expansion policy is assumed.

A second issue pertains to economies of scale. Capacity expansion cost functions exhibit economies of scale. The explicit decision here is when to expand and how much in order to take advantage of scale economies versus the costs of having too much or too little capacity. Economies of scale are not considered in this research but are treated in the proposed future research covered in Chapter 5.

Third, the issue of the time value of money is critical because of the large planning horizons associated with expansion policies. Selection of the appropriate discount rate may have a significant impact on the optimal policy. The models in Chapters 3 and 4 include a discount factor which captures the impact on the optimal policies of the time value of money over the planning horizon. Related extensions are proposed in Chapter 5.

Other important factors in the capacity expansion decision as reported by Luss (1982) include (a) the nature of demand (deterministic versus stochastic and linear versus nonlinear), (b) the impact of operating costs as a function of the technology available at the expansion times, (c) the number of facilities involved, (d) consideration of inventory, and (e) the total replacement of existing facilities by new ones.

2.2.2 Production Process Technology

A process technology strategy refers to the firm's approach to the acquisition and implementation of technology in manufacturing. Because of the power of technological change to influence industry structure and the firm's competitive advantage, this research assumes the choice of a particular production process or mix of processes is an essential ingredient to the firm's overall competitive strategy. Since technology places bounds on the organizational structure, facilities and job design, the product mix, the product characteristics, and volumes are affected by the choice of a particular process or mix of processes. Technological change not only leads to improved products but also to new substitute ways of meeting customer needs. It also often leads to the identification and exploitation of previously unfilled needs (Abell and Hammond 1979).

Faced with ever increasing foreign competition and new marketing pressures, to an unprecendented extent today firms must compete on technological grounds (Hayes and Abernathy 1980). The choice of production process technology substantially impacts on such factors as delivery, timely introduction of new products, shorter product life cycles and wider product variety.

New manufacturing capabilities of variety, rapid responsiveness and flexibility are becoming the basis for new market tactics (Goldhar and Burnham 1983). Gaining competitive success through technological superiority requires investing more heavily in cutting edge process technology as both a source of productive capacity and as a proactive mechanism to create new product/service opportunities in advance of customer demand. Therefore, the key to long-term survival is to invest, to innovate and to create values where none previously existed (Hayes and Abernathy 1980, Cahn and Dumas 1981).

Gone are the days where the equipment decisions were merely replacement decisions for similar but deteriorating technology. Accelerating technology affects the "economies of scope" as well as scale. Economies of scope imply that a firm can produce a greater product variety at a given cost. Product design, quality, productivity, maintenance requirements, work in-process inventories, layout and infrastructure are to a great extent determined by the choice of the process technology (Skinner 1966, Skinner 1978). A new technology strategy is not without risk, however. Substantially higher investment costs are required than with more conventional equipment, and more uncertainty is introduced.

Traditional Production Technology

Traditional technology falls into one of two categories of equipment: (a) special purpose, fixed automation and (b) conventional, general purpose, semiautomatic (manually operated) equipment. Traditional types of equipment are often categorized by the work configuration of the manufacturing facility. Broadly speaking, companies can be divided into manufacturing firms which are typically identified with discrete item production and process industries which are represented by continuous flows of products such as chemicals, plastics and food products. Manufacturers of discrete items can further be classified on the basis of production volumes (batch size or length of production run) and work configurations into three groups: job shop, mid-volume batch production and mass production (Groover 1980).

Both the process industries and mass production manufacturers characteristically employ special purpose equipment. In particular, mass production facilities using traditional "hard" automation with fixed transfer paths are engaged in production of high volume, standardized products. While fixed automation systems are quite inflexible to product and process changes, the unit costs are low and quality is high.

On the other end of the spectrum is general purpose, semiautomatic equipment. This conventional equipment yields the maximum product flexibility since unstandardized, low volume, custom parts and products can be produced. Typically, job shops and batch shops use this conventional general purpose equipment. The "price" for this maximum product flexibility includes extremely high production costs, high in-process inventory costs and quality losses.

Strategic consideration of conventional process technology as a manufacturing process strategy has been explored by Hayes and

Wheelwright (1979b, 1980, 1984) via a product-process matrix. The central theme of their construct is that manufacturing processes undergo a process life cycle in much the same manner as do products. As product lines evolve from low volume, unstandardized items towards high volume, standardized ones, there are concomitant shifts in the production process strategies. Hence the evolution from job shop (intermittent) production to continuous flow production strategies is observable. Hayes and Wheelwright (1979) and Krajewski and Ritzman (1985) use the process-product matrix as a basis for operationalizing the firm's manufacturing strategy.

New Process Technology

A topic of increasing interest in manufacturing management is the degree to which new factory automation should be employed in the production process. According to Groover (1980), automation is defined as technology which follows an evolutionary course of development and which is particularly concerned with the application of complex mechanical, electronic and computer-based systems in the operation and control of production processes.

New production technology falls into two main categories. First, there is technology which does not directly produce output (product) but rather enhances the productivity of labor (Gaimon 1985c). Examples of this technology include computer-aided design (CAD), computer-aided manufacturing (CAM) and computer-integrated manufacturing (CIM) (Groover 1980).

Second, there are new process technologies which directly produce or assemble output (Groover 1980, Skinner 1978, Buffa 1984). These include (a) numerical control (NC), single machines under computer control; (b) flexible machine cells (FMC), a group of NC machines or a computer controlled machine center with automatic feed, load, and unload; (c) flexible manufacturing systems (FMS), a system of several machine centers with automatic loading linked by automatic materials handling and transfer; and (d) robots, programmable machines for handling and assembling objects.

The importance of the new manufacturing technologies is that they change the economies of manufacturing to economies of "scope". In particular, for flexible automation, new technology reduces the importance of economic batch sizes since there is a significant reduction in setup and changeover times.

2.2.3 Manufacturing as a Competitive Force

In order to understand how the manufacturing function serves as a competitive force, it is important to understand the nature of demand. Market demand analysis requires a delineation of the market boundaries and how they are changing, an assessment of present and future buyer concentration and a projection of demand for the entire firm. The supplier of the product or service must then consider the character of the competition and the value-added changes to the product or services which provide distinctive competence.

Firms may employ a "selective" stimulation strategy wherein the emphasis is placed on satisfying the needs of a particular customer segment better than the competition. This selective stimulation may be carried out through the marketing department's advertisements, promotions, channels of distribution, price and other product tactics. However, in this dissertation research manufacturing is also assumed to play a key role in selective stimulation of demand. This role is captured by a market responsiveness factor which corresponds to the relative impact of the firm's enhanced capacity due to acquiring new technology and learning on the market. Manufacturing can match its functional strategies of capacity and process technology with product strategies based upon two criteria: consistency with the overall business strategy and emphasis on prioritizing tradeoffs in performance objectives (Hill 1983, Wheelwright 1984).

In order to achieve a competitive advantage in the market, manufacturing strategy should support one or more of the competitive factors corresponding to the firm's distinctive competence: cost, quality, dependability, flexibility (Buffa 1984, Wheelwright 1978, Miller and Van Dierdonck 1980, Stobaugh and Telesio 1983). (See Figure 3.) When price is viewed as the competitive weapon in the market place, cost is the variable which can allow firms to lower prices and remain profitable. Competition on the basis of price requires manufacturing select the location, product design, equipment and process technology on the basis of efficiency related criteria in order to lower the product costs. Furthermore, it suggests consideration of learning and organizational experience be considered (Wheelwright and Hayes 1985, Hayes and Wheelwright 1984).

Consideration of quality in the product design (aesthetically sound and functional) and product performance (reliability and maintainability of the product) also affords a basis for competition. Customers are often willing to pay a premium for quality enhanced products or services such as extended warranties.

A manufacturing entity capable of producing at a prespecified quality level consistently has a competitive advantage over those firms without such capabilities.

Dependability in delivery or off-the-shelf availability is important to some customers, and therefore, dependability is another competitive dimension. Also included in the concept of dependability is timely delivery of products.

Of growing importance as a competitive edge is flexibility: product and volume. Competency with respect to product flexibility is characterized by the degree to which new product and other product innovations can be introduced and the degree to which the relative mix of products can vary. Volume flexibility corresponds to the capability of the manufacturing system to react to changes in market demand (volume changes).

2.2.4 The Manufacturing Experience Curve

The strategic advantage of learning and in particular technological progress (experience) in manufacturing is well covered by Porter (1985), Abell and Hammond (1979), Wheelwright and Hayes (1985), Hayes and Wheelwright (1984) and Buffa (1984). More technical discussions of learning and technological progress are detailed in Conway and Schultz (1959), and Day and Montgomery (1983) and Yelle (1979).

Original efforts in the study of manufacturing improvements due to learning deal primarily with the operator or worker learning. Productivity and cost improvements are now recognized as resulting from a wide variety of additional sources. Organizational learning connotes the totality of the progress of an organization which learns to do a better job through changing the tasks of individuals and modifying the management and production processes. Through the total organizational experience, the product costs decline, productivity improves and capacity expands at a steady rate every time the cumulative production volume doubles.

Sources of organizational progress or experience (learning) stemming from technological change are considered in the model of Chapter 4. In fact, Porter (1985) asserts that technological change is the basis of the learning curve. Learning curve results occur due to a multiplicity of improvements including tooling changes, new methods, product design, system utilization, quality, management, and operator training. (Conway and Schultz 1959, Hayes and Wheelwright 1984, Buffa 1984, Porter 1985).

Thus, organizational experience or technological progress effects are attributed to the sum total of all production efficiencies due to (a) improved performance in the production equipment and learning by doing, (b) technological improvements derived from new product specifications and (c) new production process technologies and (d) economies of scale.

The strategic implications of the organization's experience curve relate to market share, product and process technology improvements and the margin paradox (Buffa 1984, Hayes and Wheelwright 1979a, 1984). Technological progress explains why firms with higher market shares tend to be more profitable in terms of return on investment than lower market share competitors. Firms that aspire to the role of market leader role will produce the largest cumulative number of units and can take advantage of the learning phenomena to produce at the lowest cost. Lower costs, in turn, support market responsiveness to larger volumes and higher profits. On the other hand, firms which choose a quality differentiation strategy may also benefit from learning by doing and thereby enhance their market niche with even higher margins.

Technological progress impacts strategically on the choice of product and process improvements which serve to reinforce the firm's competitive position. While the firm's own experience curve is cost-based, it is not necessarily parallel with the total industry accumulated experience upon which the industry price experience curve is predicated. Therefore, knowledge of the firm's own cost-based experience curve and the industry price-based experience curve serves to portray available options to the firm. For example, when the difference between the industry price curve and the firm's cost curve are no longer parallel, the firm may select a short-term strategy to maximize current returns by holding price constant even though costs are reduced due to organizational learning in excess of industry learning. On the other hand, firms may begin to reduce price to insure long-term profitability even though their cost curve exceeds the total cost industry curve.

The margin paradox supports the contention that a given business may be increasingly more profitable for one firm while not at all profitable for another. Buffa (1984) cites the example where the aggressive and efficient West German and Japanese steel industries invested heavily in improved process technology to exploit their improving margins. This effort served to further reinforce their competitive advantage and placed them steeper on the experience curve than their U.S. competitors. In contrast the

U.S. steel companies were slower to forge ahead with the investment in new process technology and their market share and margins diminished accordingly.

2.3 FLEXIBLE AUTOMATION AS A COMPETITIVE WEAPON

A key to a firm's strategic advantage is the new flexible manufacturing process technologies such as flexible manufacturing systems FMS (Skinner 1984, Davis et al. 1985). Incorporating many individual automation concepts and technologies such as (a) automated materials handling between machines, (b) numerical control machine tools and computer numerical control, (c) computer control over the materials handling system and machine tools (direct numerical control) and (d) group technology, an FMS is capable of processing a variety of different part types simultaneously.

Recent literature ascribes benefits to this new manufacturing technology when it supports the strategic business unit (SBU) strategy (Buffa 1984). In particular, FMS technology is deemed to have the greatest potential applicability in increasing the competitive advantage in mid-volume, discrete parts manufacturing firms (Stecke 1981, Groover 1980, Jaikumar 1984, Buffa 1984). It has been estimated that 75 percent of all parts manufacturing is produced in lots of 75 pieces or less (Starr and Biloski 1983).

Clearly, batch manufacturing entities must handle a large and ever-changing variety of items. The conventional batch manufacturing environment is typified by low machine utilization due to high setup times and bottleneck operations, and by requirements for highly skilled labor in the operation of semiautomatic, general purpose equipment.

Through the use of microprocessor computers and machine tools, FMS introduces more flexibility and versatility in batch production processes. With FMS capability, discrete parts manufacturers can make product changeovers more quickly and inexpensively with less direct labor utilization. Furthermore, the FMS technology makes batch operation with mid-volume, customized, short production run products function more like the long-run, high volume, continuous flow lines. FMS require substantially lower setup times and less work in-process inventory than conventional batch production technology. Therefore, while there exist several different forms of flexible systems, an FMS is designed to attain the efficiency of a well-balanced, machine paced transfer line while incorporating the production flexibility of a job shop to simultaneously machine multiple part types (Browne et al. 1984). The competitive opportunities ensuing from FMS are (a) increased product and process flexibility, (b) improved product and process quality, (c) production cost improvements, (d) reduced manufacturing and delivery lead times, (e) increased market responsiveness, and (f) product design excellence.

The manufacturing improvements associated with added production efficiencies are reduced (a) production plus in-process inventory costs, (b) floor space requirements, (c) materials costs, (d) materials handling, and (e) direct labor costs. Improved quality and information networks for managerial planning and control are also observed (Skinner 1984). For these reasons, this new production process strategy affords the opportunity to compete on several grounds simultaneously (such as quality and cost), which is required in the new industrial competitive arena (Abernathy et al. 1981).

2.3.1 FMS Decisions

According to Skinner (1978), the introduction and use of complex automated equipment in manufacturing requires that it not be undertaken without extensive planning. More is involved than the implementation of a new production process strategy (Graham 1985a, 1984). The technology decision entails a total systems approach involving the scrutiny of a complex network of social and technological factors with economic and strategic payoffs.

Sarin and Wilhelm (1983) provide a framework for systematizing the types of decisions that have to be identified with the design, justification and operation of the FMS. Within this framework, four levels of decisions would typically be made according to the level of management and length of planning horizon. Gershwin et al. (1984) provide an overview of a control theorist's perspective and applications by level of decision making in manufacturing systems.

The first level of decision making is "strategic analysis and economic justification." (See Figure 4.) Plans to adopt FMS and to replace existing conventional operating capacity with flexible automation constitute first level decisions because (a) the planning involves long implementation lead times, (b) significant amounts of capital and resources must be committed, and (c) a high degree of risk is involved. Namely, there are risks with costs, general economic conditions, and volume variability subject to

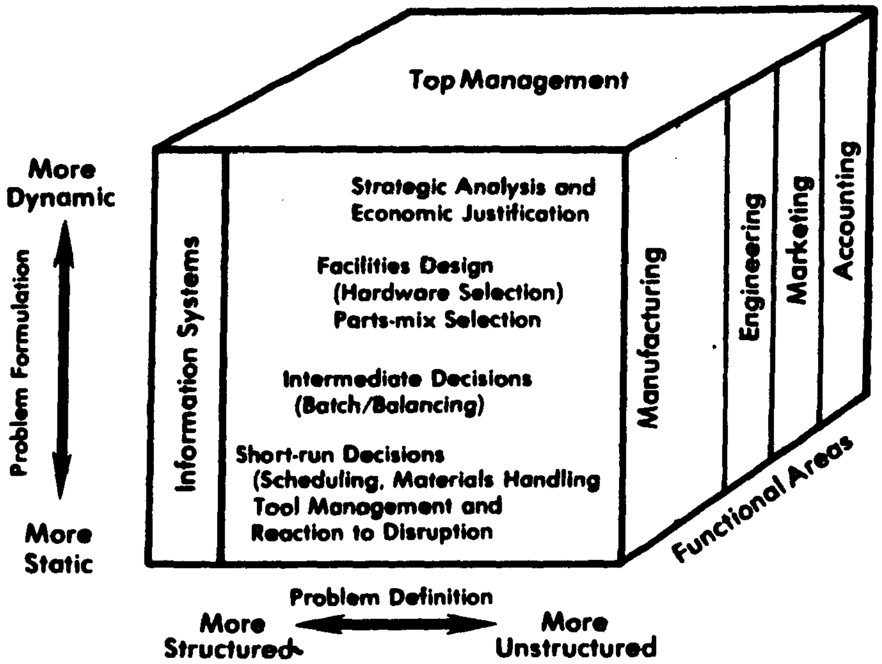

Figure 4. FMS Decisions

future sales and future product lines.

The other levels of FMS decisions are more operational and tactical in nature. The FMS design problem describes the capacity of material handling systems, the number of machine tools of each type, and the size of the buffers. The FMS operational planning activity determines the allocation of parts to pallets, fixtures and machine tools as well as the assignment of operations and cutting tools among the limited capacity tool magazines. The FMS scheduling problem concerns the sequencing of parts and continuous monitoring of the system (Stecke 1984). Figure 4 characterizes the levels of FMS decisions in a firm according to the generic integrated model for strategic planning and control portrayed in Figure 2.

2.3.2 Barriers to FMS

Given the potential benefits of FMS, barriers to widespread adoption remain (Kinnucan 1983, Brody 1985). First, there exist technological constraints for integration of individual FMS components. Second, there is a lack of expertise in most firms with this new technology. Current FMS appear to lack true flexibility and technical uncertainties due to inexperience with the technology. Third, there are inherent risks associated with the technology. The benefits of the technology are difficult to quantify and are long-term in nature. The lead time to set up the FMS may be 5-6 years. Fourth, substantial investment costs are warranted. Fifth, the fear of change in the organization and organizational inertia impede progress.

It has been reported that the cost of FMS is in the tens of millions of dollars (Brody 1985). Since it is estimated that 87 percent of discrete part manufacturers employ 50 or fewer persons, it is reasonable that such a multi-million dollar investment places FMS outside the reach of all but the largest manufacturers (Kinnucan 1983).

2.3.3 Radical Versus Evolutionary Adoption

There are two general approaches to integrating the new manufacturing facilities: radical and evolutionary (Ettlie et al. 1984, Gaimon 1985c). Consideration of the radical (or revolutionary) approach entails a dramatic changeover from the old to the new production processes. Illustrative of radical changeover processes are total retooling of an entire facility or an expansion of the technology to a large segment of the existing facility.

On the other hand, an evolutionary approach calls for a structured, incremental adoption process. Specifically, a planned and gradual renewal of the existing facility through the continuous introduction of the new technology constitutes an evolutionary approach. Because of the barriers defined in Section 2.3.2, the radical approach results in a substantially higher technological risk and a higher initial capital expenditure spread over a shorter time period than the evolutionary approach. The continuous introduction of technology also allows for the planned changes in the infrastructure which are a necessary prerequisite for a successful FMS (Herroelen and Lambrecht 1984).

While there will be some firms which choose a radical approach for the adoption of new technology, many firms will select an evolutionary strategy (Barr 1982, Kinnucan 1983). The models presented in Chapters 3 and 4 capture an evolutionary timing strategy wherein islands of automation or machine tool modules are acquired continuously over time. An evolutionary timing strategy facilitates the acquisition of FMS in stages such as beginning with an NC tool, adding another tool, grouping tools into machine cells, adding direct numerical control computers, adding the material handling system and so on (Kinnucan 1983). It is assumed the acquisition of modules helps mitigate the problem of large capital outlays as well as enhances the firm's control over the required system and organizational changes. Furthermore, as the individual modules are integrated into the plant, it is assumed that value is added to the products and services resulting in greater benefits to the firm.

2.3.4 FMS Justification Issues

The performance evaluation criteria for FMS must address both tangible and intangible decision factors. Acquisition decisions should lead to the realization of prime benefits of the FMS and their impact on the firm's competitive position. Often these benefits are neither easily quantifiable nor are they normally included in traditional capital budgetary techniques (Arbel and Seidmann 1984, Schmenner 1983, Starr and Biloski 1983). In fact, Hayes and Abernathy (1980) report that one cause of the lack of U.S. competitiveness is due to short-term cost reduction positions rather than the development of technological competitiveness. Myopic measures such as return on investment and payback, difficulties in quantifying benefits due to absence of historical cost/benefit data, and preoccupation with portfolio management are reasons for the reticence of U.S. manufacturers to investment in new flexible technology (Michael and Millen 1984).

One of the most comprehensive and insightful analyses of the unique problems associated with justifying new manufacturing technology is provided by Gold (1982a,c). Gold states that the effects of the new technology are more pervasive than the continuing flow of incremental improvements to the production environment, but rather the contributions are likely to keep increasing for extended periods of time beyond the initial installation due to (a) organizational learning and (b) rapidly advancing improvements in the technology. In Chapter 4, the strategic planning model captures the benefits of technology beyond the initial installation. Note that technological improvements are covered in the formulations of both Chapters 3 and 4.

Long-term strategic concerns ought to play a role in the decision to procure a new manufacturing technology (Wheelwright 1978, Storbough and Telesio 1983, Goldhar and Burnham 1982, Jelinek and Goldhar 1984) and require additional criteria beyond traditional measures for evaluation of equipment itself. A key criterion for an FMS decision is how the firm increases (or even holds) its market share against competitors (Williams and Tuttle 1984). FMS evaluation decisions should incorporate a wide range of benefits, over a longer time horizon with consideration of the strategic competitive thrust available due to economies of scope.

Herrolen and Lambrecht (1984) discuss the need to link technology-push strategies with global business strategies and the FMS decisions. A good FMS investment decision analysis includes: (a) re-examination of the risk premium from adoption of the new technology investment, (b) consideration of the installation of flexible automation as a dynamic time phased continuous process in which capital outlays will be spread over a longer time horizon, (c) assessment as to what would happen to the firm if the company decides not to invest in the flexible automation, and (d) consideration that production decisions impact on market share, and therefore, are more pervasive than efficiency-oriented measures alone.

FMS is more than a technology and production process strategy. It is a demand-pull strategy in that it has the potential to increase market share. Based upon empirical study, Starr and Biloski (1984) reported that FMS are adopted for other reasons than cost-effectiveness, namely quality and flexibility. Potential product quality improvement is one important intangible factor in FMS justification decisions. Use of computer controlled FMS technology increases both the precision and standardization of the output to its specifications. Customers perceive the product quality improvement in (a) consistency between parts and (b) reliability reflected in more generous warranty policies. Thus, the value-added product is due to the manufacturing improvements derived from flexible automation.

Intangible benefits from FMS flexibility are (a) the firm's heightened ability to rapidly and inexpensively change the output mix and (b) its improved responsiveness to demand fluctuations. The combined benefits of flexibility and quality improve the product attributes and thereby enhance the competitive position of the firm. This enhanced capability serves to stimulate marginal customers and increases the demand rate of existing customers (Starr and Biloski 1984). This dissertation research recognizes that the market is responsive to the enhanced outputs of FMS and as such is a competitive weapon in stimulating selective demand. As mentioned earlier, the modeling approach in Chapters 3 and 4 specifically include a market responsiveness function in the formulation.

2.4 RELATED RESEARCH

In order to address the problem of strategic decision making for the choice of a manufacturing process technology, the perennial and often most controversial problem is to select among alternative production processes (transfer line, general purpose equipment and flexible automation). The selection process must (a) evaluate the economic and intangible benefits relative to the costs and (b) determine the optimal timing of the proposed technological changeover.

The dynamic optimal changeover process involves policy formation with respect to the sizing of incremental purchases of new flexible automation over time as well as to increases and decreases in output from conventional process technology. The objective of the manufacturing process technology policies are to support the SBU strategy, and thereby maintain the long-term effectiveness of the firm.

The design of a manufacturing process strategy is complicated by the dynamic structure of the industry in which the firm operates and the markets served. The problems involve multiple variables which are typically interrelated. Quantitative tools of analysis are required when the complexity of the problem precludes the decision maker's capacity to understand the simultaneous accounting of the interrelationships among variables over time.

The value of normative dynamic models, as depicted in this research, in the formulation of strategy is that it allows the decision maker to address these complex relationships so that unexpected and counterintuitive prescriptive results may be further examined (Buzacott and Yao 1983). It is noted that even with the aid of a decision tool, the manufacturing process strategy formulation is problematic due to several factors. First, quantifying the policy in terms of goals and constraints over the planning horizon in a precise manner may be difficult. Second, obtaining data for the models often poses problems. Third, once the model has been specified and solved, experience indicates that generally two conditions may prevail: (a) the new technology offers very substantial benefits and there is no question of the optimal timing, or more likely, (b) the optimal timing for the changeover to new technology is sensitive to certain input parameters in which case the selection of specific assumptions about the dynamic decision environment may significantly affect the optimal policies.

In this section, the methodology upon which the dynamic decision models in Chapters 3 and 4 are premised is described and justified. Additionally, related modeling literature is reviewed in terms of the dissertation research.

2.4.1 Methodology

Recent developments in manufacturing management are making the needs for long-range planning and control more urgent. These developments include (a) changes in the market and economy; (b) technological complexity; (c) the rapid rate of change, increased size and complexity of decisions; and (d) larger consequences and broader scope of decision making (Bensoussan et al. 1974). Clearly, the determination of an appropriate manufacturing systems process strategy must incorporate the controled deployment of resources to enhance the firm's goal attainment.

Consideration of the long-term manufacturing process policy formulation involves at least a primitive understanding of the firm as a system. In this broad scale planning context, it is required only that the system be capable of existing in various states, the changes of which are represented by a set of differential equations. For example, if the level of market share attained by the firm at time t is a state variable, then the change in the level of market share over time can be ascribed to variables which (a) are under control of the firm (policy or control variables), (b) account for the previous state of the system and (c) consider other exogenous factors. Assuming that there are ways to impact on the states of the system, the firm may apply control policies which may act to dynamically regulate the behavior of the system. Control policies (variables) are expressed as rates of change while the state variables are given as levels or amounts.

In summary, the general control problem specified in this research consists of (a) a set of differential equations with known initial or terminal time values that represent the instantaneous rates of change in the state variables (or system to be controlled), (b) a set of constraints on the state and control variables which define the range of possible values these variables may take at time t, and (c) an objective function (performance index) which is to be maximized. Given a formulation with an objective function specified as an integral over a given planning horizon and with a system of state equations which are represented by a set of differential equations, the appropriate solution technique is optimal control theory. More detailed mathematical developments of control theory and management applications of the theory are found in Sethi and Thompson (1981), Tapiero (1977), Kamien and Schwartz (1981), Sage (1977), and Bensoussan et al. (1974).

Optimal control theory solutions provide the actions or policies which may be taken by the firm in order to control the evolution of a system over time. From the perspective of maximizing a performance index over a given planning horizon, most management applications of control theory to date are oriented towards decision making and planning. For this reason, it is judged by the author to be an important decision aiding tool for policy assessment in management and is particularly adept to analysis of manufacturing policy formulation under a variety of scenarios.

Background

Briefly, optimal control theory is an extension of the calculus of variations. The calculus of variations problem is to derive values of decision variables over time subject to the objective expressed as an integral function of dynamic decision variables (Sethi and Thompson 1981). Problems in which boundaries exist on decision variables are reasonably difficult to solve using the calculus of variations approach. However, often those bounded variables can be translated into control variables as opposed to state variables and solved easily using optimal control theory. It is this feature of control theory that distinguishes its usefulness from calculus of variations.

The roots of optimal control are twofold: developments in the United States stemmed from the theory of dynamic programming beginning with Bellman's Principle of Optimality (Bellman 1967). About the same time in the Soviet Union, a different theoretical approach, the Pontryagin Maximum Principle, was developed. The primary contribution of Pontryagin's work is the proof of the maximum principle for optimal control problems. In effect the maximum principle permits the decoupling of the dynamic problem over a specified planning horizon into a series of problems holding at each instant of time (Sethi and Thompson 1981). The collection of the optimal solutions to the instantaneous problems provides the optimum solution to the problem defined over the entire planning horizon.

There are two important considerations to note about the Pontryagin Maximum Principle: (a) the principle provides only the necessary conditions for optimality, and (b) it does not yield a computational procedure for determining the adjoint functions (Thompson 1969).

It is also noted that optimal control models provide solutions which give information not only in terms of the optimal policies derived but also in terms of the marginal value of scarce resources over time in a manner analogous to that provided by "shadow prices" in linear programming problems. In particular, adjoint variable functions (marginal value functions corresponding to each state variable) are derived in the model. The adjoint variable functions depict the change in the objective function associated with small changes in the state of the system over time.

Approaches to Control Theory

Approaches to modern contrcl theory correspond to two primary dimensions of analysis: (a) continuous versus discrete and (b) deterministic versus stochastic. Whenever the control and state variables can be approximated as piecewise continuous functions over time, continuous control theory is applicable. In this case, the system is described by a set of ordinary differential equations. One important variant of continuous control theory called impulsive control theory is also noted here. In impulsive control methodology, a finite change in the value of the state variable is explicitly permitted at any instant of time over a continuous planning horizon where the time of the impulse may also be a decision variable. Alternatively, under discrete control, the control may be applied over fixed time intervals. In discrete control, the system is denoted as a set of difference equations and the objective is summed over fixed, discrete time increments. With reference to stochastic versus deterministic control theory, the former suggests that measurement uncertainty or noise is present in the model, while in the latter case no noise is assumed to exist (Sage 1977).

In the current research, the choice of a continuous optimal control model has been made due to the desire to implement an evolutionary technology adoption strategy as specified in Section 2.3.3. Furthermore, at the broad scale strategic planning level, the author believes it is reasonable to approximate the discrete timing strategy concerning the shift in the mix of productive capacity with a continuous function. At the strategic level of analysis, the decision aiding model is developed to provide only additional insight about the problem and not to provide solutions to be followed exactly. If it were assumed that the firm adopt a radical timing strategy wherein the changeover process to the new technology is abrupt and discontinuous, such as in the opening of a new section of the plant or a new facility altogether, then an impulsive control formulation would be a more appropriate tool. In Chapter 5, the radical (discrete) adoption strategy is described as a future research extension.

The choice of specifying and solving a completely deterministic model as opposed to a stochastic model is not as clear cut. Note that an attempt to include a complete treatment of the random nature of the system would be extremely difficult. Stochastic control introduces into the problem more reality at the expense of mathematical and computational complexity.

In consideration of the practical tradeoffs between stochastic and deterministic approaches, the deterministic formulation was adopted in this research. In order to capture the relative variation in the exogenous input parameters as they impact upon the optimal policy, sensitivity analysis is performed on the formulations of Chapters 3 and 4. Research in optimal capacity expansion under uncertainly with very restrictive assumptions is underway (Davis et al. 1984). However, Davis et al. indicate that there is a strong inverse relationship between stochastic control model complexity and computational tractability. Thus, elaborate stochastic capacity expansion models may not only lead to severe computational problems but also may hamper the comprehensibility and interpretability of the results.

2.4.2 Related Modeling Research

Related research on the optimal introduction of new technology falls into two major categories: those considering the strategic implications of the optimal investment decisions and those only concerned with the more traditional approaches. Traditional modeling in capacity expansion and technological acquisition typically treat the problem of trading off the fixed costs and savings in operating costs due to the innovation. Included in this section is a summary of relevant literature employing normative (generative) techniques and models as opposed to evaluative (descriptive) methods (Gershwin et al. 1984). In the normative approach, a set of decisions are derived given a set of criteria and constraints. An evaluative technique takes a set of decisions and assesses the performance of the system under those decisions.

Traditional generative techniques consider the long-term dynamics of the decision framework. In the context of optimal capacity expansion and timing for the introduction of new technologies, mathematical techniques of dynamic programming and more recently, optimal control theory have been applied. The constraints involved in the mathematical programming problems can be very complex as more realities are modeled.

Applications of dynamic programming to capacity expansion have been a popular approach in the operations research literature (Luss 1982). More recently, Luss (1984) presented a deterministic multiperiod capacity expansion model in which a single facility simultaneously serves the demand for many products. The problem entails determination of the optimal capacity expansion increments that should be undertaken in each period over a finite planning horizon such that the total costs are minimized. Relevant costs included in the model are capacity expansion costs, idle capacity,inventory holding costs, and capacity shortage costs. Luss's (1984) model extends the classical dynamic Wagner Whitten lot size model and other variations of approaches taken by Florian, Love, Manne and Veinott and Zangwill. The model is solved using dynamic programming.

Klincewicz and Luss (1984) examine timing decisions for introducing new technology facilities. Considering the relative tradeoffs between fixed facility setup costs and savings in operating costs resulting from new technology, this paper addresses the issue of technological changes within a single capacity expansion framework. It extends the work of Hinomoto who provides a more general but more complex and less easily implemented model. Klincewicz and Luss (1984) examine the optimal timing decisions under conditions of derived linear and nonlinear demand. The decision variables considered are the demand quantities to be assigned to each of the facility types in each period.

Starr and Biloski (1984) give strategic consideration to the adoption of new FMS technology and its effects on organizational size. Their paper enlarges the scope of the decision model required to evaluate an FMS beyond consideration of production cost savings alone. Starr and Biloski's theoretical model is premised on a nonlinear breakeven analysis which purports to capture quality effects and market responsiveness at a single period in order to derive the optimal output volume (capacity) for an FMS.

Related research using optimal control theory is now presented. Vickson (1985) treats the optimal conversion from old to new production techniques when the new technique is governed by learning curve behavior. The objective is to minimize the cost of converting production from the old to the new method. It is assumed that the new production method is already owned by the manufacturer. A second formulation in Vickson (1985) considers the optimal time at which to invest in new production facilities given an exogenous price and demand level. Both models are solving using optimal control theory. In contrast to Vickson (1985), the formulations in Chapters 3 and 4 capture demand as a decision variable in the technological adoption process. Furthermore, learning is captured through reductions in the production costs in Vickson (1985) whereas in the formulation of Chapter 4, learning is captured through both reductions in the per unit production costs and through capacity expansion. In addition, in this research the learning factor is modified as further acquisitions of technology are acquired and provide system synergy.

The optimal dynamic mix of manual and automatic productive capacity has been derived assuming a radical (discrete) (Gaimon 1984b, 1982b) and an evolutionary (continuous) (Gaimon 1985a,b,c, d; 1984a; 1982a) timing strategies. In Gaimon (1982b), the model derives the optimal dynamic mix of output achieved manually and directly by new acquisitions of automation. Over the planning horizon, the levels and discrete impulse times of purchases of automation are computed as well as the planned continuous rates of increase and reduction in manual output. The objective is to minimize the costs of (a) deviating from planned levels of output, production, and changing the composition of productive capacity. The model in Gaimon (1984c) extends this model in two ways: (a) the per unit production cost associated with output from automation is reduced impulsively through the purchase of automation, and (b) the levels of acquisitions of automation are optimally determined. These models are solved using impulsive and continuous control theory techniques.

Reflecting a dynamic decision environment wherein an evolutionary timing strategy is depicted, the formulation in Gaimon (1982a) dynamically derives the optimal mix of automation and manual labor. Dynamic adjustments are made in the level of automation continuously over time. The objective of the model is to minimize the costs due to changing the level of production and the penalty costs associated with the deviation between actual production and goal levels of demand over time. It is assumed that the magnitude of reduction in the per unit production plus in-process inventory cost at a particular time due to purchase of automation at that time is not related explicitly to the level of automation accumulated through that time. The model in Gaimon (1985d) extends this formulation by assuming that the level of accumulated automation at any instant of time impacts explicitly on the magnitude of reduction of the per unit production plus in-process inventory costs (i.e. diminishing returns to scale).

Rather than acquiring automation to produce output directly, Gaimon (1985c) presents a model which determines the optimal mix of automation and labor for technology which enhances the productivity of the organization's workforce. Cost factors considered in the objective function are those due to future long-term goal level of output, maintenance costs of labor and automation, and costs of changing the level of workforce and automation.

In Gaimon (1984a) a model is introduced which examines the effect of acquiring new technology on the dynamic price, production level and capacity for a profit maximizing firm. It is shown that since it is assumed that the new technology serves to reduce the per unit cost of production, purchases of technology act to reduce the optimal price, and hence, increase the demand. In Gaimon (1985a), this formulation is extended by the assumption that automation also acts directly to increase demand due to expanded product mix and volume capabilities.

With the exception of Gaimon (1985a,b and 1984c) and Starr and Biloski (1984), the above normative research does not consider the importance of flexible automation as a competitive weapon which serves to increase the competitive position of the firm. More explicitly, the impact of stimulating demand due to the value-added nature of the output (economies of scope) from the enhanced productive capacity is not considered explicitly. The work of Starr and Biloski (1984) is limited in that it is a static approach whereas the current research in this dissertation is dynamic. Furthermore, the current research endogenously determines the optimal levels and timing of market position and productive capacity which maximizes the long-run effectiveness (net worth) of the firm.

In Chapter 3, the model derives the optimal dynamic mix of flexible and conventional technology to be employed over time. Technological progress due to organizational learning as a source of enhanced productive capacity and system synergy is captured explicitly in the formulation of Chapter 4. In Chapter 4, the optimal acquisition and reduction of existing capacity may occur simultaneously over the planning horizon so that modifications in both the level and composition of the means of production are made to maximize the long-run strength of the firm.

In both models (Chapters 3 and 4) the dynamic optimal levels of market share (demand) are derived under the assumption that the enhanced productive capacity due to new acquisitions of flexible technology stimulate demand. Thus, the strategic impact of acquiring flexible automation is captured since its anticipated effect on future demand is explicitly considered in light of SBU planned goal levels. Furthermore, the models in this dissertation research capture the relative efficiency of the new flexible production technology in reducing the per unit production plus in-process inventory costs.

2.5 SUMMARY

In order to motivate the dissertation research models presented in Chapters 3 and 4, the literature review in this chapter addresses four main topics: (a) strategic planning, (b) manufacturing strategy, (c) FMS as a competitive weapon, and (d) related modeling research.

2.5.1 Strategic Planning

Two major concepts considered are strategic decision making and strategy. Concerning the utility of developing normative models to assist in planning activities, a decision making framework guides the focus of the research towards the nature of strategy and strategic planning in contrast to other levels of decision making. Differentiation among the levels of decision making reflects fundamental differences in the decision requirements at each level. These differences emerge primarily as a result of assessing the nature of the problem and its characteristics. They illustrate the need for decision support tools to help partially formulate subsets of the complex planning problems so that the impact of strategic decisions and their tradeoffs over the long-run may be evaluated. Also, strategic decision models reflect the impact of policy on the global, more aggregate picture of the enterprise in a dynamic environment.

Portrayed in the conceptual framework is the notion of strategic planning as a dynamic concept for analyzing evolving organizational goals and objectives. The performance criteria tend to be effectiveness-oriented and the problem definition tends to be more ill-defined, complex and unstructured. Therefore, efforts such as the models given in Chapters 3 and 4 which (a) aid in the delineation of objectives and (b) assist in the determination of the relative strategic tradeoffs among competing objectives vying for limited resources can be extremely valuable for policy guidance.

The essence of strategy and strategic planning is to at least partially structure important subsets of the problem so that different scenarios about the future may be evaluated. Therefore, in light of changing and uncertain environmental conditions, alternative courses of action can be proposed. The models presented in Chapters 3 and 4 support strategic decision making because they incorporate the following concepts:

(a) salient strategic and operating variables which take into account the long-term effectiveness of the firm;

(b) the capability to evaluate the relative tradeoffs required among competing objectives, and in particular, between effectiveness-oriented and efficiency-oriented criteria;

(c) the potential for using the decision maker's judgment and intuition as well as factual data concerning the relationships and relative magnitudes of the exogenous input parameters;

(d) consideration of the dynamics of the decision making environment including the changing organizational goals, decision variables and exogenous factors; and

(e) a normative structured approach towards understanding and appraising the dynamic relationships among the three levels of organizational strategy.

2.5.2 Manufacturing Strategy

Two major decision categories constituting a significant portion of the overall manufacturing strategy are the level of operating capacity and the choice of production process technology. From a strategic stance, these two decision categories ought to be highly coupled due to their impact as a competitive weapon.

In this research, the level of capacity from both new and vintage capacity at any instant of time is measured in units of output. Acquisitions of flexible and conventional technology serve to increase the total productive capacity. Reductions in conventional capacity (Chapter 3) or vintage technology (Chapter 4) decrease the overall capacity level. Subsequently, the technology strategy adopted to support the firm's competitive advantage are linked. In other words, in this dissertation research, the timing and sizing of production technology purchases are decision variables which act to modify both the level and composition of productive capacity over time so that the firm can support its competitive position in the market place and capture greater production efficiency. The formulations in Chapters 3 and 4 resemble a dynamic breakeven analysis wherein the relative tradeoffs among multiple criteria are considered. The new technology serves as a "challenger" to the incumbent conventional technology.

2.5.3 FMS as a Competitive Weapon

Explicitly treated in this research is the prospective decision to adopt FMS as the "challenger" technology. In particular, since the process technology choice is intertwined with the product decision, an FMS is generally considered to be a viable alternative in mid-volume, mid-variety manufacturing firms when stacked up against conventional, general purpose, semiautomatic equipment.

The strategic decision to adopt flexible technology assumes the total derived benefits from the FMS due to economies of scope and process efficiency outweigh the costs. Benefits included in this research are both tangible and intangible. Production efficiencies gained from use of FMS are more easily quantified than the more intangible benefits associated with quality, delivery flexibility and other indirect cost savings.

In this research the tangible benefit of increased production efficiency derived from the proper use of flexible technology is measured by reductions in the per unit production plus in-process inventory costs. The intangible benefits of flexible technology are captured in a market responsiveness function. It is the market responsiveness to the enhanced output from flexible technology that reflects its utility as a competitive weapon. Another intangible benefit from using flexible systems technology is the derived organizational experience gained. In Chapter 4, organizational experience is covered by a technological progress factor which serves to modify the natural rate of progress as new purchases of flexible technology are made. As individual modules of FMS are acquired and implemented over time, value is added due to system synergy and learning by doing. Also note this research assumes an evolutionary or incremental integration strategy.

2.5.4 Modeling Research

Chapter 2 is concluded with a summary of related modeling research. In particular, each of the dynamic models in Chapters 3 and 4 is formulated with integral objective functions to be maximized over a predetermined planning horizon. The time varying interrelationships among decision and exogenous variables are contained in state equations represented by sets of differential equations. The solution methodology is optimal control theory.

Related modeling efforts concerned with the optimal introduction of new technology are addressed with particular attention being focused in research using optimal control theory.

CHAPTER 3

STRATEGIC ADOPTION OF FLEXIBLE TECHNOLOGY FOR THE COMPETITIVE ADVANTAGE: MODEL I

3.1 INTRODUCTION

The purpose of this chapter is to consider the strategic opportunity of determining broad scale manufacturing process strategy as a competitive weapon. Competition on an international level has sparked a resurgence of attention to the effective management of manufacturing operations. Assessment of the new industrial competition shows competitiveness is not solely predicated upon price but also upon differentiation strategies of quality, delivery, and flexibility (Porter 1985). The revitalization of the U.S. role in international markets necessitates simultaneous improvements in manufacturing efficiency and product/service characteristics (Bylinsky 1983, Voss 1985)

Recent advances in computer controled, integrated flexible manufacturing systems (FMS) has evoked much interest as a choice of manufacturing process technology (Rosenthal 1984, Davis et al. 1985). In particular, the new flexible systems technology has been deemed to have the greatest potential applicability for mid-volume, discrete parts manufacturing firms (Stecke 1981, Groover 1980). These manufacturing entities are significant because it is estimated 75 percent of all parts manufacturing in the U.S. occurs in batches of 50 pieces or less (Starr and Biloski 1984).

A mid-volume, discrete parts manufacturing environment is generally characterized by the production of a wide ever-changing variety of parts. Therefore, low machine utilization and productivity are typically observed due to the amount of time needed for machine setups during product and process changeovers as well as due to bottleneck operations arising from unstandardized work flows and variable machining requirements at the different work centers (Groover 1980). Because flexible systems technology permits automatic product changeovers with substantially reduced direct labor involvement relative to conventional equipment, increased productivity and machine utilization is possible in an FMS environment (Groover 1980, 1981; Klahorst 1981; Kusiak 1984b,c).

The importance of a production process technology does not rest entirely with the relative efficiencies gained in the manufacturing process itself but rather with its strategic impact on the firm (Skinner 1978, Hayes and Wheelwright 1984, Buffa 1985). In order to achieve organizational goals such as increased market share, growth, and profits, a firm must portray distinctive competence in at least one area. Distinctive competence refers to those attributes which distinguish the firm from its competitors. Correspondingly such factors as innovativeness, quality, responsiveness to demand, production flexibility and low production costs support distinctive competence and provide the firm with a competitive advantage in the market place.

The production process technology employed defines the scope of the product line, the price, the quantities being produced, and other product/service characteristics. Because the process technology places bounds on the manner in which a firm can compete, manufacturing decisions affect the firm's long-term survival (Skinner 1978, Kantrow 1980, Hayes and Wheelwright 1984, Buffa 1985). For this reason, strategic justification of the production process technology by top level management is warranted. At the top management level, decisions involving the appropriate choice of technology as well as the timing of its introduction must focus upon the aggregate notion of a generic type of production process to be considered rather than on the specifics of the actual design details (e.g. specific types of equipment, the layout, the number of machines, and pallets). (See Chapter 2.)

Within this framework, a strategic, multicriterion decision model is introduced to assist firms in determining the optimal mix of conventional job shop equipment and flexible automation over time. Conventional technology refers to stand alone, general purpose, semiautomatic equipment typically found in batch manufacturing environments (Krajewski and Ritzman 1985, Groover 1980). Flexible manufacturing systems technology encompasses the entire class of state of the art computer controlled and integrated automation (Kusiak 1983, 1984b,c).

The model recognizes the prospective decision to replace conventional equipment with flexible automation modules as a continuous function of time. Clearly, modeling in such a manner results in an incremental or evolutionary timing policy as opposed to a discrete or radical adoption policy. (See Chapter 2 and Ettlie et al. 1984) With respect to an incremental policy, an organization's strategic plan mandates a smooth, continuous changeover process from conventional to flexible automation within an existing plant.

Under an evolutionary course of action, the relative magnitude of each acquisition of flexible automation to the total level of productive capacity is small at any instant of time. This affords the firm the opportunity to put the appropriate infrastructure in place to accommodate the new mode of manufacturing. The infrastructure consists of the internal systems such as organizational levels, wage systems, supervisory practices production control, job design and other manufacturing and management support systems which are prerequisite to the appropriate utilization of flexible technology (Skinner 1978, Graham 1985a,b).

Mathematically, in related research other formulations considering the adoption of new technology as a continuous function of time have been solved using ordinary control theory techniques (Gaimon 1984a; Gaimon 1985a,b,c,d). In contrast to these studies, this formulation treats the potential long-term effectiveness of the new flexible technology as a proxy for maximizing the net worth of the firm at the end of the planning horizon minus applicable costs incurred over time. In particular, the model incorporates the relative importance of flexible automation as a competitive weapon in capturing market share from the competition through product and service improvements due to economies of scope.

The per unit production cost is comprised of two parts. The acquisition of flexible technology may act to reduce the first part of the per unit production costs; the second part of this cost is unaffected by the new flexible technology. Therefore, efficiencies gained in the production process due to the acquisition of flexible systems components over time is reflected in the production process through reductions in one of the two parts of the per unit production cost. Similar assumptions concerning incentives for acquiring flexible technology on reducing the per unit production costs are made by Groover (1980) and Gold (1982a) and in related research Gaimon (1985a,b,c).

A principal criterion captured in the objective of the model is attaining a goal level of market share. Empirically based literature suggests market share is often colinear with profits over certain intervals of the planning horizon. Therefore, under these circumstances, firms which attain their market share goals simultaneously attain their profit goals (Schoeffler et al. 1975, Abell and Hammond 1979, Miller and Friesen 1984). More importantly, however, the market share criterion is a measure of the effectiveness of the firm's long-run ability to compete in the market place. A recent empirical study which showed market share to be an indicator of long-run performance whereas return on investment was equated to a short-run success criterion (Thiefort and Vivas 1984).

William and Tuttle (1984) have argued the need to consider the adoption of flexible technology in terms of established market share goals as well as in terms of the more traditional capital budgeting measures such as payback, return on investment, and net present value. For these reasons, the model presented in this chapter assumes (a) goal market share levels are established over time by the firm's strategic business and (b) the market is responsive to the enhanced outputs of flexible manufacturing systems.

In addition to penalty costs incurred for deviations between the actual and the goal levels of market share over time, the objective function of the model also considers the costs of acquiring flexible and conventional technology, production plus in-process inventory, and reducing the level of conventional capacity over time. The solution obtained yields the optimal timing and sizing of flexible automation purchases as well as optimal manufacturing policies for increasing and reducing the level of output from conventional capacity over time.

A firm may modify its productive capacity at time t by (a) acquiring flexible technology only, (b) acquiring conventional technology only, (c) acquiring both flexible technology and conventional technology simultaneously, (d) acquiring flexible technology and reducing conventional capacity, and (e) reducing conventional technology only. It is noted that all productive capacity, either flexible or conventional, is expressed in units of output. Further, it is assumed the level of automation accumulated over the planning horizon is never reduced.

In Section 3.2, the notation is defined. Section 3.3 presents the mathematical model and Section 3.4 describes the model's solution. A numerical solution algorithm is described in Section 3.5. A discussion of the results with an analysis of numerical examples is presented in Section 3.6. Specifically, the discussion reviews the relative effectiveness of the flexible technology and its impact on market share, the impact of technological advancement on the acquisition of technology, and the effects of exogenous market conditions on the adoption of a manufacturing process strategy.

3.2 BASIC NOTATION

Before presenting the model the following notation is introduced. First, the endogenous variables which are optimally determined by the model are defined. Second, the exogenous variables are defined which represent the input parameters that capture the dynamic economic conditions in which the optimal solutions are obtained. Note that t represents time, $t \in [0,T]$, where T is the terminal time of the planning horizon.

3.2.1 Endogenous Variables

m(t) - level of the firm's market share at time t, $0 \leq m(t) \leq 1$, $m(0)=m_0$; (state variable).

k(t) - level of all available productive capacity at time t expressed in units of output; $k(0)=k_0$; (state variable).

y(t) - level of conventional manufacturing capacity in units of output at time t; $y(0)=y_0$; (state variable).

b(t) - level of one of the two components of per unit production plus in-process inventory costs at time t which can be reduced by the acquisition of flexible automation; $b(0)=b_0$; (state variable).

$a(t)$ – rate of increase in level of flexible automation at time t in units of output, (control variable); $a(t) \epsilon [0,A(t)]$ where $A(t)$ represents the maximum rate of increase in flexible automation that can be achieved at time t.

$h(t)$ – rate of increase in level of output from conventional equipment at time t, (control variable); $h(t) \epsilon [0,H(t)]$ where $H(t)$ is the maximum rate of increase in conventionally produced output at time t.

$p(t)$ – rate of planned reduction in level of output from conventional equipment at time t, (control variable); $p(t) \epsilon [0,P(t)]$ where $P(t)$ is the maximum rate of decrease in conventionally produced output at time t.

3.2.2 Exogenous Variables

$M(t)$ – goal level of market share at time t, $0 \leq M(t) \leq 1$.

$c_1(t)$ – cost per unit squared of purchase and implementing flexible automation at time t.

$c_2(t)$ – cost per unit squared of increasing the level of conventionally produced output at time t.

$c_3(t)$ – cost per unit squared of reducing the level of conventionally produced output at time t.

$c_4(t)$ – cost per unit of maintaining all existing operating capacity at time t.

B – One of two components of the per unit production plus inventory costs which is unaffected by the acquisition of flexible automation at time t.

$v(t)$ - penalty cost per unit squared deviation between the goal and actual levels of market share at time t.

$\gamma(t)$ - effectiveness factor associated with the relative market responsiveness to rate of acquiring new flexible technology at time t; i.e., the relative effectiveness of the rate of flexible automation acquisitions on improving the firm's market share at time t, $0 \leq \gamma(t) \leq 1/A(t)$.

$\delta(t)$ - factor associated with the natural progress (growth/deterioration) of the firm's market share at time t due to exogenous factors, such as competition, stage in life cycle and other environmental forces, $-1 \leq \delta(t) \leq G$ where G is the upper bound on the growth factor.

$\alpha(t)$ - efficiency factor associated with reductions in the per unit production plus in-process inventory cost due to the acquisition of flexible automation at time t, $0 \leq \alpha(t) \leq 1/A(t)$.

N - market saturation level in units of output.

$r(t)$ - unplanned reductions in conventional output at time t, (i.e., exogenous attrition in labor and obsolesence of conventional technology).

S_1 - value per unit market share (goodwill) at the terminal time, T.

S_2 - value per unit productive capacity at the terminal time, T.

ρ - continuous discount rate.

3.3 THE MODEL

3.3.1 The Objective Function

The focus of the dynamic strategic planning model introduced here is to maximize over the planning horizon the firm's long-term effectiveness in a competitive market minus relevant costs incurred. The effectiveness of the firm is measured by its relative emphasis placed on market share and capacity holdings at the end of the planning horizon minus the aggregated penalty costs arising from deviations between the firm's actual and planned goal levels of market share over the planning horizon. Other cost factors subtracted from the maximizing objective of the firm over the entire planning horizon correspond to production plus in-process inventory, purchasing and implementing flexible automation and/or conventional capacity (equipment, hiring and setup), reducing conventional capacity (separation and scrapping) and overall operations maintenance (preventive and repair maintenance and variable indirect costs).

The effect of this objective function is to dynamically steer the firm toward attaining its desired market position over the entire planning horizon and at the terminal time through the application of optimal control policies that act to change the mix of flexible and conventional capacity over time.

Specifically, the objective is comprised of the following: (a) the value of market share (goodwill) at the terminal time plus (b) the salvage value of the productive capacity at the terminal time, minus the discounted costs over time of (c) the weighted deviations between the actual and goal market share levels, (d) production plus in-process inventory, (e) the cost of purchasing and implementing flexible automation, (f) the cost of increasing and (g) reducing conventionally produced output, and (h) the cost of maintaining productive capacity.

Corresponding to the notation introduced in Section 3.2 and the terms (a)-(h) above, the following objective function is defined:

MAXIMIZE

$$\underbrace{S_1 m(T)e^{-\rho T}}_{(a)}+\underbrace{S_2 k(T)e^{-\rho T}}_{(b)}$$

$$-\int_0^T \{\underbrace{v(t)[m(t)-M(t)]^2}_{(c)}+\underbrace{[B+b(t)]m(t)N}_{(d)}+\underbrace{c_1(t)a^2(t)}_{(e)}$$

$$+\underbrace{[c_2(t)h^2(t)}_{(f)}+\underbrace{c_3(t)p^2(t)]}_{(g)}+\underbrace{c_4(t)k(t)}_{(h)}\}e^{-\rho t}dt \qquad (3.1)$$

It is assumed that equal penalties are incurred for both positive and negative deviations from the firm's goal market share. Goal market share levels have been carefully planned in a time phased sequence such that systematic linkages were made with the firm's anticipated overall resource capabilities over time. At times when the actual market share levels are projected to exceed the predefined company goal levels, the organizational structure of the firm needed to support the actual level of market share may be severely taxed (Ryans and Shanklen 1985). Because the planned goal levels of market share implicitly correspond to the planned time phased organizational capabilities, penalties arise from exceeding the goal market share levels over time. The objective can be easily modified to permit less severe penalties for exceeding the goal market share levels. (See Chapter 4.)

The cost of purchasing and implementing flexible automation are expressed as functions of time as are the costs associated with changing the levels of conventionally produced output. The acquisition of conventional technology is closely aligned with the requirements for highly skilled labor whereas reduction in conventional capacity reflects corresponding reductions in both the skill level and quantity of direct labor. Since each of these costs are expressed as functions of the squared magnitudes of the respective control variables, the firm is penalized with high costs corresponding to large values of the decision variables at a particular time.

As previously discussed, the model was premised on an evolutionary timing policy in order to afford management sufficient time to adapt the organizational infrastructure to corresponding changes in the composition of productive capacity (Ettlie et al. 1984). Applying quadratic costs to the decision variable enables the model to capture both the continuous timing strategy and the proportionate difficulties a firm may encounter in attempting to make dramatic changes in the means of production at any instant of time. Modeling in this fashion is consistent with the production smoothing literature for higher level decision making (Hax and Candea 1984).

3.3.2 The Constraints

The objective function described in Equation (3.1) is maximized subject to a set of constraints expressed as first order ordinary differential equations. The first state constraint depicts the rate of change in the level of market share over time. It is assumed that the dynamic change in the firm's market share is a function of the current level of market share and exogenous factors such as the impact of competition, stage in aggregate product life cycle and elasticity of demand as well as the impact of penetrating the competitor's market share through the acquisition of flexible automation at time t. Therefore, the change in market share over time is formulated as

$$m'(t)=\delta(t)m(t)+\gamma(t)a(t)[1-m(t)] \qquad (3.2)$$

with the initial condition $m(0)=m_0$ and the requirement $0\leq m(t)\leq 1$, for $t\epsilon[0,T]$.

The first term in Equation (3.2) depicts natural progression in the firm's market share due to exogenous factors at time t. First, if a natural deterioration in the market share exists, the natural progression function $\delta(t)$ is negative indicating a declining market share at time t. Second, if $\delta(t)=0$, then no natural change occurs in the firm's market share at time t. Third, $\delta(t)>0$ indicates the firm's aggregate product market share is in a natural growth phase. Therefore, the product $\delta(t)m(t)$ represents the net change in market share which the firm would expect without technological innovation.

The second term expressed in Equation (3.2) represents the net contribution of flexible automation towards the enhancement of the firm's competitive edge over time. In particular, the technology/market penetration factor, $\gamma(t)$, reflects the effectiveness of increasing the firm's market share per unit rate of increase of flexible technology held at time t. As previously discussed, flexible automation has many features which enhance the product or service, and therefore, enable the firm to capture a share of the competitor's market. For example, enhanced output from flexible automation is reflected by quality, dependability, flexibility and cost savings. This enhancement is possible due to (a) reductions in setup times resulting in faster switching and automatic tool interchange capabilities, (b) the ability to change a sequence of operations by rerouting a part through different paths, (c) the capability to adopt new product mixes and ability to adjust volume to varying demand impacts upon key competitive factors as innovation and flexibility, (d) reductions in human errors associated with conventional (manually) operated equipment and (e) the ability to work with different grades of material and to adjust tolerance levels. Finally, large reductions in highly skilled labor requirements as well as reduction in in-process inventory serve to lower production costs.

It is assumed that investment in automation never reduces market share so that the term $\gamma(t)a(t)[1-m(t)]$ is always nonnegative. Since a $a(t)\geq 0$, $m(t)\leq 1$, and $\gamma(t)\geq 0$, this nonnegativity requirement on market share is satisfied. To assure that $\gamma(t)a(t)\leq 1$, an upper bound on $\gamma(t)$ is defined such that

$0 \leq \gamma(t) \leq 1/A(t)$ for $t \epsilon [0,T]$. Note that if $\gamma(t)a(t)=1$ then the maximum effectiveness due to technological acquisition is achieved since the firm captures the total outstanding market share potential, $[1-m(t)]$, in period t. Since $\delta(t) \geq -1$, it is clear that m(t) cannot be negative. No formal constraint is imposed as an upper bound on m(t) to restrict $m(t) \leq 1$. This of course implies that it is theoretically possible for m(t) to exceed 1.0 which could be interpreted as the potential for flexible technology to increase the target population. In any realistic problem, however, the target levels, M(t), and the quadratic cost function would make the event, $m(t)>1$, unlikely. This simplification has the advantage of eliminating a troublesome state constraint (Bensoussan et al. 1974).

In Equation (3.3), the change in the per unit production plus in-process inventory cost is defined over time with the initial condition $b(0)=b_0$.

$$b'(t)=-\alpha(t)a(t)b(t) \tag{3.3}$$

This second state equation adopted from (Gaimon 1982, 1985a,b,c) characterizes the effect of technological advancement and learning on production costs over time. One component of the per unit production plus in-process inventory costs is expected to be reduced due to the acquisition of flexible automation at time t. Cost savings arise from (a) the substitution of vintage capital and labor with new equipment yielding higher productivity, less direct labor and reduced energy usage; (b) increased quality and reduced scrap implying less rework and significant direct materials savings; (c) learning; and (d) reduction in in-process inventory as a result of continuous flows and small production runs (Groover, 1980).

With respect to the reduction in the in-process inventory, the assumption is made that the level of in-process inventory is proportional to the batch size at time t. Therefore, the production plus in-process inventory costs can be combined. Letting $\alpha(t)a(t)$ represent the total percent reduction at time t in this per unit production, nonnegativity of the per unit production plus in-process inventory cost is satisfied. The magnitude of reduction in the per unit cost at time t is assumed to be proportional to the level of the cost at that time. As a result, the dynamic change in the per unit costs reflects diminishing returns to scale as additional units of flexible automation are acquired over time.

In the third state equation, the changes in the level of productive capacity at time t are portrayed. It is assumed that the productive capacity can be modified as a result of the adoption of various manufacturing process strategies. Specifically, the change in productive capacity at time t is equal to (a) the increase in output due to the acquisition of flexible automation and (b) the net change in the level of conventionally produced output. Mathematically this is expressed as follows:

$$k'(t)=a(t)+[h(t)-p(t)-r(t)] \qquad (3.4)$$

Implicit in Equation (3.4) is the assumption that the units of flexible automation acquired at time t remain within the organization for the duration of the planning horizon. In addition, the potential yield in output from the flexible technology is assumed to remain constant over the planning horizon. In other words, reductions in the level of output from the new technology are not permitted.

The firm's total level of productive capacity must be non-negative over the planning horizon so that $k(t)\geq 0$ for $t\epsilon[0,T]$. The level of output cannot exceed the available productive capacity at that time. Defining $m(t)N$ as the level of production at time t, Equation (3.5) requires the level of production be both nonnegative and less than the level of available capacity. Furthermore note that the constraint $k(t)\geq 0$ is implicitly satisfied.

$$0\leq m(t)N\leq k(t) \text{ for } t\epsilon[0,T] \qquad (3.5)$$

The fourth state equation which expresses the change in the level of conventionally produced output over time is written as

$$y'(t)=h(t)-p(t)-r(t) \qquad (3.6)$$

with the initial condition $y(0)=y_0$. In addition, the nonnegativity constraint

$$y(t)\geq 0 \qquad (3.7)$$

is required.

To complete the description of the model, the following control constraints are defined:

$$a(t)\epsilon[0,A(t)],h(t)\epsilon[0,H(t)],p(t)\epsilon[0,P(t)] \qquad (3.8)$$

Each control variable is required to be nonnegative. The upper bounds on the controls have pragmatic managerial implications. For example, $A(t)$ is the maximum rate at which the technology can be acquired by the firm at any instant of time. This bound can be predicated upon (a) the availability of flexible automation, (b) the ability of the organization's infrastructure to manage the introduction of new technology and (c) projected budgetary or cash flow considerations. The maximum rate of increase in conventionally produced output, $H(t)$, is determined by either the availability of skilled labor or conventional equipment and budget considerations. Lastly, the maximum rate of reduction in conventionally produced output $P(t)$ may be determined by managerial policy or labor contracts.

3.4 THE SOLUTION

The model defined in Sections 3.2 and 3.3 is solved using continuous control theory (Sethi and Thompson 1981, Bryson and Ho 1969). The ordinary Hamiltonian is written as

$$\begin{aligned}
H = & -\{v(t)[m(t)-M(t)]^2+[B+b(t)]m(t)N+c_1(t)a^2(t) \\
& +c_2(t)h^2(t)+c_3(t)p^2(t)+c_4(t)k(t)\}e^{-\rho t} \\
& +\lambda_1(t)[\gamma(t)a(t)[1-m(t)]+\delta(t)m(t)] \\
& +\lambda_2(t)[-\alpha(t)a(t)b(t)]+\lambda_3(t)[a(t)+h(t)-p(t)-r(t)] \\
& +\lambda_4[h(t)-p(t)-r(t)]
\end{aligned} \qquad (3.9)$$

with the adjoint variables $\lambda_1(t)$, $\lambda_2(t)$, $\lambda_3(t)$ and $\lambda_4(t)$

(marginal value functions) corresponding to the state variables m(t), b(t), k(t) and y(t), respectively. Due to the state constraints depicted in Equations (3.5) and (3.7), the following Lagrangian and complementary slackness conditions are required.

$$L=H+\mu_1(t)[h(t)-p(t)-r(t)]+\mu_2(t)[k(t)-m(t)N] \quad (3.10)$$

$$\mu_1(t)y(t)=0,\ \mu_1(t)[h(t)-p(t)-r(t)]=0,\ \mu_1(t)\geq 0 \quad (3.11)$$

$$\mu_2(t)[k(t)-m(t)N]=0,\ \mu_2(t)\geq 0 \quad (3.12)$$

The optimal solution for the adjoint variables satisfy Equations (3.13-3.16) below:

$$\lambda_1'(t)=-dL/dm(t)=(2v(t)[m(t)-M(t)]+[B+b(t)]N)e^{-\rho t}$$

$$+\lambda_1[\gamma(t)a(t)-\delta(t)]+\mu_2(t)N,\ \lambda_1(T)=S_1e^{-\rho T} \quad (3.13)$$

$$\lambda_2'(t)=-dL/db(t)=m(t)Ne^{-\rho t}+\alpha(t)a(t)\lambda_2(t),\ \lambda_2(T)=0 \quad (3.14)$$

$$\lambda_3'(t)=-dL/dk(t)=c_4(t)e^{-\rho t}-\mu_2(t),\ \lambda_3(T)=S_2e^{-\rho T} \quad (3.15)$$

$$\lambda_4'(t)=-dL/dy(t)=0,\ \lambda_4(T)=0 \quad (3.16)$$

From Equation (3.13), it is clear that the marginal value of a unit of market share at time t is a function of the magnitude of deviation between the actual and projected goal levels of market share, the per unit production costs, the relative effectiveness of acquiring flexible technology, the natural rate of change in the firm's market share and the Lagrange multiplier associated with the constraint $k(t)\geq m(t)N$ denoted in Equation (3.5). Whenever the constraint is binding, $\mu_2(t)$ is positive, and the marginal value/cost of an additional unit of market share is decreased by $\mu_2(t)N$.

From Equation (3.14), the marginal value (cost) of reducing the per unit production cost corresponds to the level of production and the net reduction in costs due to an increase in the level flexible automation. As depicted in Equation (3.15), the marginal value (cost) of an additional unit of capacity reflects with the discounted cost of maintaining that capacity and the Langrange multiplier $\mu_2(t)$. If the constraint $\dot{k}(t) \geq m(t)N$ is binding, then the marginal value function associated with an additional unit productive capacity is increased by $\mu_2(t)$ so that more capacity will be acquired. Lastly, from Equation (3.16), the marginal value (cost) of an additional unit of conventional capacity is defined at zero throughout the planning horizon. This occurs because $\lambda_4(T)=0$ and $\lambda_4'(t)=0$ for $t\epsilon[0,T]$ (Gaimon, 1985).

In Theorems 1 and 2 the optimal rate of acquiring flexible technology and the optimal rate of purchasing and reducing conventional capacity is described.

3.4.1 Theorem 1

The optimal rate of increase in output due to the acquisition of flexible automation at time t is

$$a(t)= \begin{cases} A(t), \text{ if } \phi_1(t) \geq A(t) \\ \phi_1(t) \text{ if } 0<\phi_1(t)<A(t) \\ 0, \text{ if } \phi_1(t) \leq 0 \end{cases} \quad (3.18)$$

acquisition is dependent upon the discounted cost of purchasing and implementing the flexible technology at time t as captured in the denominator of Equation 3.19.

3.4.2 Theorem 2

The optimal increase in the level of conventional output at time t is

$$h(t)= \begin{cases} H(t), \text{ if } \phi_2(t)\geq H(t) \\ \phi_2(t), \text{ if } 0<\phi_2(t)<H(t) \\ 0, \text{ otherwise} \end{cases} \tag{3.20}$$

where

$$\phi_2(t)=\lambda_3(t)/[2c_2(t)e^{-\rho t}] \tag{3.21}$$

and the optimal reduction in the level of conventional output at time t is

$$p(t)= \begin{cases} P(t), \text{ if } \phi_3(t)\geq P(t) \text{ and } y(t)>0 \\ \phi_3(t), \text{ if } 0<\phi_3(t)<P(t) \text{ and } y(t)>0 \\ 0, \text{ otherwise} \end{cases} \tag{3.22}$$

where

$$\phi_3(t)=-\lambda_3(t)/[2c_3(t)e^{-\rho t}]. \tag{3.23}$$

<u>Proof Theorem 2</u>

Taking the derivative of the Lagrangian with respect to h(t) setting it equal to zero, solving for h(t) and noting that $\lambda_4(t)=0$ for all $t\epsilon[0,T]$, gives us

$$h(t)=\phi_2(t)+[\mu_1(t)/2c_2(t)e^{-\rho t}]. \quad (3.24)$$

Similarly for $p(t)\epsilon[0,P(t)]$, we obtain

$$p(t)=\phi_3(t)-[\mu_1(t)/2c_3(t)e^{-\rho t}]. \quad (3.25)$$

The Lagrange multiplier $\mu_1(t)$ appears as a result of Equation (3.7). If $y(t)\geq 0$, $\mu_1(t)=0$ due to the complementary slackness conditions expressed in Equation (3.11). Recalling the control constraints in Equation (3.8), we obtain Equations (3.20) and (3.21).

Alternatively, if $y(t)\geq 0$ were to be violated then $\mu_1(t)$ must be obtained such that $y(t)=0$ holds. Note that $y(t)<0$ occurs only if $y(t)=0$ and $y'(t)<0$ for $\mu_1(t)=0$. From Equations 3.24 and 3.25, with $\mu_1(t)=0$ and $y'(t)<0$ we have $h(t)=0$ and $p(t)>0$. Therefore, $\mu_1(t)$ must be derived such that $p(t)=0$ holds giving us $y'(t)=0$ and $y(t)=0$. Clearly, $\mu_1(t)=-\lambda_3(t)$ is obtained. As a result, whenever the state constraint, $y(t)\geq 0$, is binding, the optimal control solutions satisfy Equations (3.20) and (3.22) as desired. This completes the proof of Theorem 2.

where

$$\phi_1(t)=\{\lambda_1(t)\gamma(t)[1-m(t)]$$

$$-\lambda_2(t)\alpha(t)b(t)+\lambda_3(t)\}/[2c_1(t)e^{-\rho t}]. \qquad (3.19)$$

Proof Theorem 1

Taking the derivative of the Lagrangian expressed in Equation (3.10) with respect to a(t), setting it equal zero and solving for a(t) yields $a(t)=\phi_1(t)$. Incorporating the control constraints, $a(t)\epsilon[0,A(t)]$ produces Equation (3.18) as desired.

The interpretation of Theorem 1 is straightforward. The first term expressed in Equation (3.19) may be positive or negative and represents the value of increasing market share due to acquiring flexible automation. Since $\lambda_2(t)$ is the value of an additional unit output due to a purchase of flexible automation, the second term which is always positive, represents the value of acquisition flexible technology in reducing the per unit production cost. The third term, $\lambda_3(t)$, is the marginal value or cost of an additional unit of capacity. This term can be either positive or negative. Notice that the impact of the numerator in (3.19) suggests that the amount of flexible automation acquired at time t is predicated upon relative marginal value (cost) of its effectiveness in penetrating market share, its relative efficiency in reducing the per unit production cost, and its contribution toward capacity requirements. If the net effect of the numerator is positive then it is optimal for the firm to acquire flexible automation. The magnitude of

From the optimal policies derived in Theorem 2, the term $\lambda_3(t)$, represents the marginal value or cost of an additional unit of capacity. Whenever $\lambda_3(t)$ is positive an increase in the level of conventional capacity is advocated whereas a negative value indicates a reduction in conventional capacity is desirable at time t. The amount of increase or decrease in conventional capacity is reduced by the magnitude of the respective discounted costs of the policy at time t. Note that $h(t)p(t)=0$ holds for all $t \in [0,T]$ so that it is never optimal to simultaneously increase and decrease the level of conventional capacity.

3.5 THE NUMERICAL SOLUTION ALGORITHM

Through the application of numerical examples, sensitivity analysis on the optimal policy provides insights to the dynamic behavior of the model with respect to the inclusion of particular values of the exogenous parameters. Clearly, some parameter values will affect the model's behavior more critically than others. Since closed form solutions do not exist, and the state, control and adjoint variables are dynamically interdependent, an iterative procedure is necessary for the computation of numerical solutions.

The numerical procedure employs discrete approximations of the continuous model represented in Section 3.3. The state and adjoint difference equations upon which the procedure is predicated are specified as follows:

$$m(t)=m(t-1)+\gamma(t-1)a(t-1)[1-m(t-1)]+\delta(t-1)m(t-1) \quad (3.26)$$

$$y(t)=y(t-1)+h(t-1)-p(t-1)-r(t-1) \quad (3.27)$$

$$b(t)=b(t-1)-\alpha(t-1)a(t-1)b(t-1) \quad (3.28)$$

$$k(t)=k(t-1)+a(t-1)+h(t-1)-p(t-1)-r(t-1) \quad (3.29)$$

$$\lambda_1(t-1)=\lambda_1(t)-\{2v(t)[m(t)-M(t)]$$

$$+[B+b(t)]N\}e^{-\rho t}-\lambda_1(t)[\gamma(t)a(t)-\delta(t)]$$

$$-\mu_2(t)N, \lambda_1(T)=S_1e^{-\rho t} \quad (3.30)$$

$$\lambda_2(t-1)=\lambda_2(t)-m(t)Ne^{-\rho t}-\alpha(t)a(t)\lambda_2(t), \lambda_2(T)=0 \quad (3.31)$$

$$\lambda_3(t-1)=\lambda_3(t)-c_4(t)e^{-\rho t}+\mu_2(t), \lambda_3(T)=S_2e^{-\rho t} \quad (3.32)$$

The logic of the procedure is straightforward and consists of three parts. In Algorithm 1, computations of the adjoint, control and state variables are made. Algorithms 2 and 3 are called by Algorithm 1 upon violation of the respective state constraints, $y(t)<0$ or $k(t)<m(t)N$.

The numerical solution procedure which is detailed in Appendix A is now briefly described. The logic of Algorithm 1, is depicted in Figure 5. First, we begin by the initializing exogenous parameters for all $t\epsilon[0,T]$. In addition, for all $t\epsilon[0,T]$ the values of the control variables are set to zero and initial guesses of the values of the state and adjoint variables provide a starting point for the ensuing iterations. Each subsequent iteration begins with the computation of the control variables starting with time

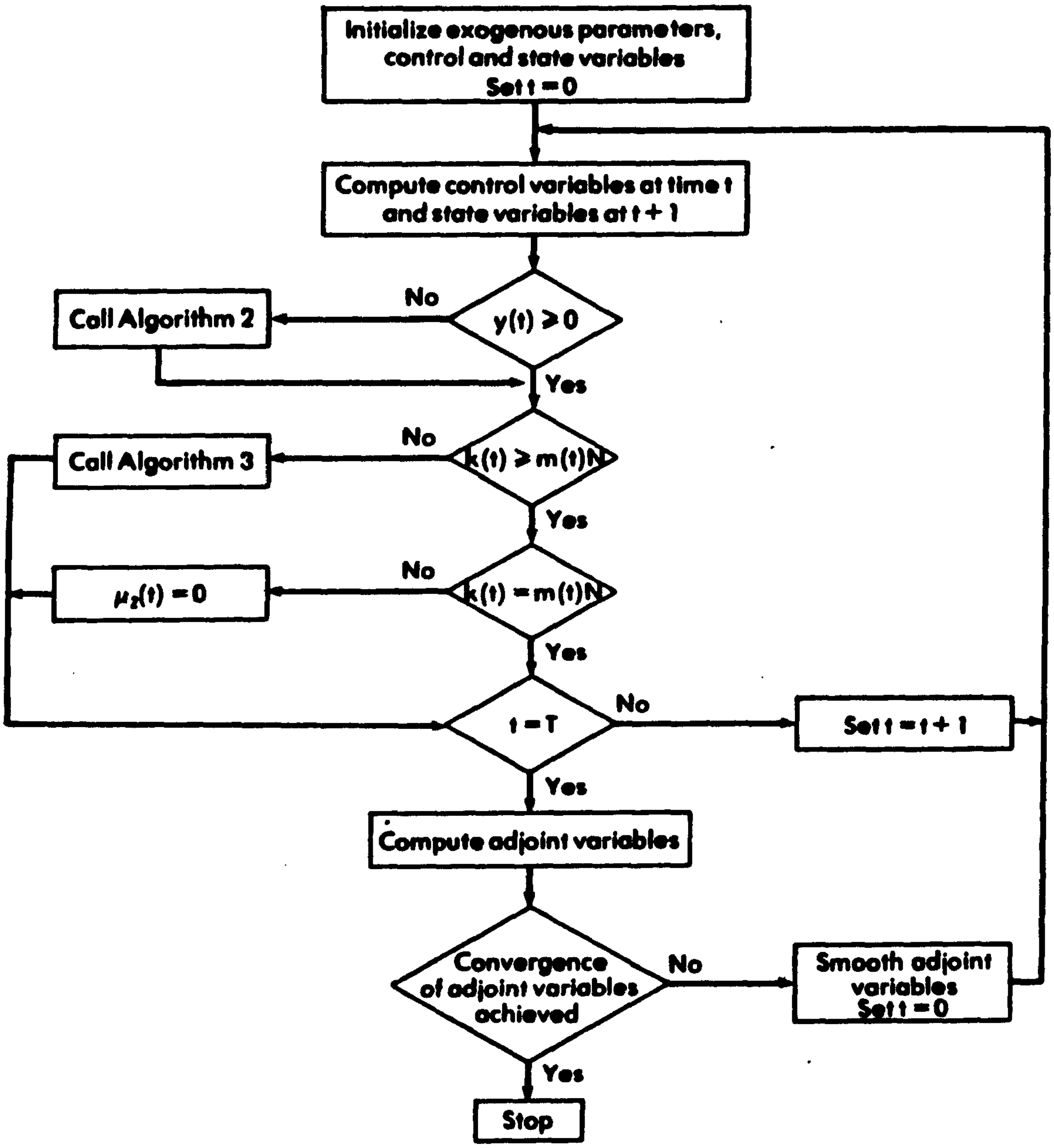

Figure 5. Numerical Solution Algorithm 1: MODEL I

zero using Equations (3.18), (3.20), and (3.22) followed by the calculation of the state variables at time t+1 using Equations (3.26)-(3.29). Therefore, the controls at time t and state variables at time t+1 are derived sequentially and forward in time over the entire planning horizon. Next, given the updated control and state variables, the values of the adjoint variables are computed backwards from time T to time 0. Convergence is achieved when the magnitude of the difference between the corresponding time values of the adjoint variables found between two consecutive iterations is less than some prespecified error for all $t \epsilon [0,T]$ and all λ_i, i=1,2,3.

Algorithm 1 checks for violations of the constraints $b(t) \geq 0, y(t) \geq 0$ and $k(t)-m(t)N>0$. To guarantee $b(t) \geq 0$ in the discrete approximation, we require $\alpha(t) \leq 1/A(t)$. Algorithm 2 is called by Algorithm 1 whenever the state constraint, $y(t) \geq 0$ is violated. Similarily, Algorithm 1 calls Algorithm 3 whenever the state constraint $k(t)-m(t)N \geq 0$ is violated. Algorithm 3 returns (a) a positive value of $\mu_2(t)$ such that $k(t)-m(t)N=0$ holds exactly, (b) the corresponding state variables at time t using the new solutions for the adjoint variables at time t-1 and (c) the control policies at time t-1.

Summarized in Table 1 are 15 candidate solutions which are tested in Algorithm 3 in order to determine feasible values of $\mu_2(t)$. Included in the feasible set are those values of $\mu_2(t)$ which are positive and which cause the controls at time t-1 to produce state variable values at time t such that $k(t)=m(t)N$ holds exactly. In the event that more than one feasible value of $\mu_2(t)$

Table 1. Candidate Solutions in Algorithm 3: MODEL I

CONTROL VARIABLES

CASE	$a(t-1)^*$	$p(t-1)^*$	$h(t-1)^*$
1	$\phi_1(t-1)$	0	0
2	$\phi_1(t-1)$	$\phi_3(t-1)$	0
3	$\phi_1(t-1)$	0	$\phi_2(t-1)$
4	$\phi_1(t-1)$	0	$\phi_2(t-1)$
5	$\phi_1(t-1)$	0	$H(t-1)$
6	0	$\phi_3(t-1)$	0
7	0	$P(t-1)$	0
8	0	0	0
9	0	0	$\phi_2(t-1)$
10	0	0	$H(t-1)$
11	$A(t-1)$	0	0
12	$A(t-1)$	$\phi_3(t-1)$	0
13	$A(t-1)$	$P(t-1)$	0
14	$A(t-1)$	0	0
15	$A(t-1)$	0	$H(t-1)$

*Reference Equations 3.18, 3.20, and 3.23, respectively.

is evaluated for any particular time period in which the state constraint had been violated, Algorithm 3 would choose the lowest $\mu_2(t)$ in the feasible set.

The candidate solutions specified in Table 1 from which the feasible set of $\mu_2(t)$ is evaluated are now summarized. For Cases 1, 8, and 11 it is required that both h(t-1) and p(t-1) equal zero exactly. Thus for each of these cases Equation (3.33) must hold.

$$\mu_2(t)=c_4(t)e^{-\rho t}-\lambda_3(t) \tag{3.33}$$

Clearly, there is one value of $\mu_2(t)$ for which this expression holds. Therefore, only one of the Cases 1, 8, 11 will be feasible since the resultant $\mu_2(t)$ will cause a(t-1) to take on exactly one value, namely, 0, $\phi_1(t-1)$ or A(t-1).

Evaluation of Cases 2, 3, 4, 5, 9, 12 and 14 requires algebraic substitution of the corresponding control variable solutions in Table 3.1 into Equation (3.34). This gives us

$$\begin{aligned} &k(t-1)+a(t-1)+h(t-1)-p(t-1)-r(t-1) \\ &=\{m(t-1)+\gamma(t-1)a(t-1)[1-m(t-1)]+\delta(t-1)m(t-1)\}N \end{aligned} \tag{3.34}$$

Whenever a control variable for any particular case is within its upper and lower control bounds, that control variable in Equation (3.34) is defined in terms of $\lambda_i(t-1)$ for i=1,2,3. Further substitution for $\lambda_i(t-1)$ in terms of $\lambda_i(t)$ produces an explicit expression for $\mu_2(t)$. The precise form of the expression varies since each case has certain control variables fixed at different upper or lower bounds. Due to the algebraic complexities involved in the evaluation of each individual case, the explicit representation of Equation (3.34) in terms of $\mu_2(t)$ are omitted.

Finally, Cases 7, 10, 11 and 15 are specified with every control variable fixed at either its upper or lower bound. In these instances, the values of $\mu_2(t)$ which (a) produce the controls at their bounds such that the respective case applies, (b) are nonnegative and (c) produce state variable such that $k(t)=m(t)N$ holds exactly are added to the feasible set.

3.6 DISCUSSION

Using the model formulated in Section 3.3, the chapter is concluded with the presentation and discussion of seven numerical examples. The examples were derived using the numerical solution algorithm described in Section 3.5. Therefore, the optimal solutions are obtained for discrete times, $t = 0,1,\ldots,T$.

Specifically, the sensitivity analysis addresses (a) the relative effectiveness of the flexible automation in capturing a portion of the competitor's market (b) the emphasis placed on achieving market share goals, (c) technological advancement and (d) the importance of flexible manufacturing technology under different market conditions. The summary of the sensitivity analysis results for each of 7 examples is depicted in Table 2. Also note that relatively small numerical values were assigned to the terminal time marginal values of market share and capacity. As a result of these small terminal time marginal values and the relatively high costs incurred over the planning horizon, the maximizing objective

Table 2. Summary of Numerical Examples: Model I

EXOGENOUS COMMON INPUT PARAMETERS: $T=10$; $M(t)=.10 + 0.1t$, $t=[0, 5]$; and $M(t)=.15$, $t=[5, 10]$; $B=10$; $b_0=20$; $k_0=65$; $y=65$; $c_2(t)=10$; $c_3(t)=10$; $c_4(t)=25$; $S_1=100{,}000$; $S_2=10$; $N=500$; $r(t)=0$; $A(t)=10$; $H(t)=30$, $P(t)=20$; $\rho=.15$

			EXOGENOUS INPUT PARAMETERS				
EXOGENOUS FUNCTIONS	EXAMPLE 1	EXAMPLE 2	EXAMPLE 3	EXAMPLE 4	EXAMPLE 5	EXAMPLE 6	EXAMPLE 7
$v(t)$	100,000	100,000	300,000	100,000	100,000	100,000	100,000
$c_1(t)$	40	40	40	40-3t	40	40	40
$\gamma(t)$	.005	.005+.001t	.005	.005	.005	.005	.005
$\delta(t)$	0.0	0.0	0.0	0.0	0.0	.05	-.05
$\alpha(t)$	.001	.001	.001	.001	.05	.001	.001
			OPTIMAL SOLUTIONS				
POLICY VARIABLES							
$\sum_{t=1}^{10} a(t)$	10.35	12.29	14.23	19.25	15.80	6.95	14.10
$\sum_{t=1}^{10} h(t)$	7.16	12.25	8.95	11.75	10.84	23.62	2.56
$\sum_{t=1}^{10} p(t)$	15.00	15.00	12.13	15.00	12.16	4.13	26.69
$m(10),(\bar{m})$	.12,(.1037)	.13,(.1031)	.14,(.1123)	.14,(.1054)	.15,(.1136)	.17,(.1302)	0.10,(.0866)
$\bar{q}^{*},(\%)^{**}$	51.87,(6.8%)	51.54,(7.5%)	56.17,(6.3%)	52.69,(6.9%)	56.80,(6.3%)	65.12,(4.7%)	43.29,(11.4%)
$k(10),(\bar{k})$	62.20,(55.41)	64.11,(55.74)	70.83,(59.93)	70.57 (56.59)	74.29 (60.62)	86.37 (68.32)	49.53 (48.87)
$y(10)$	56.73	61.82	61.39	61.32	63.24	84.06	40.43
$b(10)$	19.89	19.95	19.81	19.82	11.18	19.96	19.81
OBJECTIVE <costs>	<15,541>	<16,143>	<16,535>	<15,388>	<15,261>	<16,685>	<15,550>

$\bar{q}^{*}$ = Average production level, $m(t)N$

$\%^{**}$ = Average percentage deviation between average capacity and average production levels $[(\bar{k}-\bar{q})/\bar{k}*100]$

function values are negative in each example. Therefore, the objective function values can be interpreted as relative costs. The detailed results for each state and control variable at each time period are presented in Appendix D.

Examination of the exogenous input parameters in Table 2 provides insight concerning the firm and its environment in the examples for which the model will be illustrated. First, the firm holds at the beginning of the planning horizon a small but significant portion of the market, m_0=0.10. In each of the 7 examples, the business unit has projected an expansion policy. Reflected in the goal market share, this policy is depicted by a growth of .01 percentage point in each of the first five years in the planning horizon culminating in a maintenance market share position of 15 percent throughout the duration of the planning horizon (periods 5-10).

Second, at the outset, this firm holds about 30 percent more productive capacity, all of which is conventional capacity, than is required to meets its initial market share production requirements at time 0. Also, the magnitude of the upper limits on the control variables is indicative of evolutionary managerial policy concerning changing the mix of productive capacity. Notice that the maximum rate at which conventional capacity may be acquired is three times the maximum rate at which flexible automation can be introduced. It may be assumed that for the firms portrayed in these examples that (a) the organizational structure requires a slower rate of adoption of flexible automation to allow for required infrastructure changes as the new technology is assimulated into the organization, (b) there is some difficulty in obtaining more flexible technology due to availability from the suppliers or (c) the firm's projected cash flow places budgetary restrictions on the acquisition rate of the new flexible automation. Also, it appears from the upper bounds on the control variables that for the firm depicted in these examples it is easier to acquire conventional capacity than to reduce it even though the projected costs of acquiring and reducing it are the same throughout the planning horizon ($c_2(t) = 10$ and $c_3(t) = 10$). The maximum rates of reducing and increasing conventional capacity are 20 units per period and 30 units per period, respectively.

Third, given the total per unit production costs depicted in the examples, a substantial portion (two-thirds) of the costs can potentially be reduced due to acquiring flexible technology. However, with the exception of Example 4, where the cost of obtaining flexible automation is assumed to diminish in the future due to technological advancement, the per unit cost of acquiring and implementing flexible technology is about four times greater than the related costs for new conventional capacity. The per unit cost of maintaining productive capacity is relatively high. In fact it is nearly equivalent to the total variable production costs at the beginning of the planning horizon.

Fourth, the impact of the competitive environment on the firm is considered in the examples. Examples 1 through 5 portray a firm in a totally neutral competitive environment with no exogenous change in market share anticipated over the planning horizon. Examples 6 and 7 reflect two diverse competitive scenarios illustrating changing exogenous market conditions. In Example 6 the firm's market share is in a natural growth phase. In contrast, example 7 depicts a waning market position due to competition and other exogenous factors.

3.6.1 Base Scenario

In order to stress the relative importance of the selected exogenous functions, Example 1 serves as a base scenario from which comparisons are made. Exogenous functions that will vary from the base across the different examples are (a) the relative penalty costs that the firm ascribes to deviations between actual and goal market share levels, $v(t)$; (b) the per unit cost of acquiring new flexible automation, $c_1(t)$; (c) the relative effectiveness of the flexible technology in obtaining market share from the firm's competitors, $\gamma(t)$; (d) the natural growth/decay factor in the firm's market share, $\delta(t)$; and (e) the relative efficiency of the technology in reducing the per unit production plus in-process inventory costs, $\alpha(t)$.

A reduction in excess conventional capacity is advocated in periods 0-5 of Example 1. (See Figure 6.) In this time interval, the firm's actual market share and production levels remain constant. Not until period 5 does the firm begin acquiring flexible technology in order to meet its market share goals. However, since the output from the flexible manufacturing system is so effective in generating demand, the need for increased conventional capacity also exists. As a result, following period 5, the level of required production occurs at its upper bound, which is the level of available operating capacity. (See Figure 7.) Algorithm 2 is called from which Case 4 solutions in Table 2 are obtained with $\mu_2(6)=5.54$, $\mu_2(7)=2.59$, $\mu_2(8)=2.06$, $\mu_2(9)=1.54$ and $\mu_2(10)=21.08$.

Because the cost of maintaining productive capacity is more than twice the cost of adding or reducing conventional capacity, the optimal policies should possess a strong tendency as illustrated in this example to remain in a more tightly capacitated situation. In other words, the costs of maintaining capacity in these examples produce optimal policies reflective of an operating environment with little capacity slack. Note, however, the optimal solution varies from the initial condition described at the beginning of the planning horizon where the capacity held was significantly in excess of demand. Therefore, it is optimal for the firm to reduce the excess capacity as soon as possible. This tendency is magnified by the equivalence of $c_2(t)$ and $c_3(t)$ throughout the planning period. In Example 1, the average capacity over the planning period is only 6.8 percent greater than the average production level. Postponing purchases of flexible automation in the optimal solution partially reflect the effect of the discount factor on the costs over time. Initially, the per unit cost of output from the new flexible technology is about four times the cost of conventional output. As time passes, the benefits of obtaining market share begins to outweigh the discounted acquisition costs.

3.6.2 Relative Effectiveness of Technology and Emphasis on Market Share

The competitive benefits of the outputs of flexible manufacturing systems that impact on market share have been discussed in Chapter 2. Clearly, the relative effectiveness of the technology will vary dynamically by firm, industry and aggregate product line.

Impact of Market Effectiveness

In Example 2, the effectiveness of the technology as a competitive weapon is anticipated to increase over time [$\gamma_1(t)=.005+.001t$]. Consequently, the optimal policy advocates the acquisition of almost 20 percent more flexible automation than in Example 1. However, the initial procurement is postponed until period 8. Furthermore, in anticipation of a high degree of market responsiveness to the new technology, acquisition of new flexible technology will also generate increased total capacity needs later in the planning horizon. Conventional capacity is also acquired beginning in period 6 to help fulfill this capacity requirement. (See Figure 8.) In periods 6 and 10, the state constraint $k(t)=m(t)N$ is binding with $\mu_2(6)=0.97$ and $\mu_2(10)=31.83$, corresponding to Cases 9 and 4 in Table 1, respectively (See Figure 9.) The objective function costs in Example 2 is modestly worse (3.9 percent) than Example 1, which had not been projected. Scrutiny of the data indicates that when the technology is so highly effective in capturing demand, the firm must defray additional costs to meet its expanded capacity requirements. In anticipation of future technological advancement, the optimal policy in Example 2 suggests that the firm buy more technology later in the planning horizon to capture its improved benefits on the market and maximize its long-term effectiveness.

Impact of Emphasis on Market Share

The model is responsive to the different values a particular firm may place on achievement of market share goals. This value is expressed as a penalty cost of the squared deviations between actual market share level and the goal level over time. In Example 3, the relative emphasis on achieving a desired level of market share is increased threefold over Example 1 (300,000 versus 100,000, respectively). The optimal policy illustrates this tradeoff. (See Figure 10.)

The firm acquires more flexible technology earlier in the planning horizon. In the optimal solution of Example 3, the accumulated level of output associated with the new technology is 37.5 percent greater than that observed in Example 1. The average value of actual market share is 8.3 percent greater. No capacity slack exists in periods 6-10. (See Figure 11.) In addition, the policy exhibits fewer reductions in conventional capacity in anticipation of future capacity requirements generated by the pervasive influence of the technology in the market place. In comparison with Example 1, the Example 3 objective shows a 6.4 percent increase costs. Example 3 illustrates the tradeoffs in effectiveness-oriented and efficiency-oriented measures. In order to effectively stimulate market share, increasing the importance of meeting the goal market share was necessary. This resulted in greater total costs to the firm in Example 3 versus Example 1. Therefore, in this example increasing the deviation penalty costs produces a policy yielding a better long-run effectiveness measure at a tangible cost premium. The percentage gain in the terminal time value of market share in Example 3 reflects a 13.9 percent improvement over Example 1.

3.6.3 Technological Advancement

Technological advancement is modeled by (a) assuming that the per unit cost of acquiring flexible technology decreases over time and (b) by increasing technological effectiveness in reducing the per unit production costs over time.

Impact of Reducing Flexible Acquisition Costs

In Example 4 the cost of acquiring flexible technology is expressed as a decreasing function of time $[(c_1(t)=40-3t)]$. This example marks the situation where a considerable cost reduction in the purchase of the technology is anticipated over the planning horizon due to technological advancement. Due to the expected cost reduction of technology over time, the optimal policy advocates the initial acquisition be postponed at least one period. In particular, in Example 4, the initial purchase of flexible automation occurs in period 7 in contrast to period 6 in Example 1. (See Figure 12.) The cumulative level of output from the new technology in Example 4 is almost double that observed in Example 1. Clearly, as the cost disparity between the flexible and conventional technology diminishes, there is a greater incentive to automate. In Figure 13 excess (slack) capacity is observed in periods 7 through 9 in anticipation of future capacity needs for period 10. A 1.0 percent improvement in the objective function is observed in Example 4 compared to Example 1.

<u>Impact of Internal Cost Reductions</u>

Relative efficiencies in the manufacturing processes have been observed with the acquisition of flexible automation. In particular, the term $\alpha(t)$ reflects the reduction in the per unit production plus in-process inventory cost associated with the acquisition of the new technology. In Example 5, where $\alpha(t)$ is increased from .001 to .050, the substitution of flexible automation for conventional equipment is observed in periods 2, 3 and 4 of the optimal solution. (See Figure 14.) As a result of this substitution, the per unit production plus in-process inventory costs are reduced over time.

A comparison of the optimal policies of Examples 5 and 1 illustrates the aggregate impact of more efficient automation. Not only is a higher level of flexible technology acquired in Example 5, but it is also obtained earlier in the planning period to capture the production efficiencies. Later, as more demand is generated from the enhanced output, additional capacity must be obtained. (See Figure 15.) In periods 6 thru 10 the firm is producing at the maximum capacity level with $\mu_2(6)=2.13$, $\mu_2(7)=6.01$, $\mu_2(8)=5.08$, $\mu_2(19)=4.28$ and $\mu_2(10)=22.48$. The objective in Example 5 exhibits a 1.8 percent reduction in costs in contrast to Example 1.

3.6.4 Exogenous Market Share Growth and Decline

Many firms face exogenous changes in market share over time. Examples 6 and 7 demonstrate the effect of the changing environmental forces on the market position of a firm in the derived optimal policies.

Impact of Exogenous Market Growth

In Example 6 a firm experiences exogenous growth in the aggregate product demand (life cycle) thereby serving to increase naturally its market share over time. A comparison of Examples 6 and 1 reveals it is more cost-effective to meet the majority of the firm's capacity requirements with conventional equipment. Here the product's natural growth cycle corresponds directly with the firm's desired dynamic goal level. The derived policy illustrates that due to the exogenous future growth, little need exists for the firm to reduce its conventional equipment. (See Figure 16.) Clearly, in the growing market, the acquisition of flexible automation to increase market share may not be as vital for survival and in fact, may cause the firm to acquire a higher level of market share than planned, as illustrated in Example 6, which may tax the organization's ability to support that level of growth.

The small increase in the cumulative level of automation in the periods 8, 9 and 10 is primarily due to the high salvage value of market share in period 10. The total cumulative level of output from flexible technology acquired in Example 6 is about two thirds of that obtained in Example 1. However, the output from new purchases of conventional capacity is 230 percent greater in Example 6 than Example 1. In fact, capacity just keeps pace with production requirements beginning in period 5 until period 10 [$\mu_2(5)$=5.36, $\mu_2(6)$=13.07, $\mu_2(7)$=11.37, $\mu_2(8)$=6.5, $\mu_2(9)$=1.37, and $\mu_2(10)$=34.10]. (See Figure 17.) In fact, the firm in this example faces higher total cost than one without such exogenous growth. In Example 6, the objective function reveals 7.4 percent higher costs that in Example 1 due to the need to acquire capacity to support the exogenous market growth.

Impact of Declining Market

In a highly volatile market fraught by increased competition, a firm may face the possibility of a declining market unless the product or service to the customer can be enhanced. Example 7, poses a situation wherein the firm faces a 5 percent exogenous reduction in the market share in each period. In order to maintain market holdings through economies of scope and production efficiencies, the firm adopts flexible technology. Specifically, 36.0 percent increase in output from the new flexible technology is advocated to defray the cost of a dwindling market share. In this example, the optimal policy suggests the firm replace its conventional capacity with new flexible automation. (See Figure 18.) In order for the firm to achieve a higher actual market share value than observed in Example 7, a higher weight must be placed on the achievement of the goal market share. The impact of a dwindling market is observed in Figure 19. The objective function value in Example 7 is only negligibly lower (0.1 percent) than that of Example 1. The potential benefit of flexible automation as a competitive weapon is clearly portrayed in Example 6.

3.7 CONCLUSION

Decisions concerning the technological composition of the firm's productive capacity over time constitute an important element of a firm's manufacturing process strategy. In this chapter a normative decision model is described in which the dynamic optimal mix of flexible automation and conventional technology should be achieved continuously over time to maximize the long-term effectiveness of the firm minus relevant costs incurred over the planning horizon. Effectiveness is defined as the value at the terminal time of the firm's attained market share level and the level of productive capacity minus the total penalty costs corresponding to deviations between actual and goal levels of market share. Also reflective in the objective function are certain relevant costs due to the acquisition of flexible systems components, purchases of conventional capacity, reductions in conventional capacity, production plus in-process inventories and maintenance of productive capacity.

The purpose of the model is to assist firms in strategic planning activities corresponding to the development of a manufacturing process strategy. The model affords the manager the opportunity to investigate under various scenarios the "optimal" time phased composition of manufacturing process technology, (i.e., flexible or conventional) from an aggregate, broad-based perspective. Embodied in the goal of the model are the tradeoffs between long-term effectiveness and costs. By assuming the acquisitions of flexible automation serve to both increase market share and productive capacity as well as diminish the per unit production plus in-process inventory costs over time, a manager may examine the relative impact of the new flexible automation on the firm's competitive position and costs over time.

Analysis of the model through numerical examples has been presented wherein the relative effectiveness of the flexible technology, the firm's emphasis on attaining goal market share levels over time, the impact of technological advancement and the impact of exogenous market share growth and decline factors were specifically examined. While the total acquisitions of flexible automation varied among the examples, the strategic importance of flexible automation as a competitive weapon under the assumption of market responsiveness to the enhanced outputs (quality, price and flexibility) is scrutinized. We demonstrate that competition may be a primary motive for acquiring flexible automation. It is shown that without competition, there is much less incentive to purchase costly new flexible technology. Hence, unless flexible technology produces a magnitude of efficiencies which offset the higher acquisition costs rational firms will continue to meet capacity needs with conventional technology in abeyance of competition.

As previously mentioned, the model is applicable to those firm's whose overall strategy is to smooth the purchases of flexible automation over the planning horizon in order to provide sufficient time for the necessary infrastructure changes to accommodate the new technology. In order to model the desired smoothing, quadratic costs were assumed in the objective function in Equation 3.1. It should be noted the specific cost assumptions expressed in Equation 3.1 are not required to derive solutions;

however, depending upon the cost functions assumed, different optimal policies for the control variables would be advocated and the numerical solution could be obtained by modifying the algorithm presented in Section 3.5.

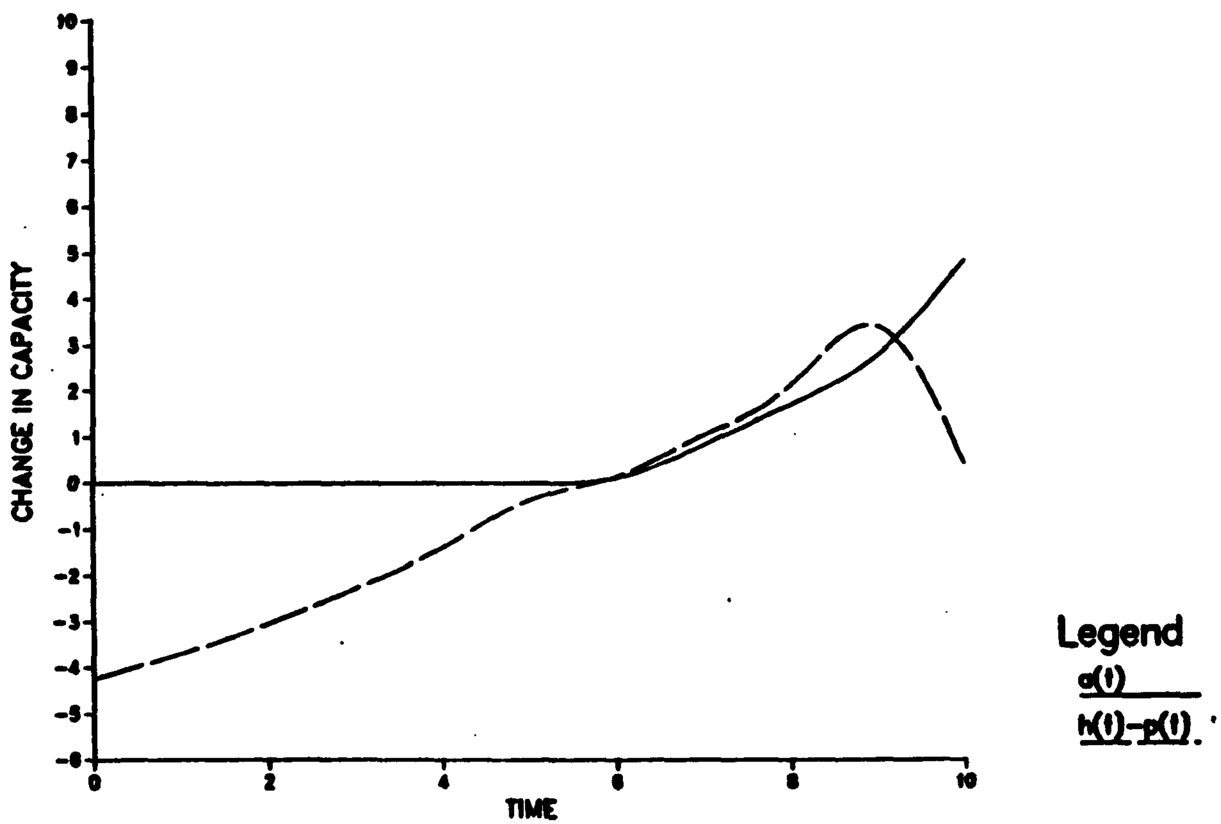

Figure 6. Optimal Control Policies: Example 1

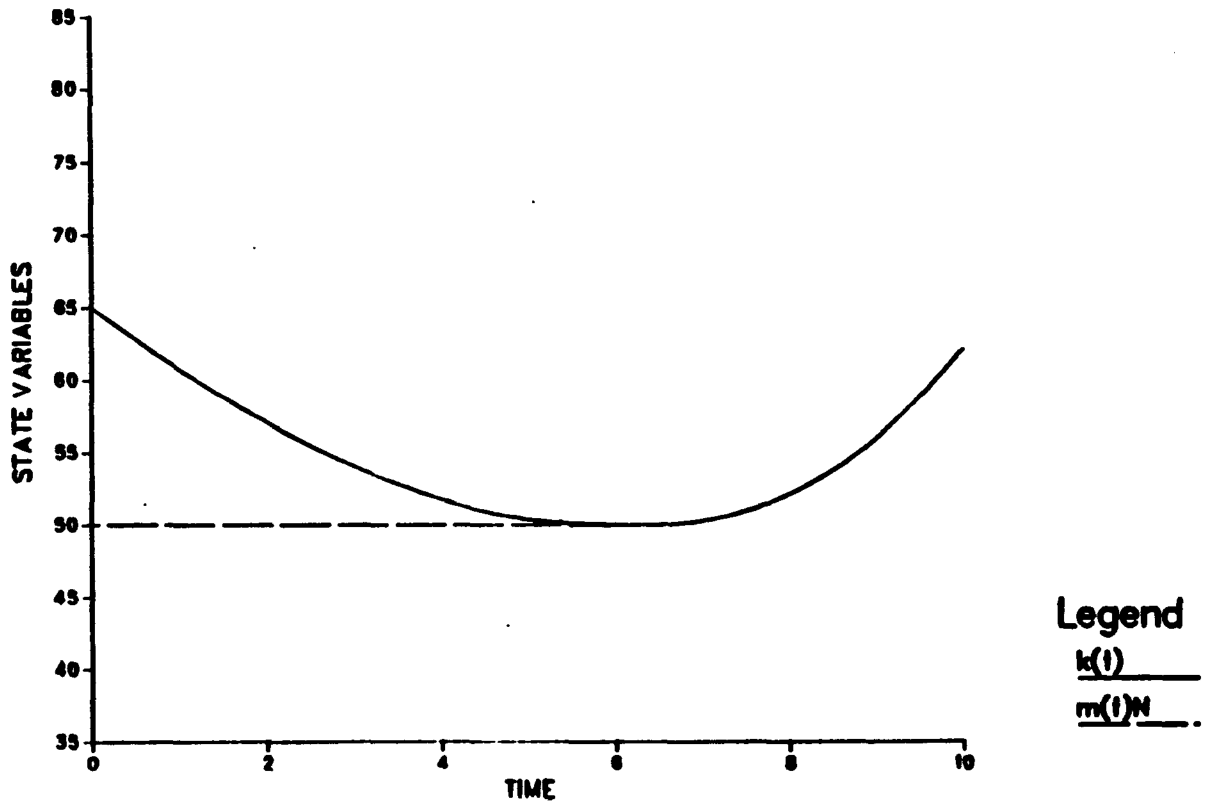

Figure 7. Total Capacity and Production Levels: Example 1

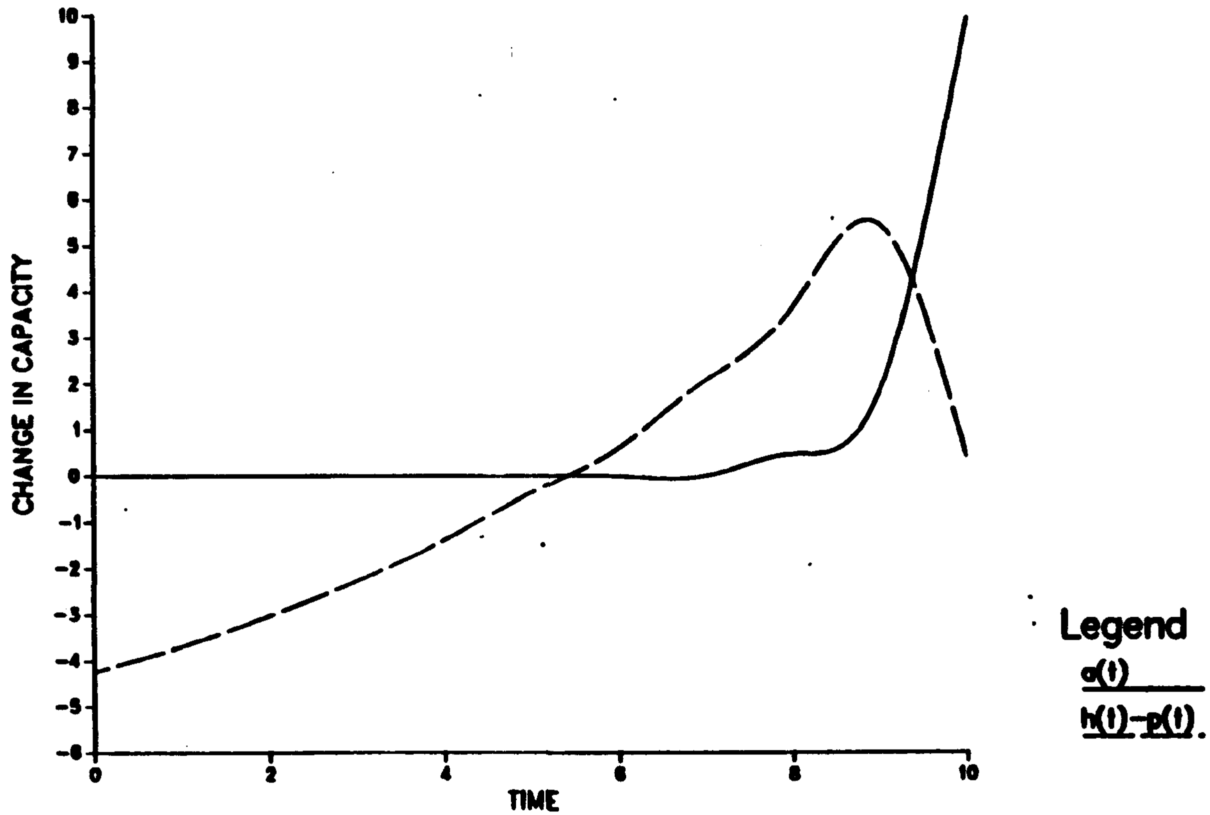

Figure 8. Optimal Control Policies: Example 2

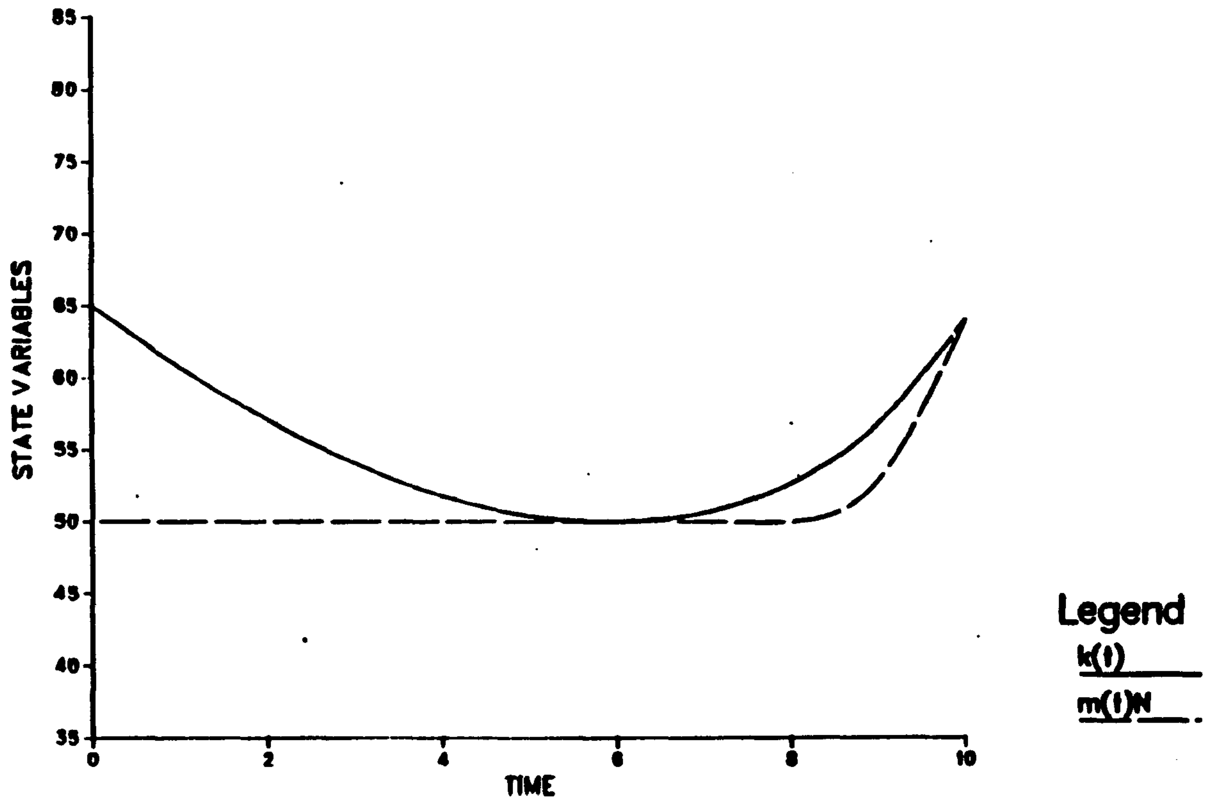

Figure 9. Total Capacity and Production Levels: Example 2

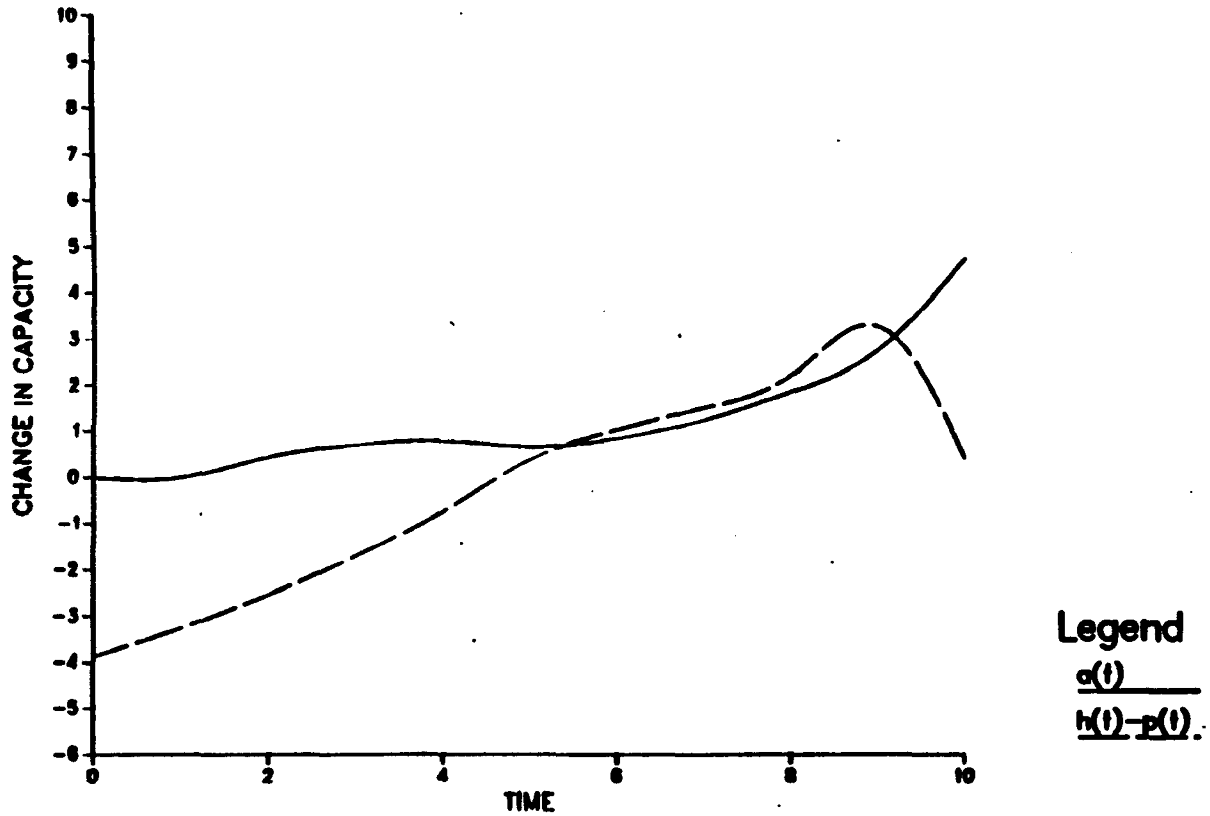

Figure 10. Optimal Control Policies: Example 3

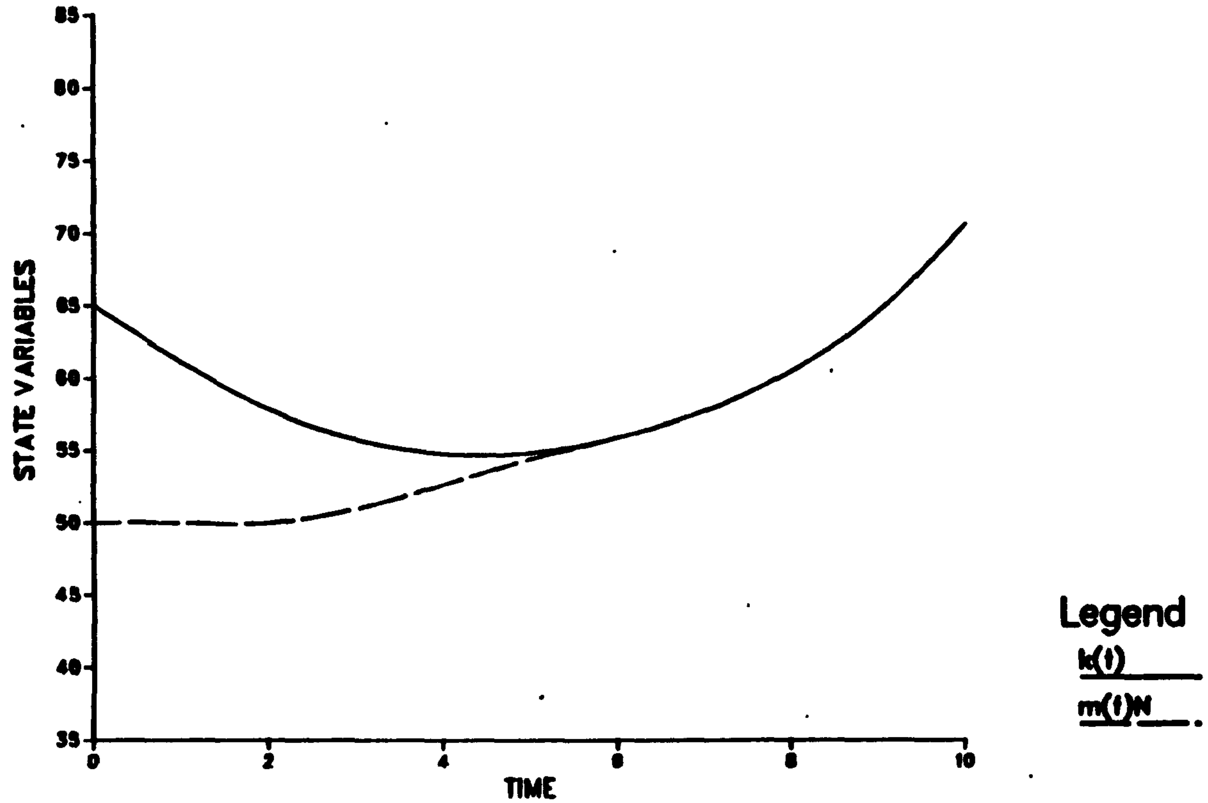

Figure 11. Total Capacity and Production Levels: Example 3

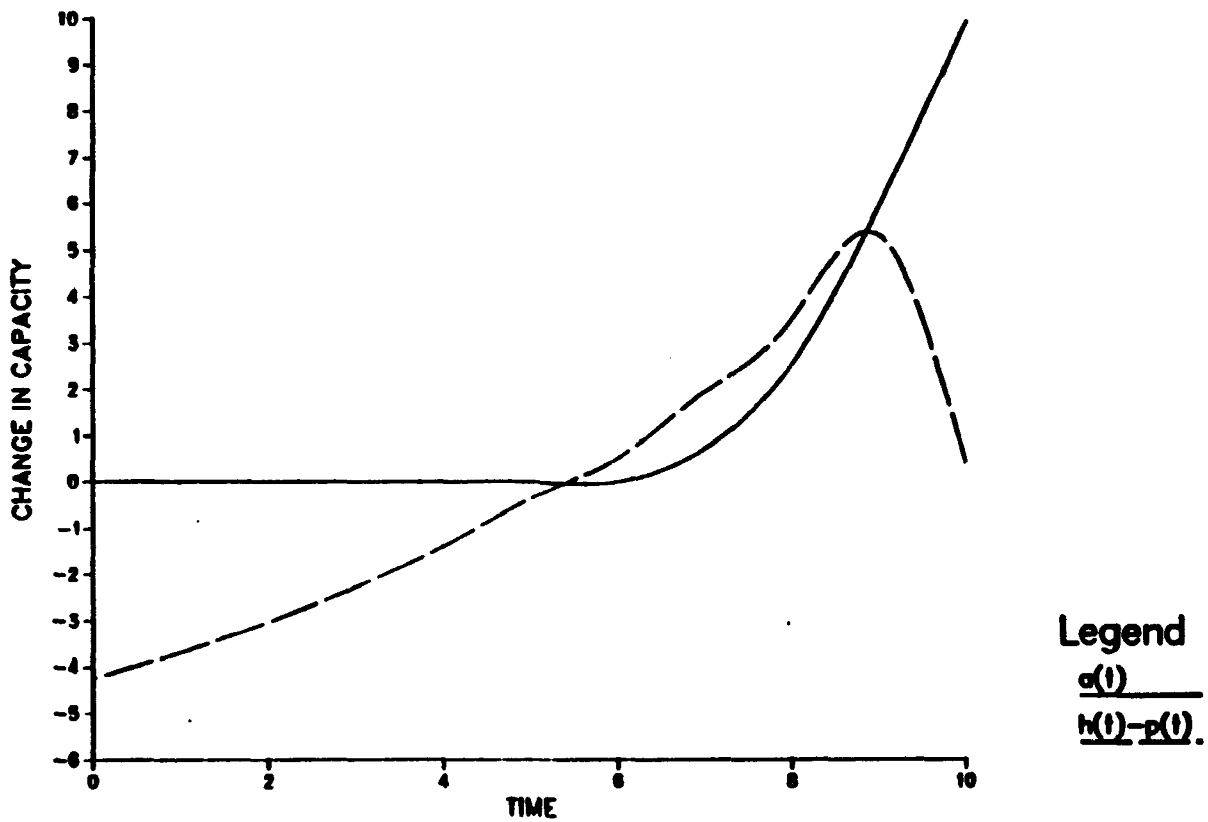

Figure 12. Optimal Control Policies: Example 4

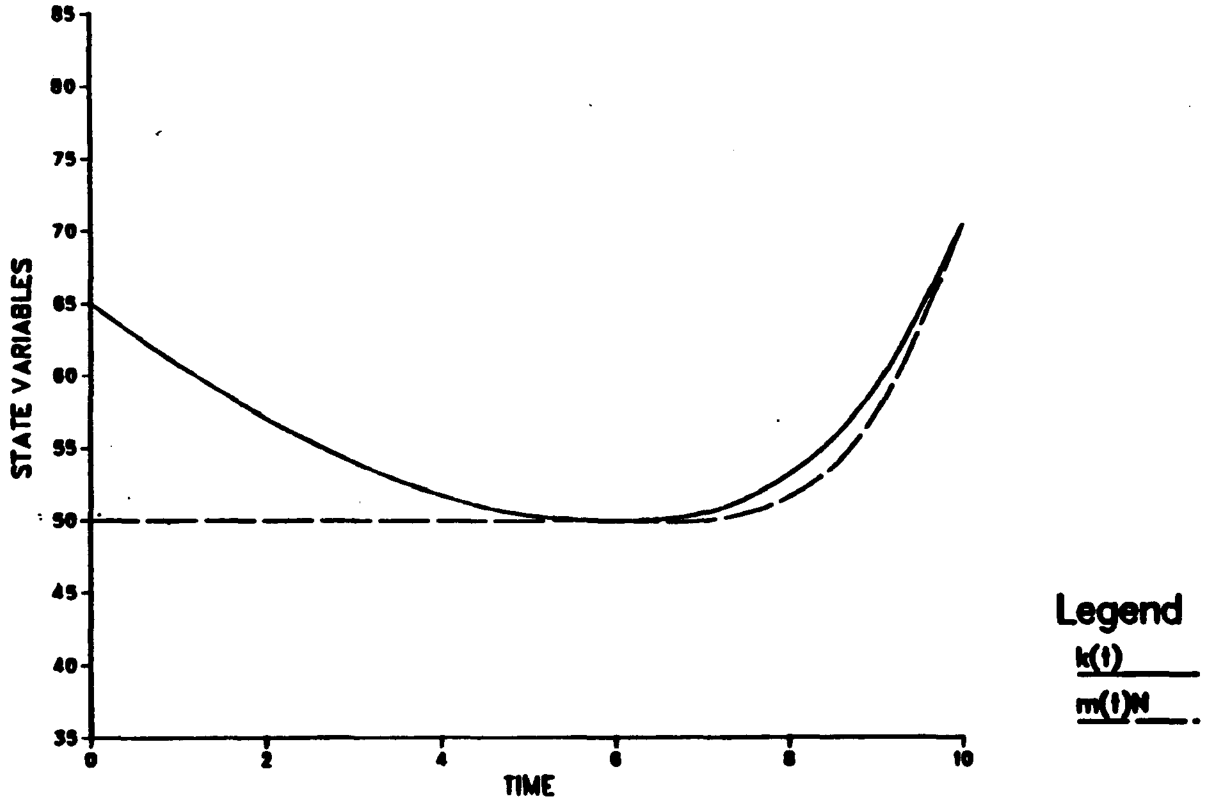

Figure 13. Total Capacity and Production Levels: Example 4

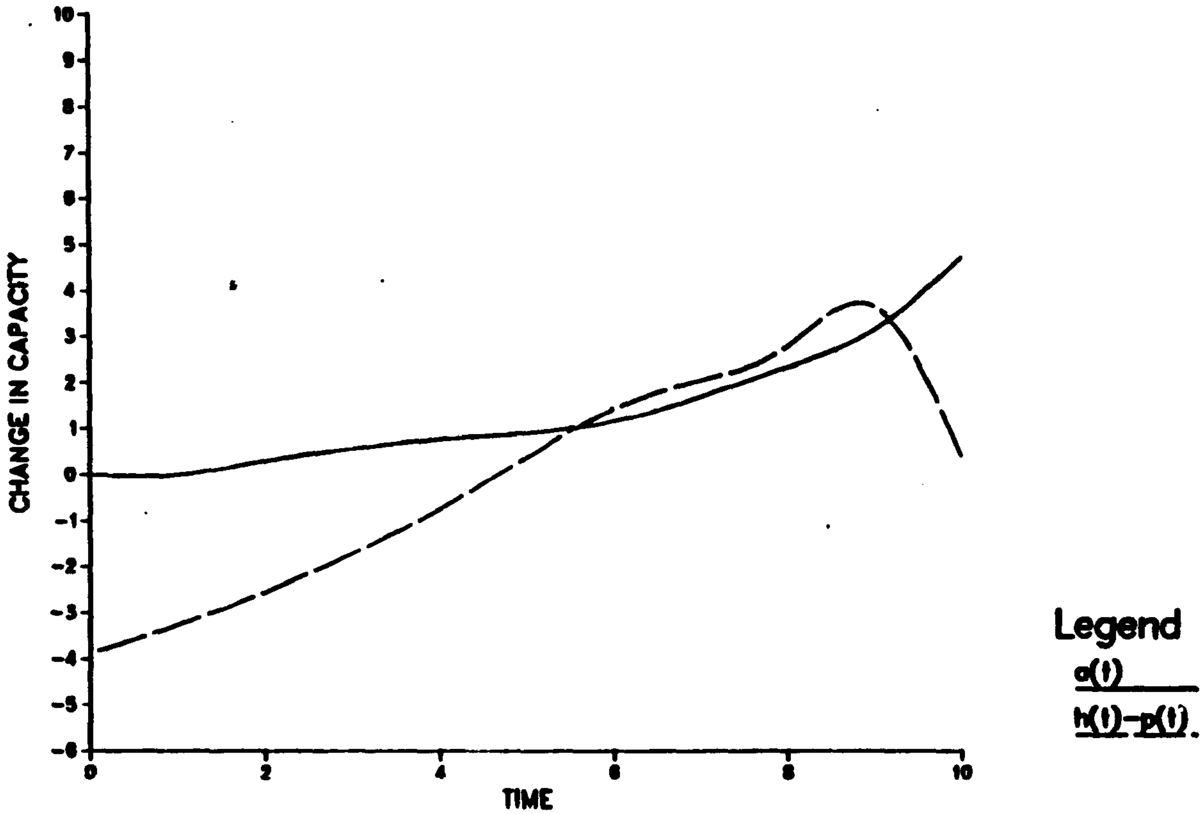

Figure 14. Optimal Control Policies: Example 5

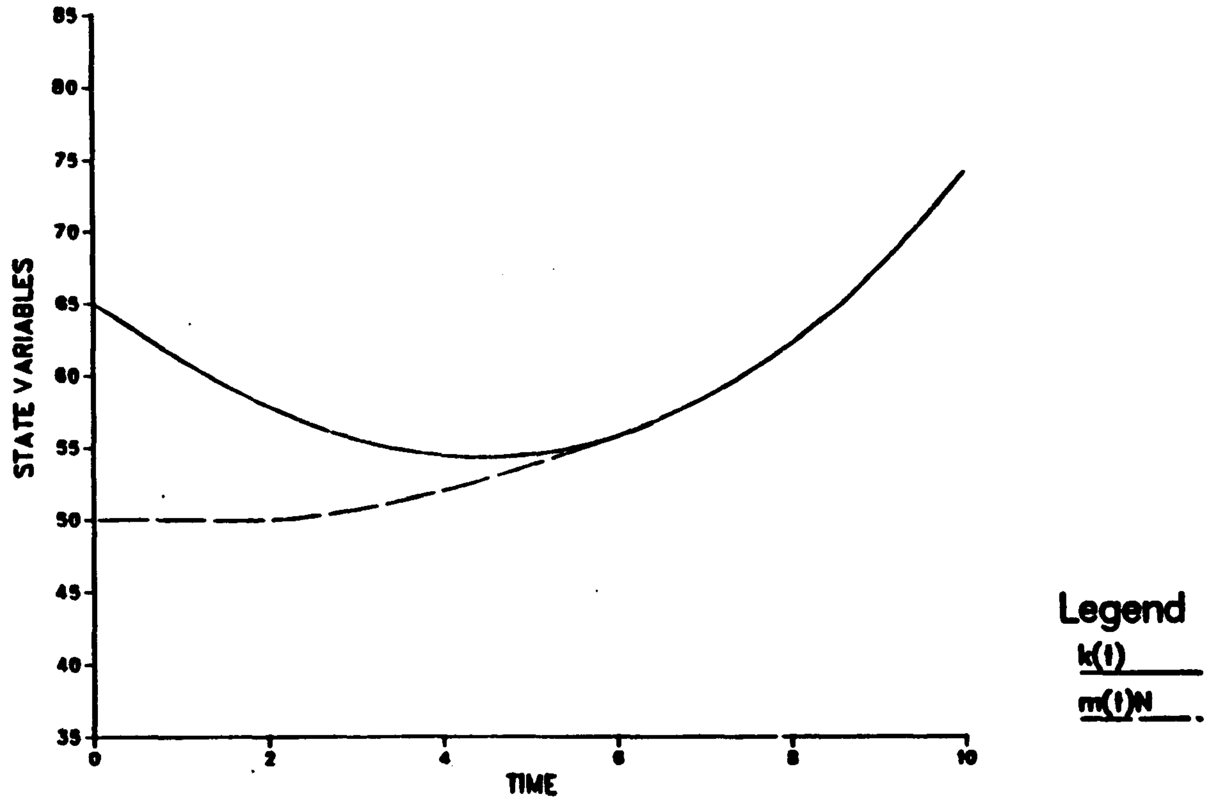

Figure 15. Total Capacity and Production Levels: Example 5

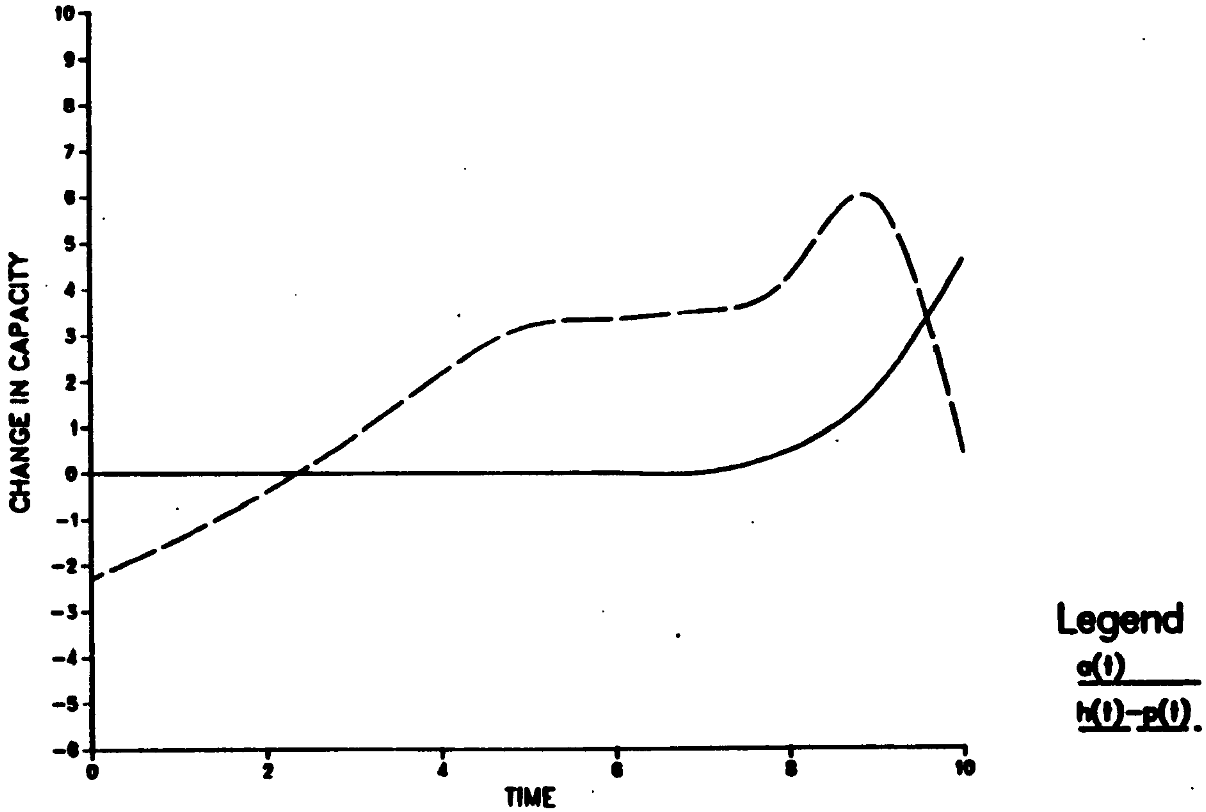

Figure 16. Optimal Control Policies: Example 6

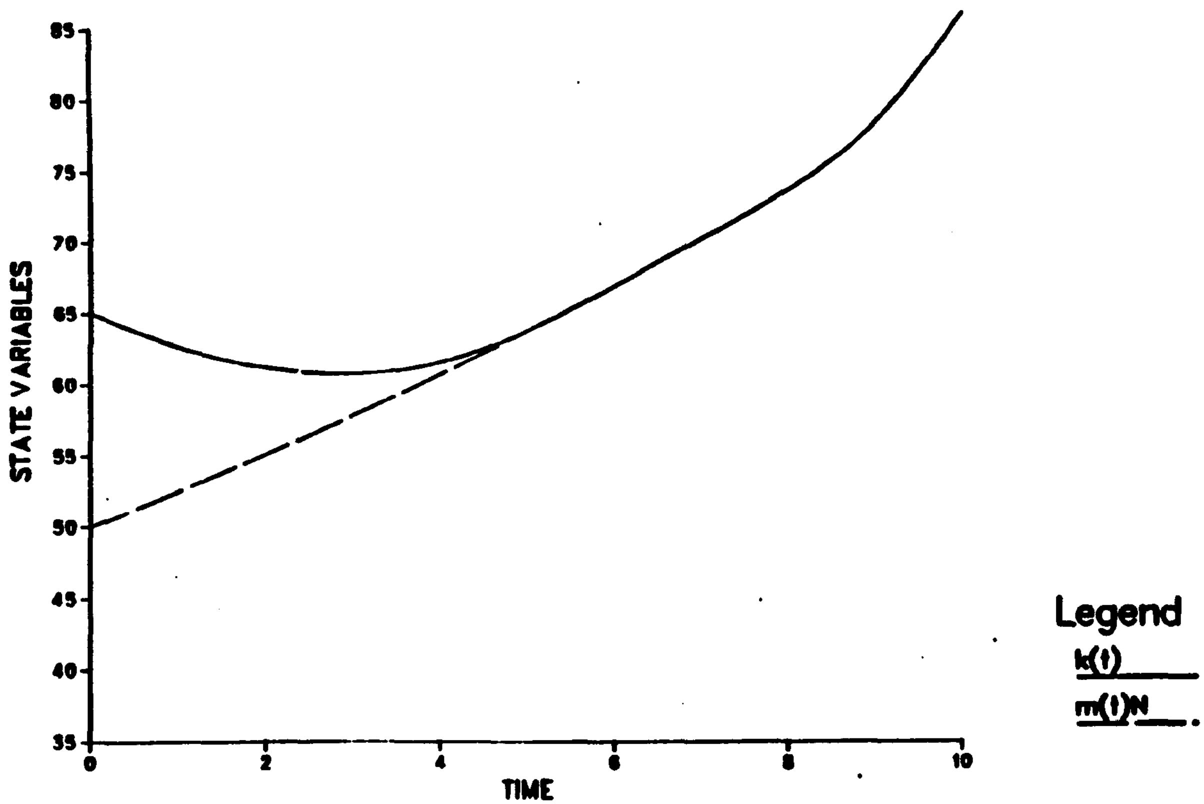

Figure 17. Total Capacity and Production Levels: Example 6

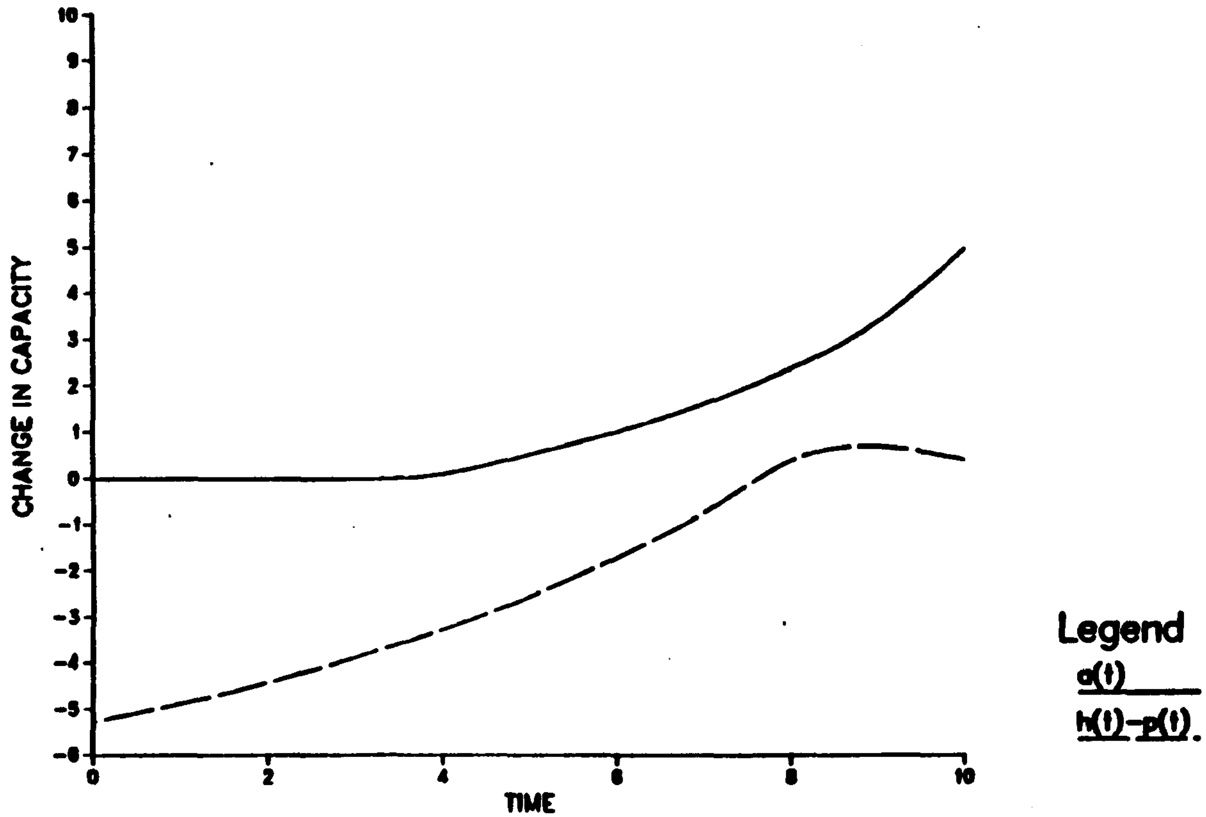

Figure 18. Optimal Control Policies: Example 7

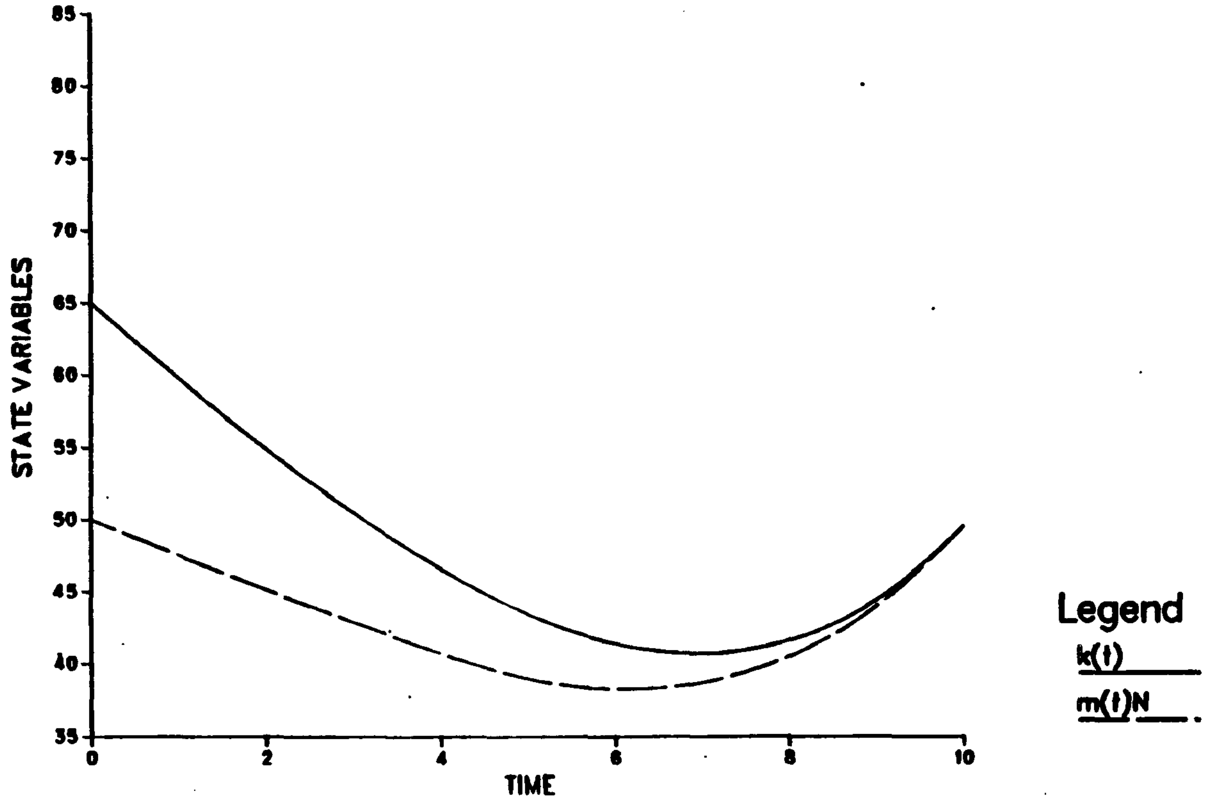

Figure 19. Total Capacity and Production Levels: Example 7

CHAPTER 4

OPTIMAL ACQUISITION OF FMS TECHNOLOGY SUBJECT TO TECHNOLOGICAL PROGRESS: MODEL II

4.1 INTRODUCTION

The managements of manufacturing firms are beset with complex strategic decisions. In particular, the firm must consider the composition of productive capacity and the technology to be employed. Because of the accelerating rate of technological change, a high degree of uncertainty exists not only over the economic life of the new equipment but also upon its pervasive influence on the firm's competitive position. Technology influences both the industry structure and the boundaries upon which the firm operates. Firms must determine whether or not it is better to invest now or wait for the next generation of technological improvements. The strategic importance of new technology as a competitive weapon in manufacturing systems is well-documented (Skinner 1978; Abernathy et al. 1981; Hayes and Abernathy 1980; Hayes and Wheelwright 1979b, 1984; Buffa 1984; Porter 1985).

This chapter treats the dynamic strategic problem of the optimal timing and sizing of purchases of new flexible manufacturing systems (FMS) technology where technological progress can reasonably be hypothesized. A dynamic decision model is introduced in which the strategic impact of acquiring new flexible manufacturing systems components is examined. The objective function is multicriterion and addresses the tradeoffs among competing goals.

Specifically, the objective of the model is to maximize the strength of the firm at the terminal time. The strength of the firm is a proxy variable for the firm's relative net worth and is defined by the respective discounted values placed upon the levels of demand, productive capacity and technological progress factor at the end of the planning horizon minus discounted costs incurred over time. Dynamic costs considered in the model are those corresponding to (a) penalties for deviations between actual and planned levels of demand, (b) the acquisition of new flexible manufacturing technology, (c) reductions in the level of vintage technology, (d) production plus in-process inventory and (e) penalties arising from under and overutilization of operating capacity.

First, the model captures the impact of flexible automation on the level and composition of productive capacity both at the actual time of acquisition and beyond. Second, the model considers the relative influence of flexible automation and organizational experience on demand over time. Third, the model treats the effect of flexible automation on the per unit production costs over the planning horizon.

In order to address the relationship between productive capacity and the acquisition of flexible automation, it is assumed that capacity is augmented at the time of each purchase. Further, the effect of cumulative experience with the new flexible process technology on increasing the level of productive capacity beyond the time of initial acquisition is demonstrated. With respect to the issue of cumulative experience, it is assumed that the level of capacity expands as a result of organizational learning (Yelle 1979, Joskow and Rozanski 1979, Andress 1954).

Consideration of organizational learning which encompasses the collective learning from all sources within the firm is important for strategic aggregate modeling in a production environment (Ebert 1976, Hayes and Wheelwright 1984). Organizational learning is primarily associated with changes in technical knowledge attained by the firm and to a lessor extent labor learning (Hirsch 1952). Empirically, technological progress, a major component of organizational learning, has been shown to be valuable in assessing learning in a capital intensive environment where the learning curve phenomena might have otherwise been thought to be inapplicable (Hirschmann 1984).

When planning for the acquisition of flexible automation, the importance of technological progress based upon cumulative experience cannot be overlooked. In fact, Porter (1985) states technological change is the basis of the learning curve. Technological experience must be considered in a flexible manufacturing systems environment because of (a) the inherent complexity of the new technology modules, (b) the difficulties which arise in the integration of complex systems, (c) limited managerial and organizational experience with this technology, (d) the required innovations in product designs and (e) new process start ups. These factors require modification of managerial practices and transfer of technical knowledge for maximum productivity and improved system utilization over time (Jaikumar 1984; Gerwin 1982; Gold 1985a,b,c). Further, as components of flexible automation are acquired, learning serves to increase capacity due to a manufacturing synergy function. Manufacturing systems synergy occurs as the various pieces of flexible technology are tied together and enhance the performance of other capacity currently in place (Meredith 1985).

Besides impacting on the firm's operating capacity, the effectiveness of flexible automation on enhancing the firm's ability to compete in the market place is assumed. This assumption is predicated upon the supposition the outputs of the productive system are enhanced as a result of acquiring new flexible technology and technological progress. The product is improved in terms of quality, price, innovativeness in design, delivery, service, and production volume and mix flexibility. These product and service characteristics directly affect the firm's demand over time (Bylinsky 1983; Gold 1982a,c; Davis et al. 1985; William and Tuttle 1984; Abell and Hammond 1979).

Clearly, flexible automation affords certain manufacturing firms the opportunity to pursue a broader marketing strategy thereby capturing a portion of their competitor's demand (McDougall and Noori 1985, Starr and Biloski 1983, Davis et al. 1985). For example, flexible automation offers mid-volume batch manufacturing firms the opportunity to compete on both price and product differentiation (Strobaugh and Telsio 1983, Goldhar 1984).

The per unit production plus in-process inventory cost is comprised of two parts. One part of this cost is unaffected by acquiring new technology. The acquisition of flexible technology acts to reduce the second component of the variable costs of production over time. Certain costs such as those associated with in-process inventory, scrap, rework, and utilization of raw materials are assumed to diminish as flexible automation is purchased (Groover 1980; Gold 1982a,c). Also, it is postulated that as subsequent purchases of technology are made over time the magnitude of reduction in the per unit cost decreases (i.e. diminishing returns are observed).

In related research, the effect of acquiring automation on increasing capacity and reducing production costs is considered. However, the capacity improvements due to technological progress and the market response in terms of demand are not included (Barr 1982; Hinomoto 1965; Kamien and Schwartz 1972; Gaimon 1982a, 1985a,b,d). Furthermore, this previous research does not permit decisions regarding the underutilization of capacity and use of short-term measures to meet demand in excess of capacity. In Chapter 3, while market responsiveness to automation is considered, neither technological progress nor temporary capacity expansion measures are treated explicitly.

We assume all demand is satisfied at the time it is required through the available operating capacity or through the use of short-term measures which increase capacity (e.g. overtime and reductions in scheduled maintenance). Hence, sales equals demand and no backlogging or backordering of demand occurs. Dynamic adjustments in the level of operating capacity are made through purchases of new flexible technology and reductions in existing productive capacity. Acquisitions of new flexible automation either augment and enhance capacity currently in place or substitute for vintage capacity. Furthermore, it is assumed the firm desires to adopt on evolutionary timing strategy with respect to the acquisition policy. Therefore, the level of productive capacity is modified continuously over time as the modules of new flexible capacity are linked together. Under an evolutionary course of action, it is assumed the relative magnitude of each acquisition of flexible automation and reduction of vintaged operating capacity to the total level of productive capacity is small at any instant of time. (See Chapter 1 and 3.)

In Sections 4.2 and 4.3, respectively, the notation and the model are defined. Decision policies are derived as continuous functions of time indicating both (a) the optimal rate at which flexible automation modules should be acquired and (b) the optimal rate at which the level of existing capacity should be reduced over time. Further, it is demonstrated under the assumptions of the model that as technology becomes outdated, newer equipment may be acquired to replace existing capacity so that the composition of productive capacity is upgraded. It is shown that technology may be acquired to improve the firm's level of demand or to reduce operating costs over time even if no increase in productive capacity is desired.

A numerical solution algorithm is presented in Section 4.5. Illustrative examples of optimal policies and resultant state variables under varying exogenous conditions are discussed in Section 4.6. Specifically, the numerical examples illustrate the impact of acquiring flexible automation on demand, operating capacity, relative efficiency, and technological progress.

4.2. BASIC NOTATION

Prior to the formal presentation of the model the basic notation is introduced. First, the decision variables which are endogenously determined by the model are presented. Second, the exogenous input parameters are defined. These exogenous variables capture the dynamic environment in which a particular optimal solution is obtained. Note that t represents time, $t \in [0,T]$, where T is the terminal time of the planning horizon.

4.2.1 Endogenous Variables

$s(t)$ = level of demand as a function of the firm's available market share at time t expressed in units of output, $s(0)=s_0$; (state variable).

$k(t)$ = total level of operating capacity at time t, expressed in units of output at time t, $k(0)=k_0$; (state variable).

$\alpha(t)$ = technological progress factor which indicates the percentage level at time t corresponding to productivity improvements in operating capacity due to learning, $0 \leq \alpha(t) \leq 1$, $\alpha(0)=\alpha_0$; (state variable).

$x(t)$ = accumulated level of flexible technology acquired over the planning horizon through time t expressed in units of output, $x(0)=x_0$; (state variable).

$c_3(t)$ = level of one of two components of the per unit production plus in-process inventory costs at time t that can be reduced by the acquisition of flexible technology, $c_3(0)=c_{30}$; (state variable).

$a(t)$ = rate of increase in the level of flexible technology held at time t expressed in units of output, $a(t)\epsilon[0,A(t)]$, where A(t) represents the maximum rate of increase in flexible automation that can be achieved at time t; (control variable).

$r(t)$ = rate of scrapping/reducing the level of existing operating capacity (a mix of conventional and flexible technology) at time t expressed in units of output, $r(t)\epsilon[0,R(t)]$, where R(t) represents the maximum rate of scrapping of capacity permitted at time t; (control variable).

4.2.2 Exogenous Variables

$\hat{s}(t)$ = predetermined goal level of demand expressed in units of output at time t.

$c_1(t)$ = cost per unit squared rate of purchasing and implementing flexible technology at time t.

$c_2(t)$ = cost per unit squared rate of scrapping or reducing capacity at time t.

d = a coefficient reflecting the most effective (desired) level of operating capacity utilization, $0<d\leq1$.

$c_4(t)$ = cost per unit squared deviation between demand and the desired level of capacity utilization at time t.

$c_5(t)$ - cost per unit deviation between demand and the desired level of capacity utilization.

$B(t)$ - one of two components of the per unit production plus in-process inventory costs which is unaffected by the acquisition of flexible automation at time t.

$v(t)$ - cost per unit squared deviation between the goal and actual levels of demand at time t.

$\gamma_1(t)$ - effectiveness factor associated with the market response that occurs as a result of enhanced capacity, either due to new acquisitions of flexible technology or as a result of technological progress at time t, $0 \leq \gamma_1(t) \leq 1/A(t)$.

$\gamma_2(t)$ - rate of growth/deterioration in firm's demand at time t, $-1 \leq \gamma_2(t) \leq H$, where H is a predetermined upper bound on the growth factor.

$\psi(t)$ - percent reduction in the technological progress factor due to natural change at time t, $0 \leq \psi(t) \leq 1$.

$\phi(t)$ - effectiveness of the flexible automation on improving the technological progress factor due to system synergy at time t, $0 \leq \phi(t) \leq 1$.

$\beta(t)$ - efficiency factor associated with the percentage reduction in the per unit production plus in-process inventory costs due to acquiring new flexible technology at time t, $0 \leq \beta(t) \leq 1/A(t)$.

N - total market demand expressed in units of output.

G_1 - value per unit demand (goodwill) at terminal time, T.

G_2 = value per unit capacity at the terminal time, T.

G_3 = value per unit technological progress factor at the terminal time T.

ρ = continuous discount rate.

4.3. THE MODEL

4.3.1 The Objective Function

Using the notation introduced in Section 4.2, Equation (4.1) represents a dynamic, multicriterion objective function. Strategic factors of strength and cost are weighed in order to determine the optimal level of demand and the optimal composition of productive capacity. Therefore, the objective of the model is defined to maximize the discounted 'strength' of the firm at the terminal time minus the discounted costs incurred over the planning horizon.

The firm's strength is a proxy variable for the firm's relative net worth. Relative strength is captured as the sum of the total discounted values at the terminal time associated with the firm's level of demand, productive capacity and the technological progress factor minus penalty costs corresponding to deviations between actual and planned levels of market demand over the planned horizon. In addition, other costs reflected in the objective function include those corresponding to changes in the level and composition of productive capacity, the use of short-term capacity expansion measures, underutilization of operating capacity and production plus in-process inventory. The model captures the firm's market share in the objective function by defining a desired level of demand in terms of the total market and corresponding strategic business unit (SBU) goals.

MAXIMIZE

$$[G_1 s(T)+G_2 k(T)+G_3 \alpha(T)]e^{-\rho T}-\int_0^T \{v(t)[s(t)-\hat{s}(t)]^2$$

(a) (b)

$$+c_1(t)a^2(t)+c_2(t)r^2(t)+[B(t)+c_3(t)]s(t)$$

(c) (d) (e)

$$+c_4(t)[dk(t)-s(t)]^2-c_5(t)[dk(t)-s(t)]\}e^{-\rho t}dt \qquad (4.1)$$

(f) (g)

The objective can be decomposed as follows: (a) the firm's discounted strength at the terminal time minus the discounted costs over the planning horizon comprised of (b) the squared deviation between the actual and goal levels of demand, (c) the cost of obtaining and implementing new flexible automation, (d) the cost of reducing the current level of operating capacity, (e) the production plus in-process inventory cost, and (f) and (g) corresponding to the costs of deviations between actual demand and the desired level of capacity utilization, respectively.

Note the fixed operating and production costs are omitted from the objective function. These fixed costs are present regardless of the composition of the productive capacity, and therefore, are considered to be sunk costs which are irrelevant to the decision making process.

The demand goal level in (b) is assumed to have been exogenously established according to the firm's overall competitive strategy as defined by the SBU, the expected aggregate product life cycle and the total available market. In this formulation, any actual demand deviations from the desired level are equally penalized. When demand exceeds the goal, the firm's organizational structure may be severely strained (Ryans and Shanklin 1985). On the other hand, underachievement of the desired demand goal has direct bearing on the firm's long-term survival and competitive position.

Anticipated to vary over time are (c) the costs of purchasing and implementing the new flexible technology and (d) the costs of reducing productive capacity. These costs are formulated as quadratic functions to reflect (a) the evolutionary timing strategy of continuous acquisitions (See Chapter 3.) and (b) the proportionate difficulties which may arise due to large changes in the means of production at any single instant of time (Hax and Candea 1983).

The costs defined in (f) and (g) are penalty functions corresponding to deviations between the actual level of demand and the desired level of capacity utilization over time. The desired level of capacity is defined as dk(t) and has been empirically identified as the capacity utilization level with minimal unit costs (Baetge and Fischer 1982). It may also be identified to correspond with the term 'capacity cushion' (Hayes and Wheelwright 1984).

The linear term (g) serves to change the magnitude of the total deviation costs according to the sign of $c_5(t)$. By defining $c_5(t)>0$, a firm places more emphasis on maintaining operating capacity at a level in excess of demand rather than on being short of capacity. In this situation, it is desirable to maintain excess capacity in order to meet temporal demand fluctuations. Here the firm would expect to employ less frequently short-term capacity measures to meet demand in excess of prespecified desired level of capacity utilization over time.

Alternately, a firm may emphasize maximum capacity utilization and desire to rely more heavily on short-term capacity expansion measures to meet temporal demand fluctuations. In this instance, $c_5(t)<0$ will impose a heavier penalty whenever capacity exceeds actual demand. Note the similarity of (f) and (g) with the asymetric formulation of overtime and undertime specified in the HMMS model (Holt et al. 1960, Hax and Candea 1983). A similar construction could be applied to (b) if asymetry in the relative importance of underachieving or overshooting planned demand goals exists.

4.3.2 The Constraints

Five equations are introduced to depict the dynamics of the state variables. First, changes in the level of demand are defined in Equation (4.2) as the sum of the change in the selective demand and the primary demand (Abell and Hammond, 1979). As previously discussed, it is assumed that the acquisition of flexible technology serves to enhance the productive capacity and thereby offers a competitive advantage in the market place due to economies of scope. In other words, the outputs of the new automation influence the price charged, the quality of the product, the degree of customization and innovation in design, the volume produced, reductions in delivery lead time and general system flexibility (Bylinsky 1983; Gold 1982a,c; Davis et al, 1985).

Selective demand is that portion of the competitor's demand which the firm obtains through enhanced capacity. It is assumed that the productive capacity is enhanced at time t due to the value-added contributions of new acquisitions of flexible automation plus capacity gains corresponding to technological progress. This enhanced operating capacity, $[a(t)+\alpha(t)k(t)]$, serves as a market stimulus and $\gamma_1(t)$ represents the market responsiveness to the value-added capacity at time t. Therefore, $\gamma_1(t)[a(t)+\alpha(t)k(t)]$ represents the total percentage gain in selective demand due to the total enhanced productive capacity acquired at time t. The term $\gamma_1(t)[a(t)+\alpha(t)k(t)][N-s(t)]$ is comprised of the product of the total percentage gain in selective demand due to $[a(t)+\alpha(t)k(t)]$ units of enhanced capacity and the total level of the demand currently held by the firm's competitors. Therefore, this term represents the total increase in demand due to acquiring the new flexible technology and technological progress over time. It is assumed the purchase of new flexible technology never reduces the firm's aggregate product demand.

Primary demand occurs as a result of exogenous changes in the market. The total effect of the outside influences on demand is encompassed by the term $\gamma_2(t)s(t)$, where $\gamma_2(t)$ represents the exogenous market growth/decay factor per unit demand at time t. Thus, $\gamma_2(t)$ includes the effects of the position of the aggregate product in its own life cycle, changes in the elasticity of demand due to competitive forces or consumer preferences, the general economic climate, or other environmental forces which impact on demand at time t. Given the bounds on $\gamma_1(t)$ and $\gamma_2(t)$, it is clear from Equation (4.2) that $s(t)\geq 0$ holds for $t\epsilon[0,T]$, so that no backlogging of demand occurs.

$$s'(t)=\gamma_1(t)[a(t)+\alpha(t)k(t)][N-s(t)]+\gamma_2(t)s(t) \qquad (4.2)$$

The change in the level of new flexible technology accumulated through time t is shown in Equation (4.3). The initial level of flexible automation held by the firm at time zero is denoted by x_0. Changes in the level of flexible automation occur as a result of new acquisitions over time. The term x(t) is a proxy variable indicative of the firm's cumulative experience with new technology at time t and, in later state equations, serves to reflect diminishing returns in organizational learning and system synergy.

$$x'(t)=a(t) \qquad (4.3)$$

In Equation (4.4), the change in the firm's total productivecapacity is expressed as the sum of the new flexible technology acquired minus planned reductions in the existing operating capacity plus the net additions due to technological progress. The parameter $\alpha(t)$ is a factor reflecting improvements in system utilization and productivity caused by technological progress per unit capacity held by the firm. Here improvements in layouts, machine loading, machine speeds, yields, use and integration of system components, and improvements in management methods contribute to learning (Porter 1985). Due to the quadratic penalty term (4.1.f) in the objective function, given appropriate weights, positive levels of operating capacity, $k(t)>0$, are assumed to hold over the planning horizon for all realistic problems (Bensoussan et al. 1979).

$$k'(t)=a(t)-r(t)+\alpha(t)k(t) \tag{4.4}$$

The composition of productive capacity is upgraded when new flexible technology is substituted for vintage existing capacity. In this case, both $a(t)>0$ and $r(t)>0$ occur simultaneously at time t. The state constraint presented in Equation (4.5) assures that the rate of reduction in existing capacity at time t, $r(t)$, decreases the level of capacity in place prior to the acquisition, $[k(t)-a(t)-\alpha(t)k(t)]$, and not the newly purchased flexible technology.

$$k(t)-a(t)-\alpha(t)k(t)\geq r(t) \tag{4.5}$$

As described in Section 4.1, an evolutionary or incremental timing policy is assumed where the organization's strategic plan mandates a smooth, continuous changeover from old to new technology within an existing plant. Furthermore, given this management policy, the relative magnitudes of change in the composition of capacity are small at any instant of time. In particular, $R(t)$ and $A(t)$ would be small relative to $k(t)$. Clearly, for any particular solution, the exogenous input parameters which would cause Equation (4.5) to be violated would be inconsistent with this underlying tenet of the model concerning an evolutionary timing strategy. For this reason, the state constraint represented in Equation (4.5) is not treated explicitly in the model.

The fourth state equation defines the change in the level of the technological progress factor over time. Equation (4.6) is comprised of two parts. First, $\alpha(t)$ is exogenously reduced over time as the firm gains more technological knowledge and experience. Here the term $-\psi(t)\alpha(t)$ represents the natural rate of change in $\alpha(t)$ at time t. A relatively large value of $\psi(t)$ corresponds to a relatively steep learning curve where capacity increments due to technological progress become negligible rather quickly where the inverse is true when $\psi(t)$ is relatively small.

Second, $\alpha(t)$ is increased over time due to the effectiveness of subsequent acquisitions of flexible technology which serve to further reduce direct labor hours, yield better utilization of capacity and provide system synergy as the modules of flexible technology are integrated. Here the term $\phi(t)a(t)/x(t)$ acts to modify the natural rate of progress due to the system synergy afforded by purchases of new flexible capacity. The larger the value of $\phi(t)$, the greater the system synergy afforded by the new flexible technology acquisitions.

Note that effectiveness of acquisitions of new technology on the technological progress factor is subject to diminishing returns. As a result after some time period, only negligible improvements in capacity utilization and productivity will be observed as a result of continued acquisitions of new technology. The rate at which the marginal benefits of technological experience decline over time is a function of the exogenous input parameters $\psi(t)$ and $\phi(t)$.

$$\alpha'(t) = -\psi(t)\alpha(t)[1-\phi(t)a(t)/x(t)] \qquad (4.6)$$

In addition to increasing capacity and demand, the acquisition of flexible technology reduces the per unit production cost. For example, reductions in scrap, raw materials, in-process inventories and storage are frequently cited as reasons for acquiring flexible technology. The fifth state equation illustrates the manner in which flexible automation is assumed to reduce this production cost. The percent reduction in the per unit plus in-process inventory cost corresponds to the proportional production efficiencies gained from the acquisition of flexible systems technology. Efficiency is captured by the parameter $\beta(t)$.

In Equation (4.7), the magnitude of the reduction in this per unit cost is shown to be proportional to the level of the per unit production plus in-process inventory cost at time t. Since $\beta(t)a(t)$ represents the total percentage reduction in $c_3(t)$ due to the acquisition of flexible automation at time t, it follows that $c_3(t) \geq 0$ holds for all $t \epsilon [0,T]$.

$$c'_3(t) = -\beta(t)a(t)c_3(t) \tag{4.7}$$

The formulation of the model is completed by the control constraints specified in Equation (4.8)

$$a(t) \epsilon [0,A(t)], \; r(t) \epsilon [0,R(t)] \tag{4.8}$$

The interpretation of the lower bound of zero on the control constraints is straightforward. However, the upper bounds are subject to managerial interpretation. The maximum rate of increase in the acquisition of flexible automation at time t may be constrained by factors such as budget, ability of the organizational infrastructure to assimilate the technology, and the availability of the technology. The maximum rate of reduction in existing capacity may be restricted due to labor contracts, the ability of the organization to make production process changeovers, and the impact of such changes on the organization.

4.4 THE SOLUTION

The model defined by Equation (4.1)-(4.8) in Section 4.3 consists of an objective function which is integrated over time, and a set of constraints expressed as differential equations. To solve this formulation, techniques of optimal control theory are applied, (Sethi and Thompson 1981, and Bryson and Ho 1969).

The Hamiltonian to be maximized is defined in Equation (4.9).

$$
\begin{aligned}
&H[s(t),x(t),k(t),\alpha(t),c_3(t),a(t),r(t),\lambda_1(t),\lambda_2(t),\\
&\quad \lambda_3(t),\lambda_4(t),\lambda_5(t)] = H\\
&H=-\{v(t)[s(t)-\hat{s}(t)]^2+c_1(t)a^2(t)\\
&\quad +c_2(t)r^2(t)+[B(t)+c_3(t)]s(t)\\
&\quad +c_4(t)[dk(t)-s(t)]^2-c_5(t)[dk(t)-s(t)]\}e^{-\rho t}\\
&\quad +\lambda_1(t)\{\gamma_1(t)[a(t)+\alpha(t)k(t)][N-s(t)]+\gamma_2(t)s(t)\}\\
&\quad +\lambda_2(t)[a(t)]+\lambda_3(t)[a(t)-r(t)+\alpha(t)k(t)]\\
&\quad -\lambda_4(t)\psi(t)\alpha(t)[1-\phi(t)a(t)/x(t)]\\
&\quad -\lambda_5(t)[\beta(t)a(t)c_3(t)] \qquad (4.9)
\end{aligned}
$$

where $\lambda_1(t)$, $\lambda_2(t)$, $\lambda_3(t)$, $\lambda_4(t)$ and $\lambda_5(t)$ are the adjoint variables corresponding to the state variables s(t), x(t), k(t), $\alpha(t)$, and $c_3(t)$, respectively. The adjoint variables are interpreted as the marginal values or costs of the corresponding state variables at time t.

The necessary conditions for optimality (Bryson and Ho 1969, Sethi and Thompson 1981), are specified in Equations (4.10-4.21):

$$s'(t)=\gamma_1(t)[a(t)+\alpha(t)k(t)][N-s(t)] + \gamma_2(t)s(t),\ s(0)=s_0 \quad (4.10)$$

$$x'(t)=a(t),\ x(0)=x_0 \quad (4.11)$$

$$k'(t)=a(t)-r(t)+\alpha(t)k(t),\ k(0)=k_0 \quad (4.12)$$

$$\alpha'(t)=-\psi(t)\alpha(t)[1-\phi(t)a(t)/x(t)],\alpha(0)=\alpha_0 \quad (4.13)$$

$$c_3'(t)=-\beta(t)a(t)c_3(t),c_3(0)=c_{30} \quad (4.14)$$

$$\lambda_1'(t)=-dH/ds(t),\ \lambda_1(T)=G_1e^{-\rho T} \quad (4.15)$$

$$\lambda_2'(t)=-dH/dx(t),\ \lambda_2(T)=0 \quad (4.16)$$

$$\lambda_3'(t)=-dH/dk(t),\ \lambda_3(T)=G_2e^{-\rho T} \quad (4.17)$$

$$\lambda_4'(t)=-dH/d\alpha(t),\ \lambda_4(T)=G_3e^{-\rho T} \quad (4.18)$$

$$\lambda_5'(t)=-dH/dc_3(t),\ \lambda_5(T)=0 \quad (4.19)$$

$$dH/da(t)=0,\ \text{for } a(t)\epsilon[0,A(t)] \quad (4.20)$$

$$dH/dr(t)=0,\ \text{for } r(t)\epsilon[0,R(t)] \quad (4.21)$$

Applying the optimality conditions expressed in Equations (4.10-4.21), the following solutions are obtained in Sections 4.4.1-4.4.5 for the adjoint variables. Note that the adjoint equations are defined as differential equations with known terminal time boundary values so that solutions are obtained from backwards integration.

4.4.1 Marginal Value of Demand

The marginal value function for an additional unit of demand at time t (Equation (4.22)) is equal to the sum of the discounted values of the (a) weighted deviation of demand from the goal minus (b) the total per unit production plus in-process inventory cost (c) the weighted deviation of demand from the desired level of operating capacity plus, (d) the linear penalty cost coefficient corresponding to the deviations of demand from the desired level of operating capacity, and (e) the marginal value function multiplied by the net effectiveness of the technology. Terms (a) through (e) are subtracted from the salvage value of demand (goodwill) at the terminal time.

Therefore, the marginal value of an additional unit of demand is reduced (increased) by an amount proportional to the respective discounted cost of the deviation associated with actual demand that exceeds (is less than) the goal level of demand or that exceeds (is less than) the desired level of operating capacity. The marginal value of an additional unit of demand is increased whenever $c_5(t)<0$ indicating that the firm's preference is for overutilization of capacity from the desired level and is willing to more frequently make use of short-term capacity expansion measures. Furthermore, increases (decreases) in the marginal value of demand are proportional to the relative effectiveness (ineffectiveness) of the enhanced capacity on capturing demand from the competition and to the relative reduction in the per unit production plus in-process inventory cost.

$$\lambda_1(t) = G_1 e^{-\rho T} - \int_0^T \{\underbrace{(2v(t)[s(t)-\hat{s}(t)]}_{(a)} + \underbrace{[B(t)+c_3(t)]}_{(b)}$$

$$\underbrace{-2c_4(t)[dk(t)-s(t)]}_{(c)} + \underbrace{c_5(t)}_{(d)}\} e^{-\rho t}$$

$$\underbrace{+\lambda_1(t)[\gamma_1(t)[a(t)+\alpha(t)k(t)]-\gamma_2(t)]}_{(e)}\}dt,$$

$$\lambda_1(T) = G_1 e^{-\rho T} \qquad (4.22)$$

4.4.2 <u>Marginal Value of the Cumulative Level of Flexible Technology</u>

In Equation (4.23), the marginal value of an additional unit of technology at time t is expressed as a function of the relative impact of the technological progress factor subject to diminishing returns. Here the marginal value function is negative at time t whenever the marginal value of an additional unit of technological progress factor is positive.

$$\lambda_2(t) = -\int_0^T \{\lambda_4(t)\psi(t)\alpha(t)\phi(t)a(t)/x^2(t)\}dt, \quad \lambda_2(T) = 0 \qquad (4.23)$$

4.4.3 Marginal Value of Capacity

The marginal value of an additional unit of capacity at time t (Equation 4.24) is expressed as a function of the discounted value over time of (a) the weighted deviation of demand from the desired level of operating capacity (b) the linear cost coefficient of demand in excess of capacity, (c) marginal value of enhanced capacity on obtaining the competitor's market, the marginal value of capacity times the technological progress factor, and the salvage value of capacity at the terminal time. Therefore, demand in excess of capacity at time t serves to increase the marginal value function at time t and prior to time t. Also note that whenever $c_5(t)>0$, the marginal value function is increased by the discounted value of $c_5(t)$.

Furthermore, the marginal value of an additional unit of capacity is modified by the technological progress factor in two ways. First, since $0 \leq \alpha(t) \leq 1$, it is clear that the sign of the marginal value of additional capacity determines the impact of technological progress on the marginal value function. For example, if the marginal value of an additional unit of capacity is negative, then prospective capacity gains from learning act to further reduce the marginal value function since capacity expands automatically whenever the value of the technological progress factor is of sufficient magnitude. Second, $\lambda_3(t)$ is increased if the marginal value function of demand is positive such that additional enhanced capacity due technological progress acts to capture demand from the competition.

$$\lambda_3(t) = G_2 e^{-\rho T} - \int_0^T \{ (2c_4(t)d \; [dk(t) - s(t)] - c_5(t)d) e^{-\rho t}$$

(a) (b)

$$- \lambda_1(t)\gamma_1(t)\alpha(t)[N - s(t)] - \lambda_3(t)\alpha(t) \} \; dt,$$

(c) (d)

$$\lambda_3(T) = G_2 e^{-\rho t} \qquad (4.24)$$

4.4.4 Marginal Value of Technological Progress

From Equation (4.25) the marginal value of an additional unit of the technological progress factor at time t is expressed as its salvage value at the terminal time plus the integral from time t through T of the marginal value of demand times the effectiveness of the enhanced capacity to increase demand plus the marginal value of capacity minus the marginal value of an additional unit of technological progress times the magnitude of the per unit change in the technological progress factor. Therefore, the marginal value of technological progress is increased whenever (a) its value as a stimulus to demand is positive, (b) the marginal value of an additional unit of capacity is positive and (c) the net contribution due to system synergy and learning is possible. Accordingly, if the marginal value of an additional unit of technological progress factor is positive then the marginal value function is increased whenever the net benefit from the flexible automation exceeds the natural rate of reduction in progress.

$$\lambda_4(t)=G_3e^{-\rho T}+\int_0^T\{[\lambda_1(t)\gamma_1(t)k(t)[N-s(t)]+\lambda_3(t)k(t)$$

(a) (b)

$$-\lambda_4(t)\psi(t)[1-\phi(t)a(t)/x(t)]\}dt,\ \lambda_4(T)=G_3e^{-\rho T} \quad (4.25)$$

(c)

4.4.5 The Marginal Value of a Reduction in the Per Unit Production Cost

The marginal value of a reduction in the per unit production cost at time t is equal to the integral from time t through T of the discounted demand level plus the marginal value of an additional reduction in production cost times the total percentage reduction in cost due to the acquisition of a(t) units of flexible automation. Clearly, the marginal value of a reduction in the per unit production plus in-process inventory cost is increased through the acquisition of flexible automation since $\lambda_5(t)\leq 0$ for all $t\epsilon(0,T)$. In Gaimon (1985), it is shown the adjoint variable $\lambda_5(t)$ satisfies $\lambda_5(t)<0$ for all $t\epsilon[0,T]$ when the corresponding state variable $c_3(t)$ is defined as in Equation (4.7). Therefore, the marginal value of reducing the per unit production cost at time t is equal to (a) the saved production costs at time t plus (b) the total value associated with reducing the per unit cost following time t.

$$\lambda_5(t)=-\int_0^T[s(t)e^{-\rho t}+\lambda_5(t)\beta(t)a(t)]dt,\ \lambda_5(T)=0 \quad (4.26)$$

(a) (b)

4.4.6 Optimal Control Policies

The optimal policies by which the level and composition of productive capacity are modified are expressed in Theorems 1 and 2. Due to their simplicity, the proofs are omitted. However, it is noted that the optimal control policies correspond to the optimal conditions defined in (4.20) and (4.21), respectively.

Theorem 1

The optimal rate of acquiring flexible technology as a source of productive capacity at time t is

$$a(t) = \begin{cases} A(t), \text{ if } \theta_1(t) \geq A(t) \\ \theta_1(t), \text{ if } 0 < \theta_1(t) < A(t) \\ 0, \text{ if } \theta_1(t) \leq 0 \end{cases} \qquad (4.27)$$

$$\text{with } \theta_1(t) = \{\underbrace{\lambda_1(t)\gamma_1(t)[N-s(t)]}_{(a)} + \underbrace{\lambda_2(t)}_{(b)} + \underbrace{\lambda_3(t)}_{(c)} + \underbrace{\lambda_4(t)\psi(t)\alpha(t)\phi(t)/x(t)}_{(d)}$$

$$\underbrace{-\lambda_5(t)\beta(t)c_3(t)}_{(e)}\}/\underbrace{[2c_1(t)e^{-\rho t}]}_{(f)} \qquad (4.28)$$

To interpret the optimal policy for acquiring flexible technology, we examine Equation (4.28). The numerator consists of five terms at time t: (a) the marginal value of demand taken from the competition due to the acquisition of flexible automation, (b) the marginal value of an additional unit of flexible technology, (c) the marginal value of an additional unit of productive capacity, (d) the marginal value of an increase in the technological progress factor due to a purchase of flexible automation and (e) the marginal value of reducing the per unit production cost due to a unit purchase of flexible automation.

Therefore, Equation (4.28) represents the net marginal contribution to the objective function of a unit increase in flexible technology at time t divided by the discounted purchase costs (f) of the flexible technology. Clearly, if the numerator of Equation (4.28) is positive, then it is optimal to acquire flexible automation. However, the magnitude of the technology acquired at time t is inversely proportional to the cost of the acquisition so that a higher purchase cost corresponds to a lower rate of acquisition at time t. Also note, even if the marginal value of an additional unit of capacity is negative, it may be optimal for the firm to purchase new technology in order to take advantage of the other benefits afforded (e.g., increase in demand, technological progress, and lower production costs).

It is interesting to note the impact of the technological progress factor on the optimal acquisition policy. Specifically if the increase in capacity following an acquisition at time t due to the accumulated experience with the flexible technology is not negligible, then a reduction in the optimal rate of acquisition occurs. Therefore, a smaller acquisition of new flexible technology is optimal at time t since future increases in capacity are anticipated as a result of experience. In this case, since $\lambda_2(t)<0$ and $\lambda_4(t)>0$ as illustrated from Equations (4.23) and (4.25), increases in a(t) influence future rates of acquisition due to technological progress. Also note from Equation (4.27) that the maximum rate of acquisition of flexible technology at time t cannot exceed the managerially defined upper and lower bounds. Whenever $\theta_1(t) \geq A(t)$, then A(t) units of flexible automation is acquired whereas $\theta_1(t) \leq 0$, indicates no purchases of the new technology is to be obtained at time t.

<u>Theorem 2</u>

The optimal rate of reducing existing productive capacity is

$$r(t) = \begin{cases} R(t), \text{ if } \theta_2(t) \geq R(t) \\ \theta_2(t), \text{ if } 0 < \theta_2(t) < R(t) \\ 0, \text{ if } 0 \leq \theta_2(t) \end{cases} \qquad (4.29)$$

$$\text{with } \theta_2(t) = \{-\lambda_3(t)\}/[2c_2(t)e^{-\rho t}] \qquad (4.30)$$

The interpretation of (4.29) is straightforward from Equation (4.30). It is clear that the firm should reduce the level of existing capacity whenever the marginal value of decreasing capacity is positive ($\lambda_3(t) < 0$). The optimal rate of reduction in the level of capacity is tempered by the discounted cost of reducing capacity.

From the optimal policies derived in Theorems 1 and 2, exactly four optimal strategies exist: (I) a(t)=0, r(t)=0; (II) a(t)=0, r(t)>0; (III) a(t)>0, r(t)=0; and IV) a(t)>0, r(t)>0. In Strategy I, the level and composition of productive capacity remains unchanged. In this situation, the sum of the marginal values of the combined benefits from technology acquisitions are less than the sum of the marginal costs at time t. Also, since there are no planned reductions, it is advantageous for the firm to maintain the same level of operating capacity for its present utilization or in anticipation of future capacity needs.

Strategy II differs from Strategy I since the marginal value of capacity is negative so that the firm reduces existing capacity. In contrast with Strategies I and II, in Strategy III, the firm needs additional units of operating capacity. In addition to meeting capacity needs, the firm will derive other benefits as a result of acquiring flexible technology such as future increases in demand and capacity due to technological progress as well as reduced operating costs.

Strategy IV warrants special interpretation. Here, despite the negative marginal value of an additional unit of capacity, the acquisition of new flexible technology is advocated. Therefore, the net benefits from the acquisition of flexible automation accrued over time outweigh the negative marginal value of an additional unit of capacity. Therefore, in Strategy IV the firm is both acquiring and scrapping technology simultaneously so that updated equipment is acquired to replace and enhance existing operating capacity. It also serves to enhance future capacity due to future progress improvements. Note that the existing operating capacity may be a mix of both conventional and flexible technology and the benefits are relative to the mix currently in place.

4.5 NUMERICAL SOLUTION ALGORITHM

The optimal solution obtained for the model developed in Equations (4.1)-(4.8) is expressed as a function of the input parameters. For any given set of input conditions, certain factors may be more critical than others. In order to assess the relative importance of the varying environmental conditions a firm may face, sensitivity analysis may be performed. Numerical solutions derived from the analyses provide insight to the dynamic behavior of the model with respect to the inclusion of a particular set of values of exogenous variables.

Closed form solutions do not exist for the model defined in Equations (4.9)-(4.21) in Section 4.3. Furthermore, due to the dynamic interdependence of the state, control and adjoint variables over time, an iterative procedure is warranted in order to derive numerical solutions. The iterative procedure requires the discrete approximation of the differential equations that define the dynamics of the state and adjoint variables.

The state adjoint difference equations used in the algorithm are expressed in Equations (4.31)-(4.40) below:

$$s(t+1)=s(t)+\gamma_1(t)[a(t)+\alpha(t)k(t)][N-s(t)]+\gamma_2(t)s(t) \qquad (4.31)$$

$$x(t+1)=x(t)+a(t) \qquad (4.32)$$

$$k(t+1)=k(t)+a(t)-r(t)+\alpha(t)k(t) \qquad (4.33)$$

$$\alpha(t+1)=\alpha(t)-\psi(t)\alpha(t)[1-\phi(t)a(t)/x(t)] \qquad (4.34)$$

$$c_3(t+1)=-\beta(t)a(t)c_3(t) \qquad (4.35)$$

$$\lambda_1(t)=\lambda_1(t+1)-\{2v(t+1)[s(t+1)-\hat{s}(t+1)]+[B(t)+c_3(t)]$$
$$-2c_4(t+1)[dk(t+1)-s(t+1)]+c_5(t+1)\}e^{-\rho(t+1)}$$
$$-\lambda_1(t+1)\{\gamma_1(t+1)[a(t+1)+\alpha(t+1)k(t+1)]-\gamma_2(t+1)\} \qquad (4.36)$$

$$\lambda_2(t)=\lambda_2(t+1)-\lambda_4(t+1)\psi(t+1)\alpha(t+1)\phi(t+1)a(t+1)/x^2(t+1) \qquad (4.37)$$

$$\lambda_3(t)=\lambda_3(t+1)-(2c_4(t+1)d[dk(t+1)-s(t+1)]$$
$$-c_5(t+1)d)e^{-\rho(t+1)}+\lambda_1(t+1)\gamma_1(t+1)\alpha(t+1)[N-s(t+1)]$$
$$+\lambda_3(t+1)\alpha(t+1) \qquad (4.38)$$

$$\lambda_4(t)=\lambda_4(t+1)+\lambda_1(t+1)\gamma_1(t+1)k(t+1)[N-s(t+1)]$$
$$+\lambda_3(t+1)k(t+1)$$
$$-\lambda_4(t+1)\psi(t+1)[1-\phi(t+1)a(t+1)/x(t+1)] \qquad (4.39)$$

$$\lambda_5(t)=\lambda_5(t+1)-s(t+1)e^{-\rho(t+1)}-\lambda_5(t+1)\beta(t+1)a(t+1) \qquad (4.40)$$

The logic of the algorithm is straightforward from the well-known 'Shooting Method' solution to the two-point boundary problem (Sethi and Thompson 1981). The algorithm is summarized in Figure 20 and the corresponding detailed description and Fortran code appears in Appendices E and F, respectively.

The algorithm is now briefly described. In the first iteration, initialization of all exogenous and endogenous variables is required. First, the exogenous input parameters are initialized for all $t\epsilon[0,T]$. Second, the control variables are set to zero and the state variables are set to their initial time values for all $t\epsilon[0,T]$. Third, the adjoint variables are computed using Equations (4.36)-(4.40).

Then for each subsequent iteration, the optimal control variables are first computed using Equations (4.27 and 4.29) and the solutions for the state variables are derived sequentially in the forward direction using Equations (4.31-4.35). To guarantee $c_3(t)\geq 0$ in the discrete approximation, we require $\beta(t)\leq 1/A(t)$. Also, Algorithm 1 checks for violation of state constraint,

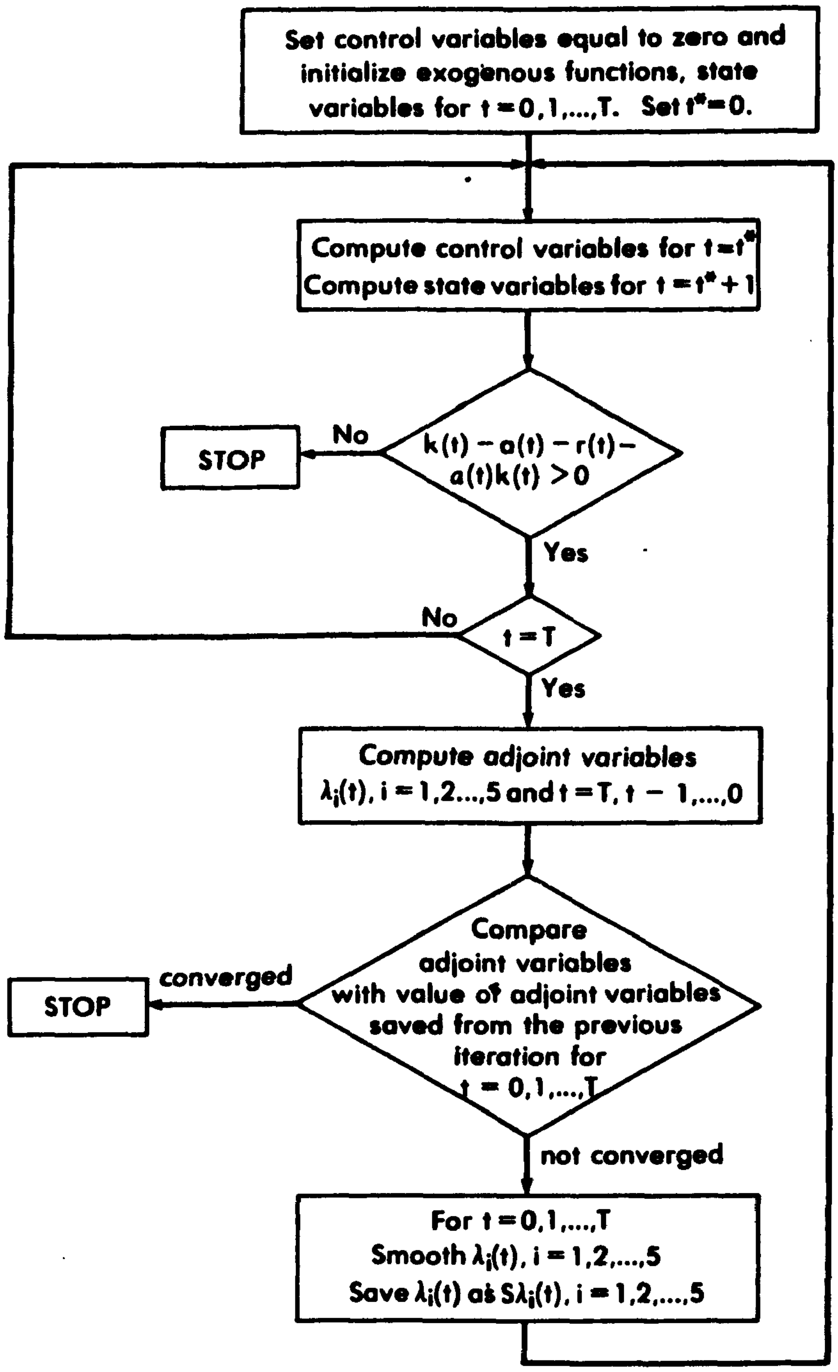

Figure 20. Flow Chart of Numerical Solution Algorithm 1: MODEL II

$k(t)-a(t)-\alpha(t)k(t)\geq r(t)$. If a violation occurs, we stop since the model is inconsistent with the assumed evolutionary timing strategy.

Next, using the newly derived state and control variables, the adjoint variables are recomputed backwards in time from time T. Convergence is obtained whenever the magnitude of difference between the corresponding values of the adjoint variables in two consecutive iterations is less than some prespecified error for all $\lambda_i(t)$, $i=1,2,\ldots,5$ and $t\epsilon[0,T]$. Upon the completion of any iteration in which convergence has not been achieved, the adjoint variables are exponentially smoothed and saved as $S\lambda_i(t)$. Smoothing aids in achieving a faster convergence. A similar algorithm has been employed in Gaimon 1985.

4.6 DISCUSSION

The chapter is concluded with a presentation and discussion of illustrative examples that are solved using the numerical solution algorithm presented in Section 4.5. The purpose of the sensitivity analysis is to offer insight concerning the relative impact of various environmental conditions (exogenous parameters) on the optimal solutions over time.

In Table 3, a summary of the numerical solutions for eight examples is given. The common exogenous input functions which are held constant in each of the examples and for each time period, $t=0, 1, \ldots, T$ are given in Table 3.

Note that since $s_0=50$ and $k_0=40$ hold in each example, it is assumed that the firm employs short-term measures to meet demand that occurs in excess of capacity at the initial time. This may

Table 3. Summary of Numerical Examples: Model II

EXOGENOUS COMMON INPUT PARAMETERS: $T=10$; $\hat{s}=50+5t$ for $t=0,1,\ldots 8$ and $\hat{s}=80$ for $t=8,9,10$; $c_{30}=20$; $k_0=40$; $s_0=50$; $x_0=0.5$, $\alpha=.0001$; $A(t)=12$; $R(t)=10$; $c_4(t)=20$; $c_2(t)=40$; $B(t)=0$; $\psi(t)=.5$; $c_5(t)=0$; $d=1.0$; $N=500$; $G_1=500$, $G_2=100$; $G_3=500$; $\rho=.25$

EXOGENOUS INPUT PARAMETERS								
EXOGENOUS FUNCTIONS	EXAMPLE 1	EXAMPLE 2	EXAMPLE 3	EXAMPLE 4	EXAMPLE 5	EXAMPLE 6	EXAMPLE 7	EXAMPLE 8
$c_1(t)$	100	100	100	100-5t	100	100	100	100
$v(t)$	50	50	50	50	100	50	50	50
$\phi(t)$	.001	.001	.001	.001	.001	.001	.001	.05
$\gamma_1(t)$	.001	.00005	.001	.001	.001	.001	.001	.001
$\gamma_2(t)$	0.0	0.0	0.0	0.0	0.0	-.02	+.02	0.0
$\beta(t)$	.001	.001	.04	.001	.001	.001	.001	.001
OPTIMAL SOLUTIONS								
CONTROL POLICIES								
$\sum_t a(t)$, $(\sum_t a(t)/T)$	61.92,(5.63)	13.44,(1.22)	62.56,(5.69)	70.80,(6.44)	75.68,(6.88)	74.38,(6.76)	48.43,(4.40)	59.45,(5.04)
$\sum_t r(t)$,$(\sum_t r(t)/T)$	19.37,(1.76)	1.03,(0.09)	19.73,(1.79)	22.56,(2.05)	26.69,(2.43)	35.43,(3.22)	2.32,(0.21)	20.23,(1.84)
STATE VARIABLES								
$k(10)$,$(\sum_t k(t)/T)$	81.07,(63.87)	51.88,(47.87)	81.34,(64.17)	85.21,(64.95)	87.54,(67.91)	77.45,(62.11)	84.63,(65.05)	81.57,(64.93)
$s(10)$,$(\sum_t s(t)/T)$	76.47,(64.20)	50.29,(50.18)	76.74,(64.43)	79.59,(65.12)	82.31,(67.58)	70.03,(61.14)	83.65,(67.48)	77.05,(64.96)
$c_3(10)$,$(\sum_t c_3(t)/T)$	18.82,(19.37)	19.74,(19.84)	1.19,(6.72)	18.69,(19.33)	18.57,(19.22)	18.59,(19.26)	19.08,(19.49)	18.87,(19.39)
$\sum_t a(t)/T$	.000125	.00007	.00013	.00012	.00015	.00013	.00011	.00670
$\sum_t (k(t)-s(t))/T$	-0.32	-2.31	-0.25	-0.17	0.33	0.97	-2.43	-0.025
$\sum_t (s(t)-\hat{s}(t))/T$	9.44	23.45	9.21	8.52	6.05	12.50	6.16	8.68
OBJECTIVE <costs>	<33,459>	<77,560>	<31,210>	<31,010>	<41,215>	<49,637>	<21,351>	<30,871>

represent a typical scenario for a firm which is either postponing its decision to acquire new technology or one which has placed emphasis on maximum utilization. Also note that relatively small numerical values are assigned to the terminal time marginal values of the strength factors of demand, capacity and technological progress factor. As a result of these relatively small terminal time marginal values and the relatively high tangible costs incurred, the objective function values are negative in each example. (See Table 3.) Therefore, the objective function values for the examples can be interpreted as relative costs. The detailed input and output data for each example is located in Appendix G and H respectively. In particular, the exact values for each decision variable over the the planning horizon are also in Appendix H.

4.6.1 Base Scenario

In Example 1, the exogenous functions which are not common to each example are defined as c (t)=100, v(t)=50, $\phi(t)=.001$, $\gamma_1(t)=.001$, $\gamma_2(t)=0.0$, and $\beta(t)=.001$ for t=0,1...,T. At the initial time, penalties accrue as a result of demand in excess of capacity. As a result, no reductions in operating capacity are advocated in periods 0 and 1 since the firm requires as much capacity as possible in order to reduce its reliance on short-term capacity expansion measures. The acquisition of flexible automation that occurs in periods 0 and 1 primarily act to increase the level of existing operating capacity. However, in periods 3 through 9. Strategy IV is prevelant since the optimal policy advocates the simultaneous acquisition of flexible automation and reductions in the existing operating capacity. (See Figure 21.) The substitution of new flexible technology for existing capacity is observed. This substitution of updated capacity for vintage capacity occurs primarily as a result of the relative effectiveness of the new technology on capturing demand from the competition in order to improve market performance. (See Figure 22.) Since the optimal policy advocates a higher level of capacity than demand and demand is less than the goal, the flexible technology serves as a marginal stimulus for selective demand. Hence, a higher level of flexible capacity is required overall in order to improve the firm's competitive position.

4.6.2 Demand and Operating Capacity

To illustrate the impact that the effectiveness of capturing the competitor's demand has on the optimal acquisition policy, Example 2 is presented. Example 2 is defined such that the effectiveness factor $\gamma_1(t)$ is substantially reduced relative to Example 1. As a result, the total purchase of new technology is approximately one-fifth (21.7 percent) of the level advocated in Example 1. Furthermore, very little substitution of new for old capacity was depicted in Example 2. The total reductions in Example 2 were 5.3 percent of those advocated in Example 1. Therefore, in Example 2, flexible technology is essentially purchased as a source of operating capacity to reduce penalties associated with demand that occurs in excess of capacity. (See Figure 23 and 24.)

The value of the objective function in Example 2 is 31.8 percent worse than in Example 1 where the market responsiveness factor was greater. A comparison of Examples 1 and 2 illustrates the strategic importance of capturing the potential impact on demand that results from effective acquiring flexible automation. Therefore, the acquisition of flexible automation is shown to be a major technological strategy when the market is responsive to the enhanced capacity of the firm. If the effectiveness factor is not significant in enhancing the firm's competitive position, then the firm must adopt strategies other than automation to assure value and strength.

4.6.3 Increasing Relative Efficiency

To analyze the effect that the relative efficiency of the flexible automation has on reducing the per unit production plus in-process inventory costs, sensitivity analysis is performed on the efficiency parameter $\beta(t)$. In Example 3, the relative efficiency indicative of the percentage reduction in production costs due to automation is four times greater than in Example 1 ($\beta(t)$=.04 versus $\beta(t)$=.001, respectively).

In these examples two findings are noted. First, the total magnitude of acquisitions of flexible automation are only about 1 percent greater in Example 3 in comparison with Example 1 and the difference in the total magnitude of reductions is likewise small. Only about 1.9 percent more reductions overall were incurred in Example 3 versus Example 1. Second, while the total aggregated acquisitions varied only modestly in Examples 1 and 3, the timing of the adoption and substitution of old for new was different. Due to the improved attractiveness the flexible technology on reducing the production costs, the relative magnitudes of flexible automation purchases advocated by the optimal policy were slightly larger earlier in the planning horizon as were the reductions in existing operating capacity in Example 3 over Example 1. (See Figures 25 and 26.)

Thus, the optimal policies derived in Examples 1 and Examples 3 suggest that technologies with different production efficiencies will impact on the firm's timing strategy for its adoption when the market effectiveness in terms of economies of scope are large. In this case,the relative magnitude of flexible purchases remained about the same in total. However, the flexible technology was acquired earlier in the planning horizon to gain as soon as possible the benefits of improved production efficiency. The total impact of the more efficient technology is demonstrated by a 6.7 percent improvement in the objective function computed over the planning horizon in Example 3 compared to Example 1.

4.6.4 Relative Costs

In Example 4, the per unit cost of acquiring and implementing flexible technology is expected to diminish over time due to technological advancement and other factors. As a result, both a greater magnitude of purchases of flexible automation and more reductions in vintage capacity occur in Example 4 in contrast to Example 1. In particular a 14.3 percent increase in the total magnitude of acquisitions and a 16.5 percent increase in the total magnitude of reductions occurs in Example 4 relative to Example 1. (See Figure 27.) Therefore, there is greater substitution of new technology for old. The maximizing objective function value is 7.3 percent greater since the reduced purchase costs enable greater acquisitions of flexible technology which serve to reduce production costs and lower deviation penalty costs. Figure 28 portrays the levels of the demand, production and capacity over time. Example 4 illustrates the relative tradeoffs over time in acquisition costs versus benefits (effectiveness in goal attainment and production efficiencies).

In order to ascertain the relative importance of attaining the planned demand levels, Example 5 places twice the weight on the cost coefficient v(t) as compared to Example 1 (v(t)=100 versus v(t)=50, respectively). Therefore, the relative tradeoffs in the objective function of cost versus benefit of attaining demand goals may be observed. In order to bring the actual level of demand closer to the planned demand goal, the Example 5 solution advocates more than a one-fifth increase in the purchase of flexible technology relative to Example 1, (75.68 versus 61.92 units acquired over the planning horizon, respectively). (See Figure 29.)

Since higher penalty costs are incurred with deviations of actual demand from planned levels, the increase in the optimal rate of acquisition in Example 5 over Example 1 serves to increase demand. (See Figure 30.) Therefore, as more substitution of new technology for old occurs, exemplified by the relative rates of reduction in existing capacity, the total level of reduction in existing operating capacity in Example 5 is 37.8 percent higher than Example 1. Furthermore, the objective function cost is approximately 23.2 percent higher in Example 5 than in Example 1. Accordingly, the more emphasis the firm places on attaining the goal level of demand in this example, the greater the overall costs it may incur. These penalty costs must be viewed strategically in terms of the importance of long-term survival and the competitive advantage achieved.

4.6.5 Exogenous Market Growth and Decay

In the model, it was noted that the primary demand level is subject to change naturally (exogenously) over time due to the corresponding stage of the aggregate product in the life cycle, competition and other outside environmental factors. The effect of a declining primary demand is illustrated by comparing the solutions in Examples 1 and 6. Example 6 differs from Example 1 by setting $\gamma_2(t)=-.02$ versus $\gamma_2(t)=0.0$. Therefore, Example 6 reflects an exogenously declining level of demand over the planning horizon.

In Example 6, 20 percent more flexible technology is acquired relative to Example 1 in order to increase demand and compensate for lost sales that result from outside environmental forces. (See Figure 4.12.) Furthermore, there is an 82 percent increase in the total prescribed level of reductions to existing capacity advocated in Example 6 relative to Example 1. (See Figure 32.) This result occurs since relatively large acquisitions of flexible automation were made to increase demand and to concomitantly increase capacity. Therefore, greater substitution of more effective productive capacity is observed.

The objective function is 48.4 percent worse in Example 6 than in Example 1. These findings suggest that a firm in a highly competitive market may choose to place a greater emphasis on the marginal value of demand and experience at the terminal time than those expressed in Example 6. In other words, G_1 and G_3 would be given higher values. Note in contrast, in Chapter 3 where the firm faced a highly competitive market, large changes in the objective were not observed. This is primarily due to the fact that the market responsiveness factor was substantially greater in the examples of Chapter 3 than it is here (.005 versus .001, respectively).

In contrast to Example 6, Example 7 examines the effect of exogenous growth in the firm's demand. In Example 7, $\gamma_2(t)=+.02$ versus $\gamma_2(t)=0.0$ in Example 1. Due to the exogenous growth, less effort is required to bring actual demand closer to the planned demand goal. Therefore, 21.7 percent fewer purchases of flexible technology are observed in Example 7 relative to Example 1. Also, in order to keep pace with exogenously rising demand, a substantial portion of capacity was maintained over the planning horizon. (See Figures 33 and 34.) Specifically, in Example 7, 88.0 percent fewer reductions in existing capacity occur as compared with Example 1. The maximizing objective function in Example 7 is almost 36.2 percent greater than that of Example 1 indicating less effort is required to meet demand and capacity goals. Also, in comparison with a similar example depicted in Chapter 3, contrasting findings with respect to the objective function value are observed. Once again this diversity may be attributed to the relative differences in the exogenous input parameters, in particular, to the market responsiveness factor.

4.6.6 Impact of Technological Progress

In Example 8, the effect that technological progress and system synergy have on the levels productive capacity and demand of the firm is examined. In Example 8, the degree the technological progress factor is modified. Here $\phi(t)=.05$ is defined as opposed to $\phi(t)=.001$ in Example 1. Since subsequent purchases of new technology due to technological progress cause not only proportional increases in the level of available operating capacity but also serve to enhance capacity, the optimal solution obtained for Example 8 advocates 4.0 percent fewer acquisitions of flexible technology than in Example 1. (See Figure 35.) In addition, 4.4 percent more reductions in existing capacity are observed in Example 8 relative to Example 1. Therefore, since the purchase of flexible technology at time t has a greater impact on increasing future capacity and demand due to learning, less flexible automation is purchased and more reductions of old technology occur. A 7.7 percent increase in the objective function value is observed in Example 8 relative to Example 1. The gain in the objective function observed in Example 8 occurs due learning and technological progress which act to stimulate demand and increase capacity. Therefore, due to technological progress and system synergy, we obtain (a) reduced penalty costs for deviations between the actual demand and the planned goal levels and between capacity and demand and (b) reduced acquisition costs over the planning horizon. Clearly, this illustrates that technological progress is a strategic variable to be considered in the acquisition decision. (See Figure 36.)

4.7 CONCLUSION

In this chapter, a dynamic model has been presented that permits investigation of the optimal timing and sizing of modifications in the composition and level of productive capacity where technological progress can reasonably be hypothesized. It is assumed that the acquisition of flexible technology acts to increase the firm's demand, capacity and the technological progress factor and to reduce the firm's per unit production costs. Through a series of numerical examples, the model analysis illustrates how selected environmental conditions impact the decision to acquire flexible technology over time.

Sensitivity analysis is performed on the model and the impact of (a) the effectiveness of flexible automation in capturing selective demand (b) the relative efficiency of technology as a source of operating capacity, (c) cost structures, (d) exogenous market growth and decay and (e) the technological progress factor are examined. Under the assumptions of the model, the sensitivity analysis shows that the largest substitution of new flexible technology over existing capacity occurs when (a)the flexible technology is effective as a competitive weapon in a declining market, (b) the cost of the technology is projected to decrease over time and (c) it serves to enhance capacity due to modification of the natural rate of technological progress. Furthermore, in a growing market, the additional benefits offered by the acquisitions of flexible technology in terms of augmenting existing capacity requirements are observed.

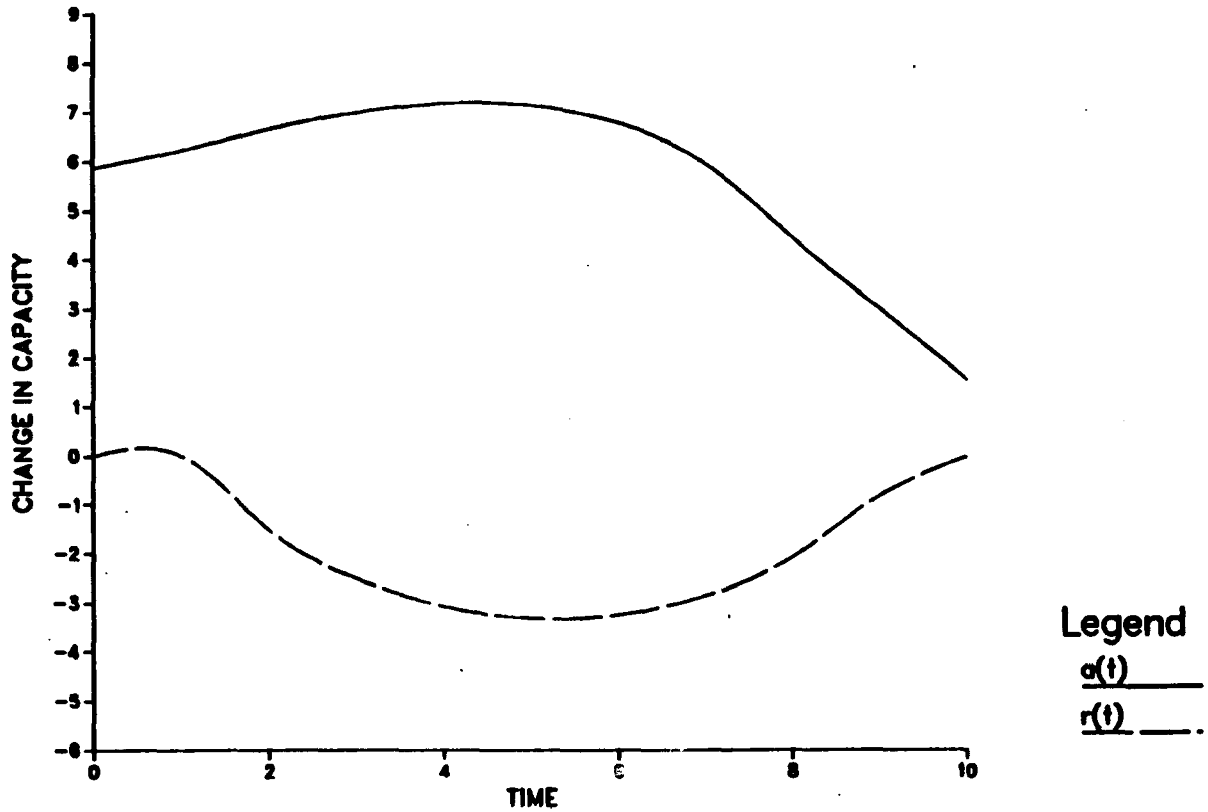

Figure 21. Optimal Control Policies: Example 1

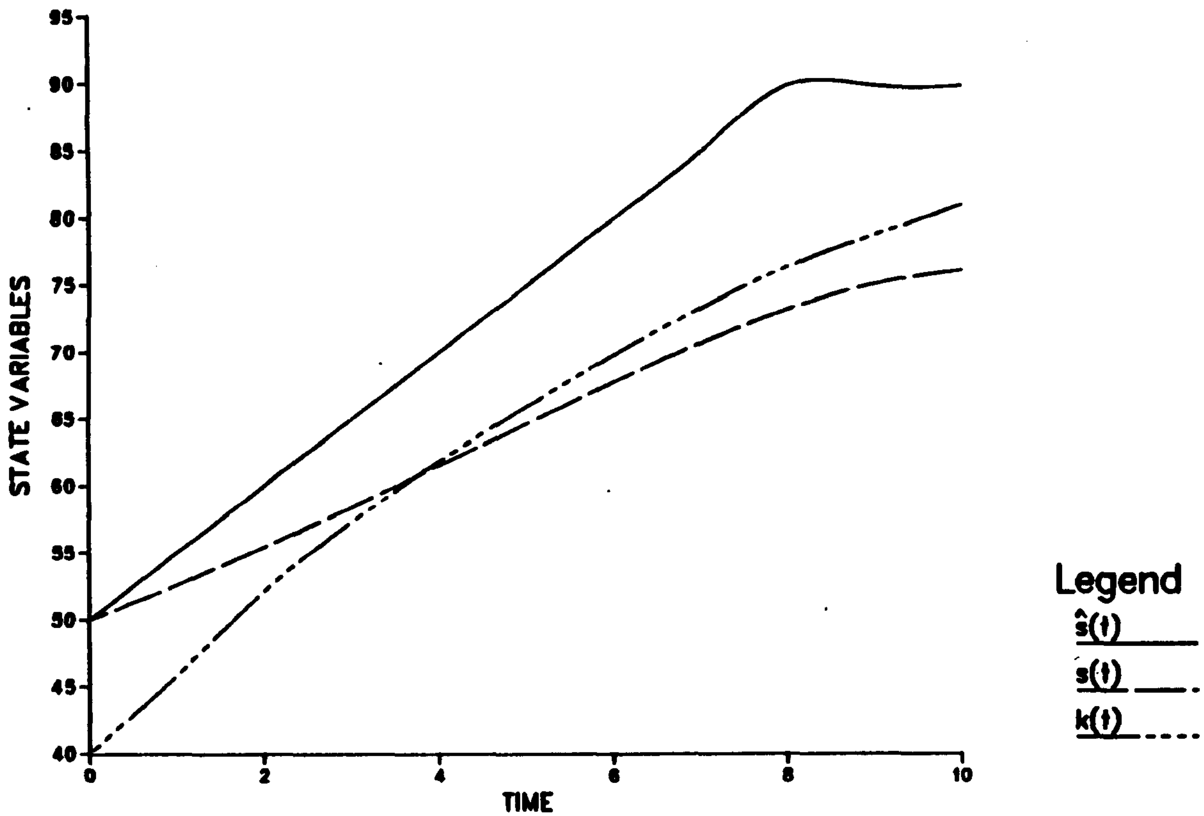

Figure 22. Goal Demand, Actual Demand and Capacity: Example 1

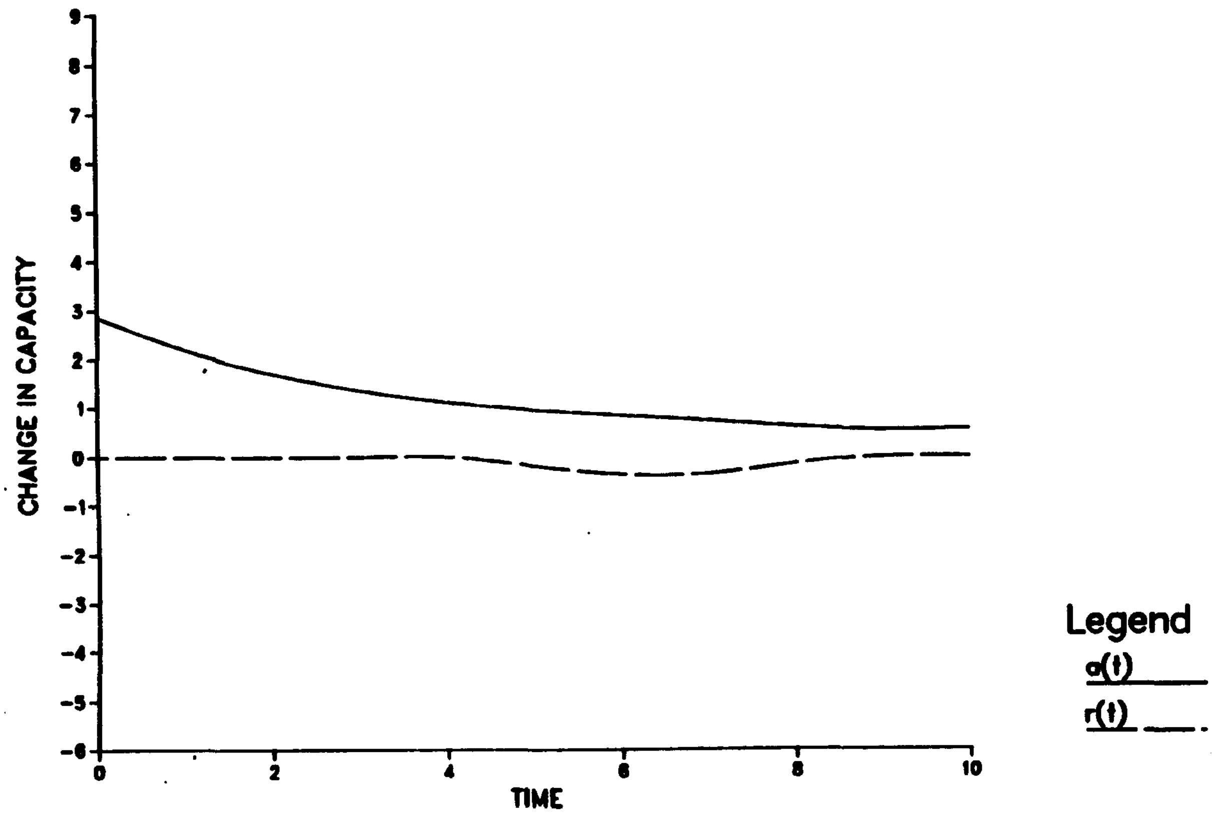

Figure 23. Optimal Control Policies: Example 2

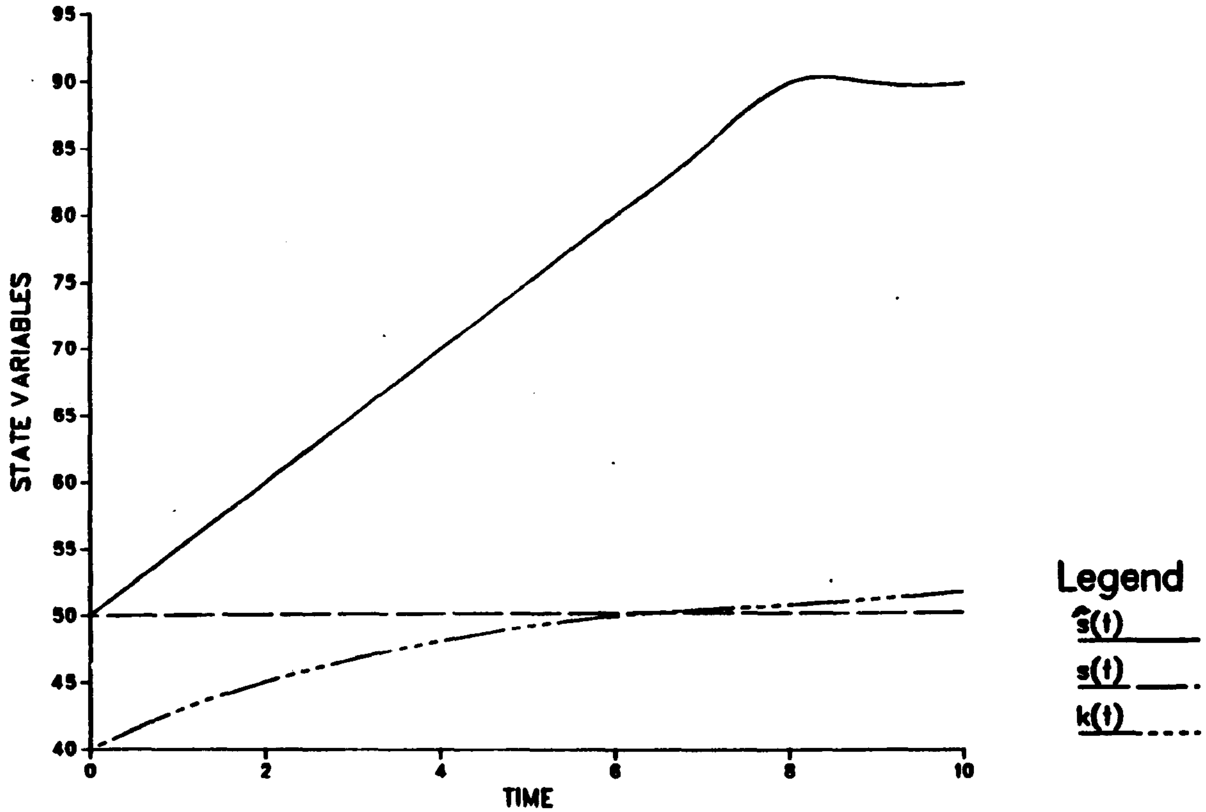

Figure 24. Goal Demand, Actual Demand and Capacity: Example 2

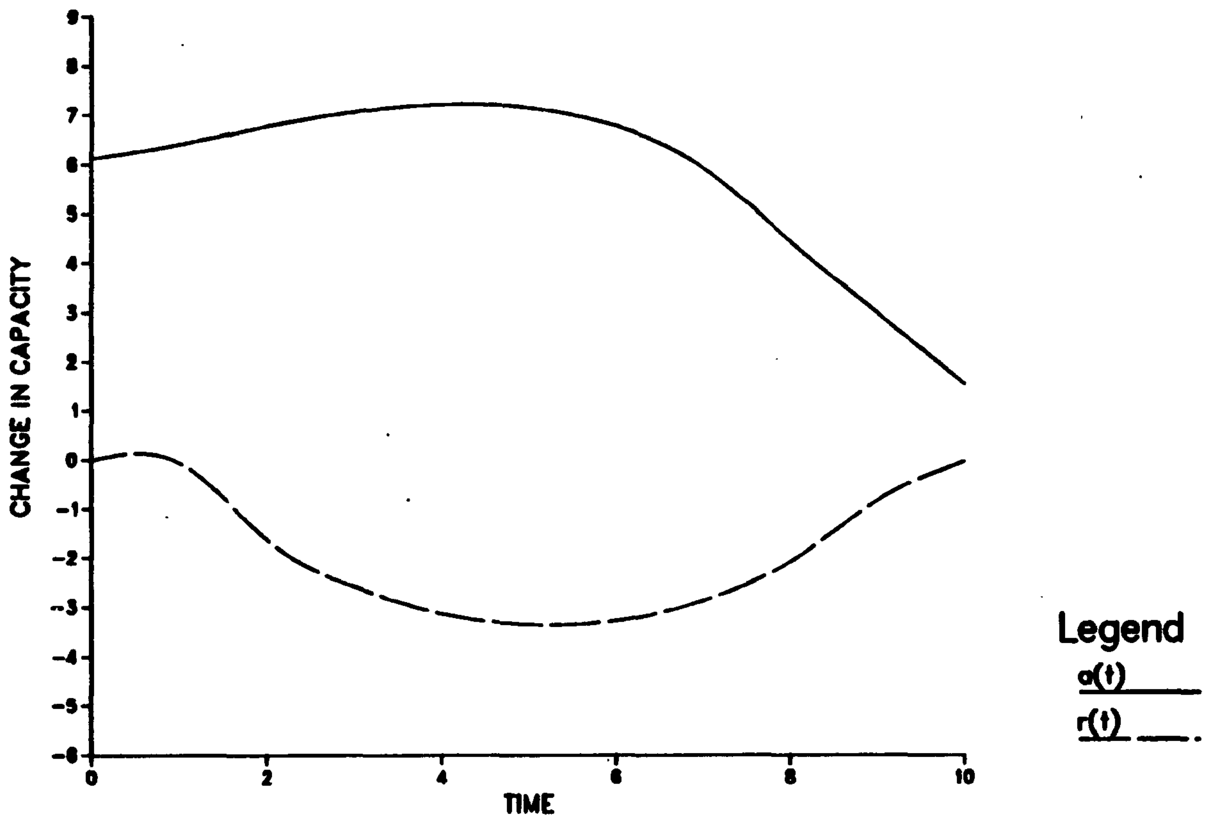

Figure 25. Optimal Control Policies: Example 3

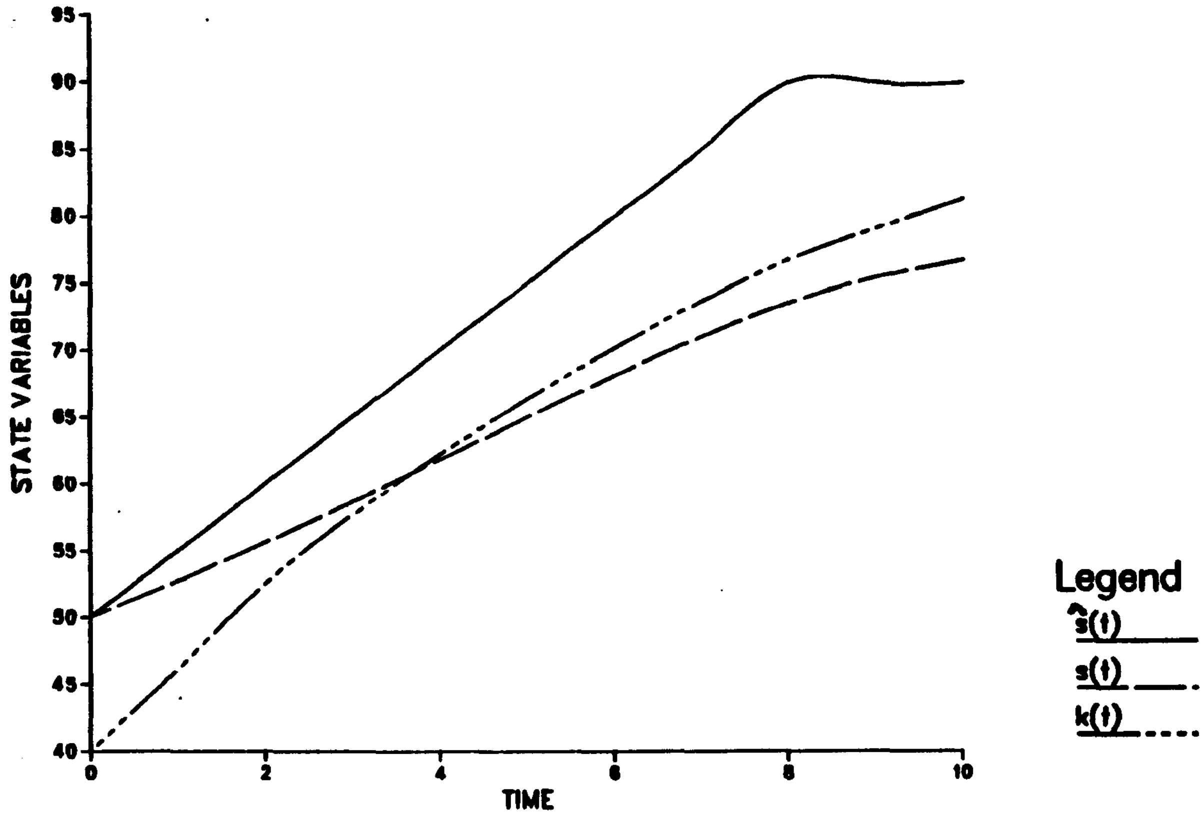

Figure 26. Goal Demand, Actual Demand and Capacity: Example 3

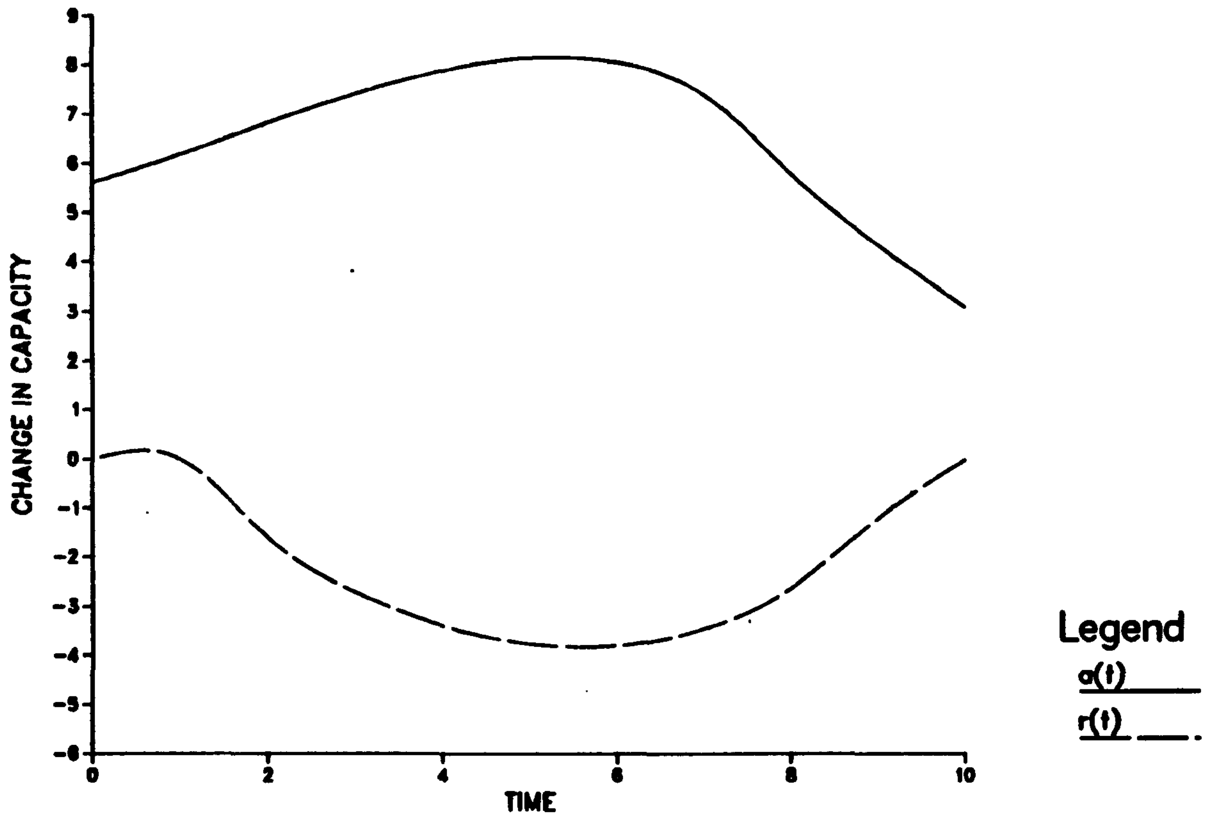

Figure 27. Optimal Control Policies: Example 4

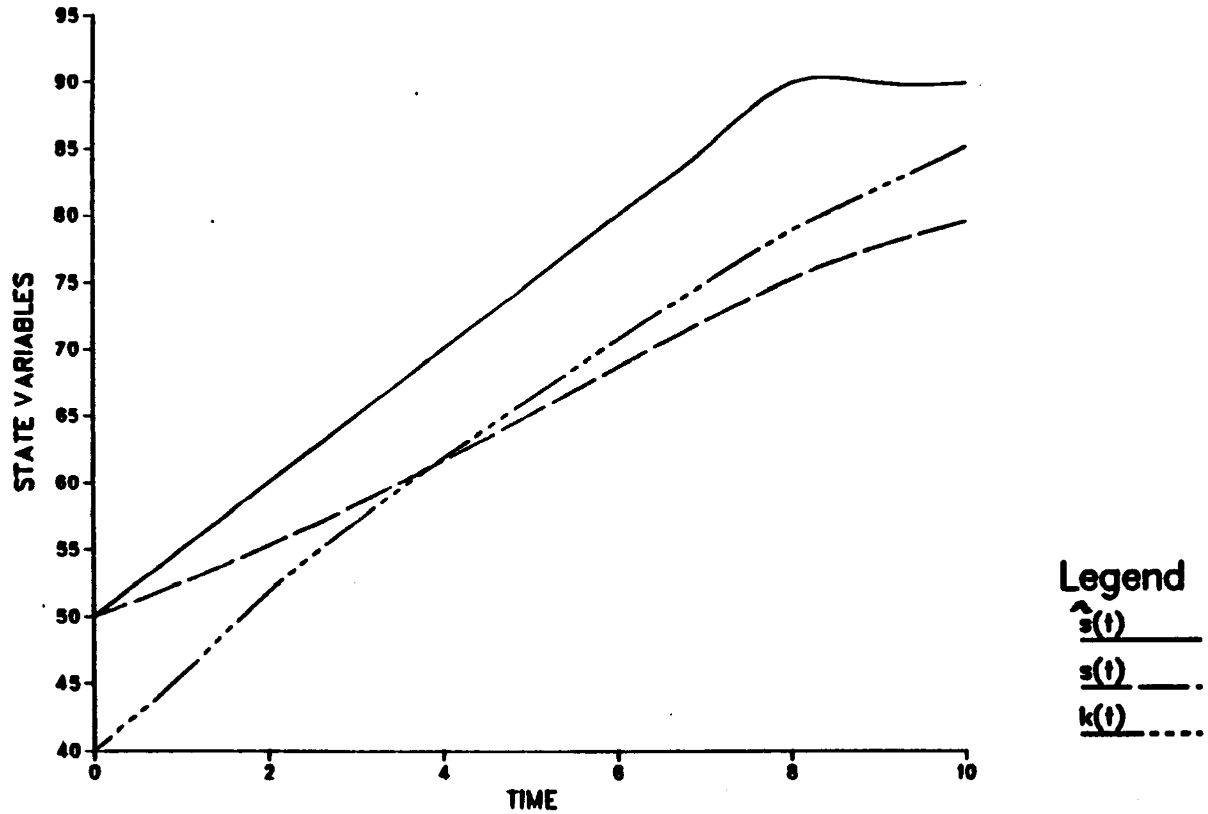

Figure 28. Goal Demand, Actual Demand and Capacity: Example 4

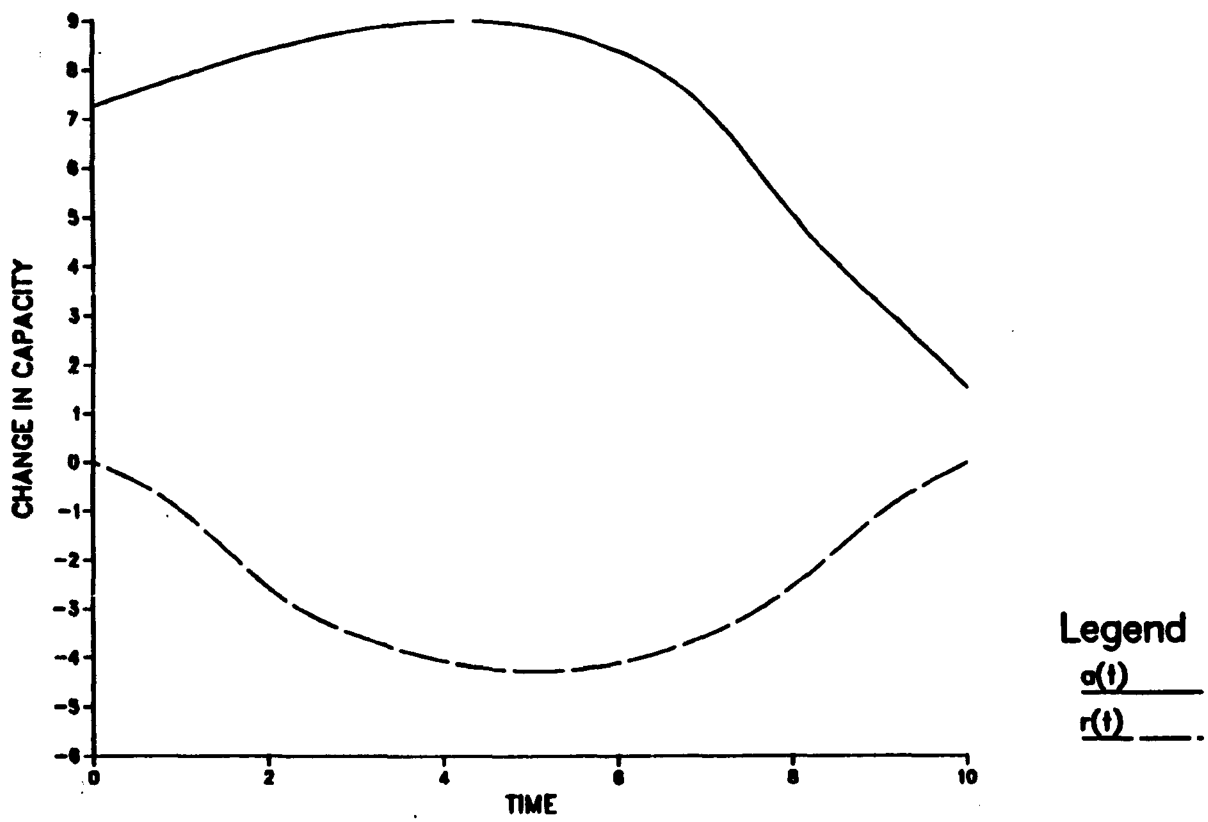

Figure 29. Optimal Control Policies: Example 5

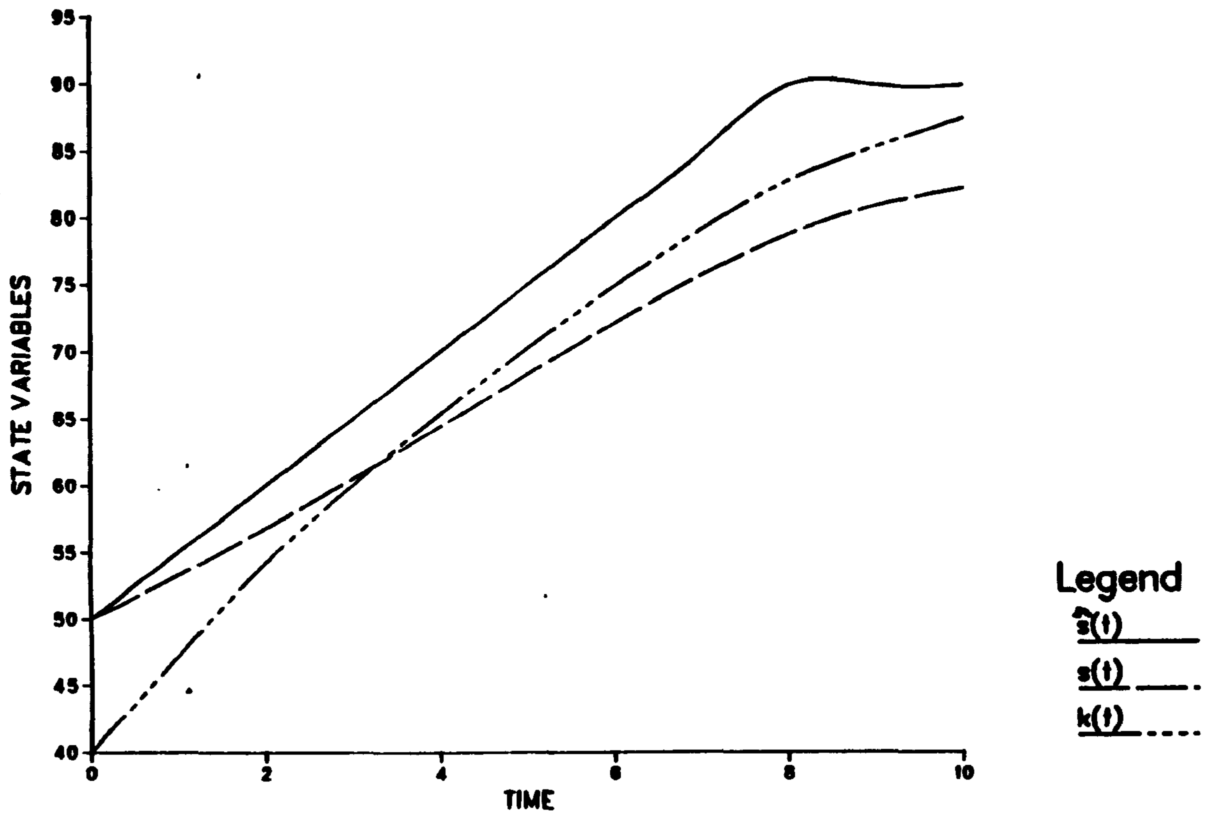

Figure 30. Goal Demand, Actual Demand and Capacity: Example 5

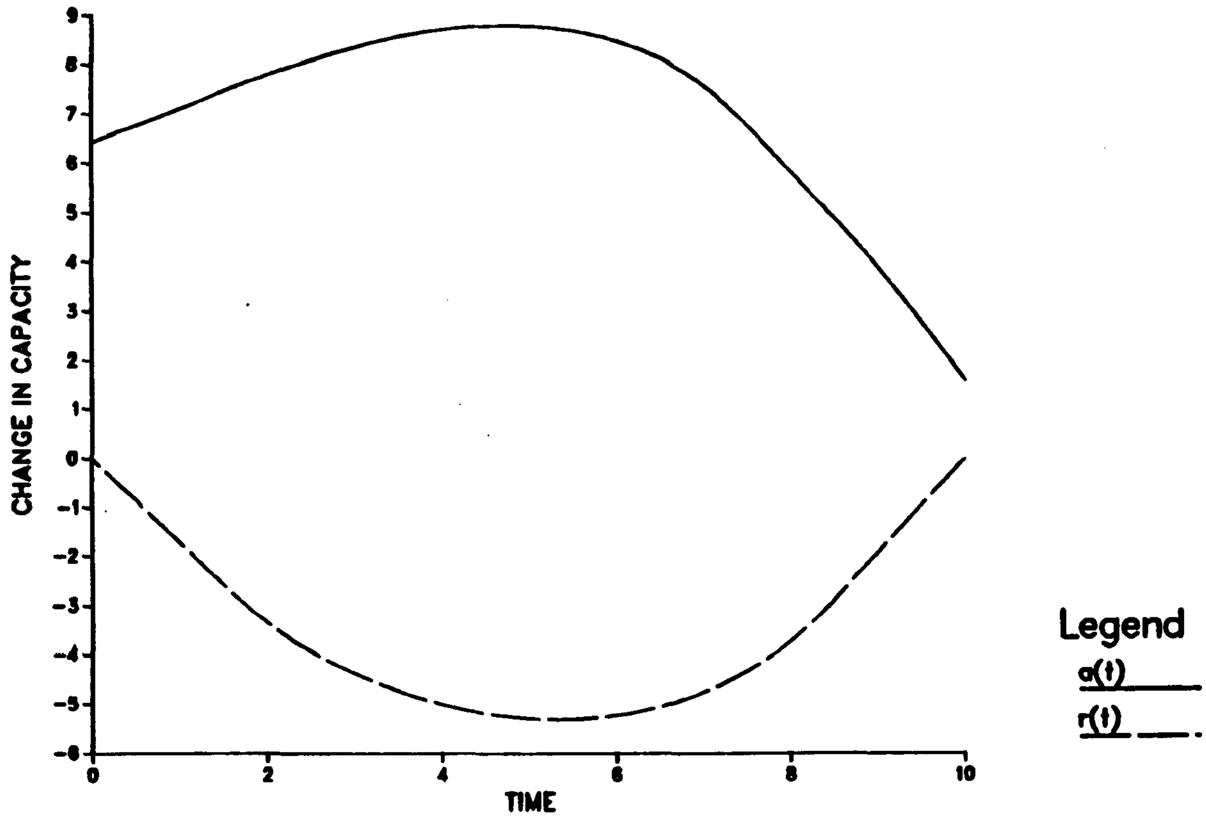

Figure 31. Optimal Control Policies: Example 6

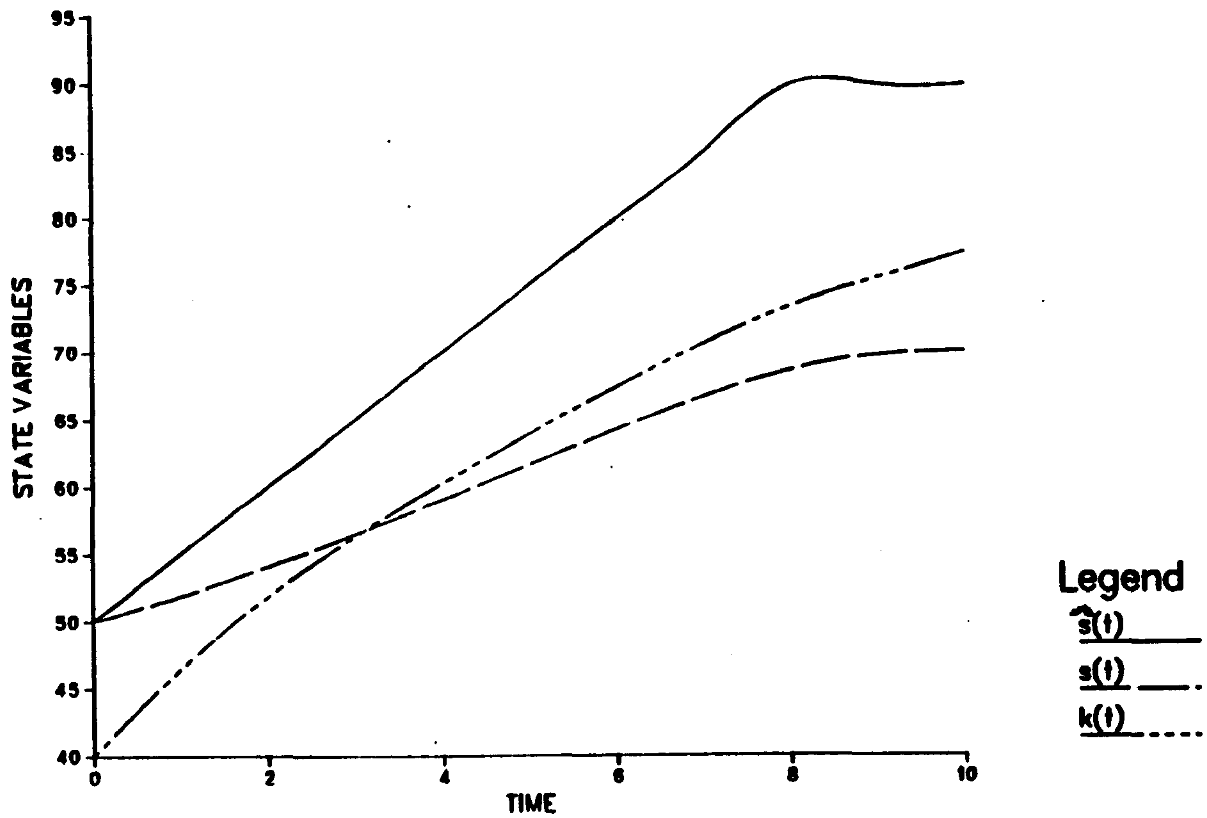

Figure 32. Goal Demand, Actual Demand and Capacity: Example 6

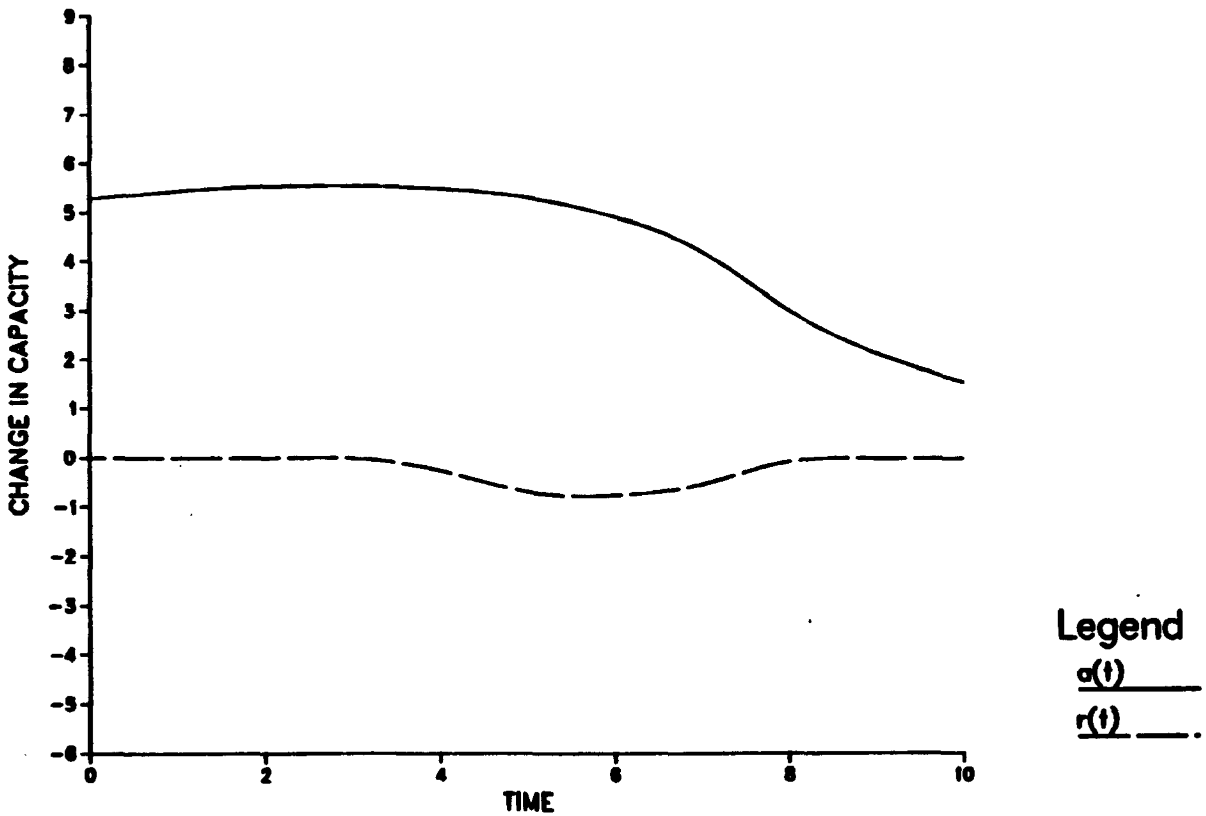

Figure 33. Optimal Control Policies: Example 7

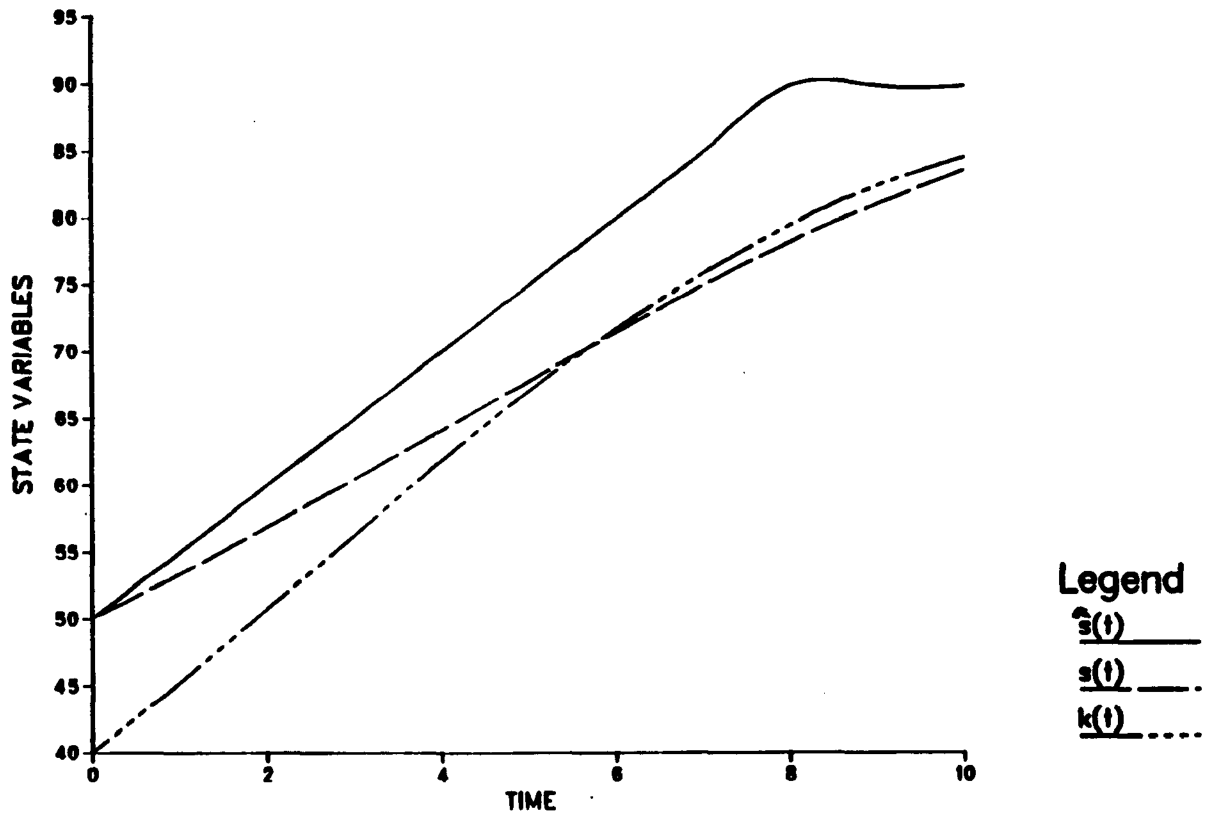

Figure 34. Goal Demand, Actual Demand and Capacity: Example 7

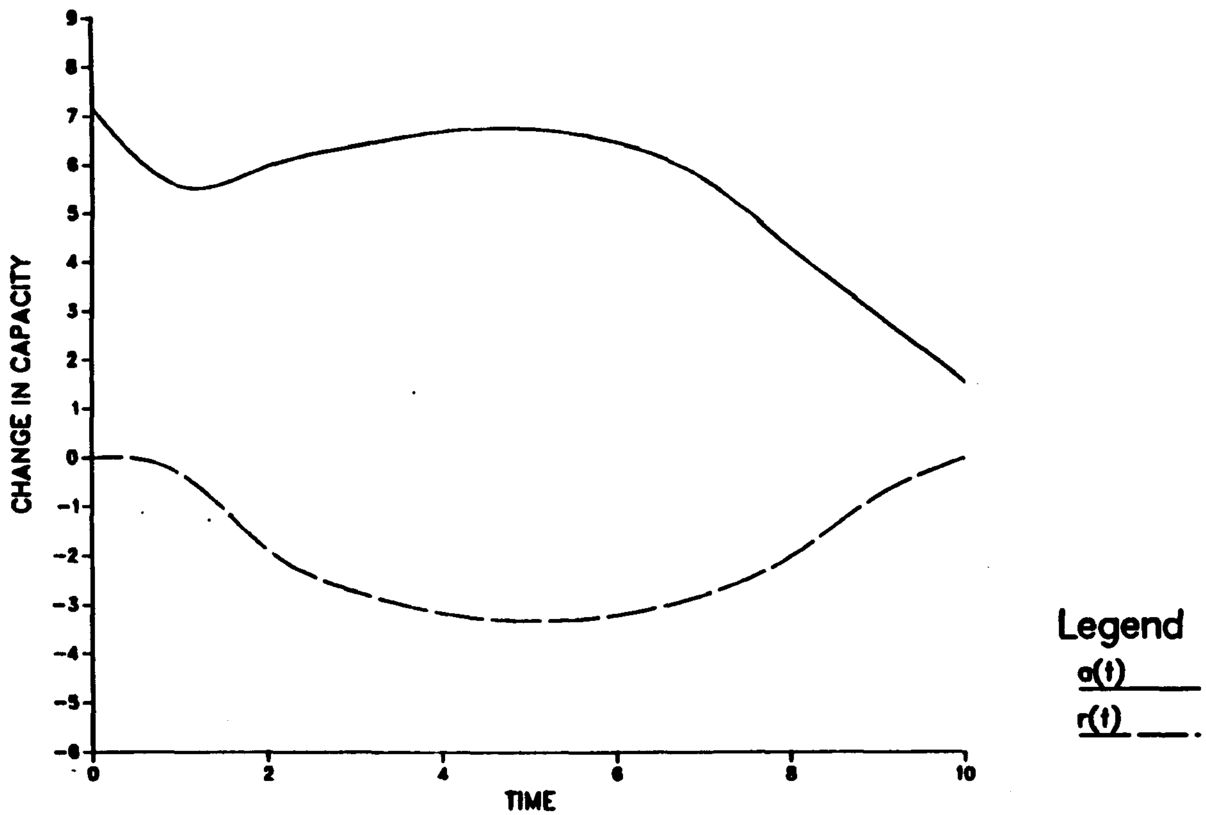

Figure 35. Optimal Control Policies: Example 8

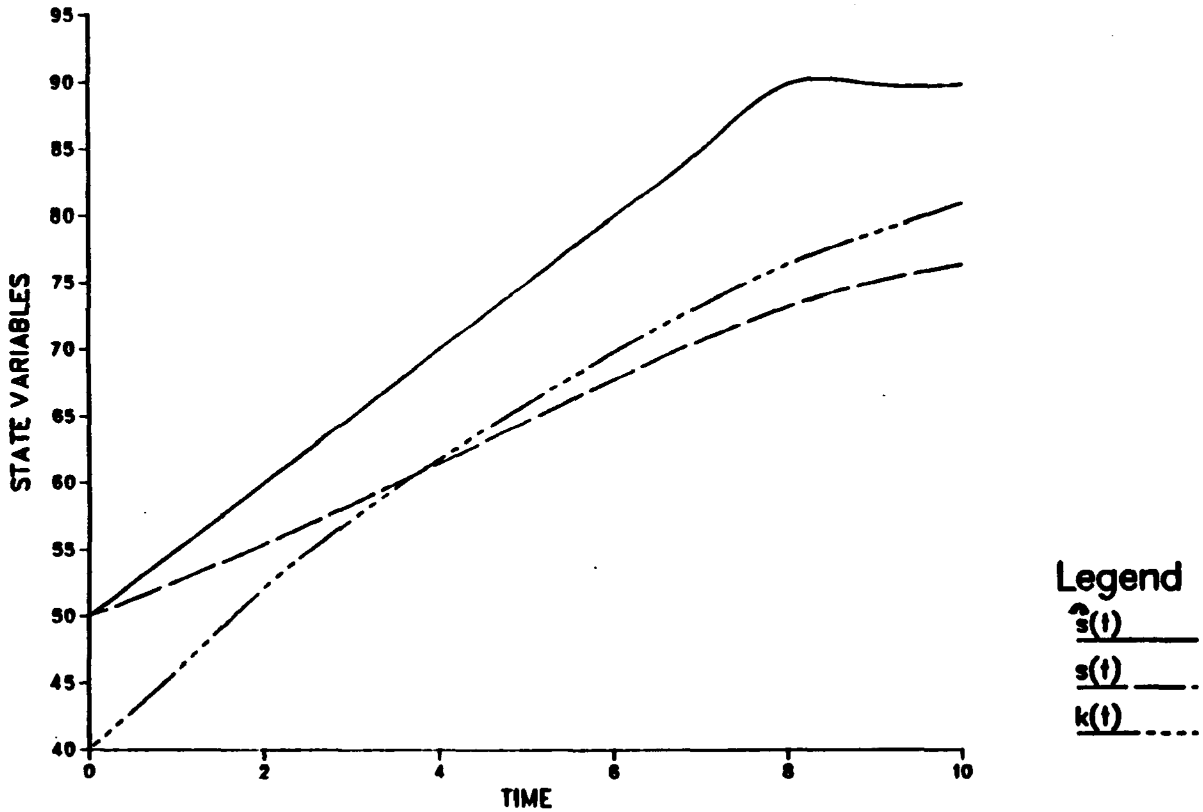

Figure 36. Goal Demand, Actual Demand and Capacity: Example 8

CHAPTER 5

CONCLUSION AND TOPICS OF FUTURE RESEARCH

5.1 RESEARCH OVERVIEW

Decisions concerning the appropriate choice and dynamic mix of flexible systems automation and conventional manufacturing process technology as a source of productive capacity constitutes a significant portion of a manufacturing strategy. Indeed, the mix of process technology has direct bearing upon the firm's overall competitive position and the ability of the strategic business unit to achieve a competitive advantage. Given the dynamic optimal mix of flexible and conventional manufacturing process technology, the firm's levels of market share (demand), capacity, production costs, and learning may be derived over time.

In this dissertation research, two dynamic decision support models are formulated in which the dynamic optimal composition of production capacity is determined which maximizes the long-run performance (effectiveness/strength) of the firm minus the relevant costs. The composition of productive capacity is reflected by the units of output resulting from flexible automation and conventional equipment. Given the formulation of the objective to maximize the long-term effectiveness of the firm over time subject to constraints specified as differential equations, each model was solved using optimal control theory.

5.2 MODEL ASSUMPTIONS

Certain underlying assumptions are deemed to hold in both the models of Chapter 3 and Chapter 4. These assumptions describing the dynamic decision environment for which the models are applicable are delineated as follows:

(a) The market is responsive to the acquisition of flexible technology. In particular, the firm's market share (demand) may be modified due to the value-added enhanced output from the newly acquired flexible automation. A market responsiveness function is defined to capture the strategic benefits of the technology. Embodied implicitly in the market response function is the dynamic impact of price, dependability, quality, and other economies of scope due the enhanced outputs of flexible systems technology.

(b) The production plus in-process inventory costs are reduced due to the acquisition of flexible systems technology. Operating cost reductions due to acquiring flexible automation correspond to learning, reduced wage costs, improved productivity and improved utilization of raw materials, space and energy.

(c) An evolutionary (incremental) timing strategy is to be used. (See Chapter 2). In the evolutionary strategy a gradual shift over time from conventional to new flexible systems technology is assumed. Incremental adoption strategy is consistent with a smoothed, continuous acquisition policy wherein flexible technology modules (islands of automation) are purchased over time. The magnitude of changes in the composition of productive capacity at any instant of time is relatively small compared with the total level of capacity at that time. Therefore, the costs of (a) acquiring flexible automation and (b) changing the level of conventional capacity are modeled in terms of the rate of change squared (quadratic functions).

(d) All cost functions are functions of time reflecting the anticipation of technological advancement, learning and inflation. All cost functions are exogenous with the exception of one of two components of the per unit production costs which may be reduced due to acquiring flexible technology. Furthermore, quadratic costs on the decision variables were assumed in the objective function to achieve the desired smoothing of the changeover process in order to be consistent with the firm's evolutionary timing strategy. Penalty costs were also modeled as quadratic functions to reflect the undesirability of large deviations between certain variables. It should be noted that specific cost functions expressed in the objective function are not required to derive optimal solutions; however, depending upon the cost functions assumed, different optimal policies for the control variables would be advocated.

(e) Regardless of the mix, maintenance costs correspond to the totality of the available productive capacity. In other words, all direct and indirect cost reductions due to the acquisition of flexible technology are accounted for in the per unit production plus in-process inventory costs.

(f) All demand is satisfied at the instant it is required through the firm's own available operating capacity at that time.

Hence no inventory or backlogging/backordering is permitted. In Chapter 3, underutilization of operating capacity is allowed in the model; however, no short-term capacity expansion measures may be employed. The upper bound on production is the level of capacity available at time t. In Chapter 4, both underutilization and short-term capacity expansion measures are permitted in the model.

(g) The market saturation level is exogenous and fixed over the planning period.

(h) Technological progress (organizational learning) occurs. The total impact of technological progress is captured in the efficiency factor corresponding to the percentage reduction in the per unit production costs due to acquiring automation, however, no capacity impact is recognized in the formulation of Chapter 3. In Chapter 4 technological progress is reflected through reduced production costs, increased operating capacity due to productivity improvements, and gains in demand due to enhanced (value-added) outputs.

(i) In the formulation of Chapter 3, system synergy occurs subject to diminishing returns as flexible systems modules are integrated.

(j) A deterministic formulation is adequate for broad scale strategic analysis. While random variation certainly occurs in the real world, modeling various scenarios through sensitivity analysis is sufficient to give broad-based insight on the dynamic decision environment. Furthermore, at the strategic level of analysis, the decisions provided by the model are to give policy guidance and managerial insight concerning the problem. In fact, the level of aggregation is so broad and the level of abstraction is so great, it is doubtful that the decisions can be implemented exactly.

5.3 RESEARCH EXTENSIONS

Given the set of assumptions outlined in Section 5.2, it is recognized that future research is warranted in two areas: Model extensions and empirical research.

5.3.1 Model Extensions

Given that the adoption of new flexible systems technology is subject to a variety of concerns, the models introduced in Chapters 3 and 4 are limited by the assumptions posed and other important considerations which may be omitted. Outlined below are plausible extensions to the models depicted in Chapters 3 and 4.

Extensions of Chapter 3

Future research pertaining to Chapter 3 includes:

(a) The exogenous attrition rate function could be modified such that attrition is an endogenous function of the level of conventional technology available at time t. Furthermore, if attrition were not desirable, a cost term corresponding to the rate of attrition at time t could be added to the maximizing objective function.

(b) The capacity maintenance costs for conventional versus new flexible systems technology may be distinct and subject to different risk factors. In this case, the level of flexible automation would be monitored throughout the planning horizon through the addition of a state equation reflecting the level of flexible automation accumulated over time. The costs of maintaining both conventional and flexible technology should be accounted for separately in the objective.

(c) The market responsiveness function $\gamma_1(t)$ could be made an endogenous function of the relative proportion of automation to total capacity. The greater the magnitude of flexible technology relative to the total, the more cost reductions and quality, delivery and flexibility improvements would be expected. In other words, $\gamma_1(t)$ would reflect the value-added improvements in capacity due to a greater proportion flexible automation in the manufacturing environment.

(d) The cost of acquiring flexible automation could be modified to account for economies of scale. In other words, larger incremental purchases offer economies of scale. Therefore, economies of scale will affect the timing and sizing of capacity expansion projects.

(e) The costs of acquiring and reducing productive capacity could be made linear in the control. Therefore, smoothing the changeover process is either (a) not considered important to the firm or (b) explicitly handled by the upper bounds of the control variables.

Extensions of Chapter 4

Modifications to the formulation of Chapter 4 might include the following:

(a) The market saturation level N could be made an endogenous function of the level of enhanced capacity. In other words, the enhanced production capabilities serve to expand the market into broader segments.

(b) Separate the market responsiveness function into two components: (1) that associated with the rate of acquiring new flexible technology and (2) that corresponding to the technological progress. This, in effect allows for the possibility of two different responsiveness functions.

(c) Rather than an evolutionary timing strategy, consider the possibility of a radical adoption policy. Acquisitions of flexible technology would occur impulsively at optimally derived discrete times.

(d) Allow for anticipatory inventory by including inventory costs in the goal and in the demand state equation.

5.3.2 Empirical Analysis

Empirical analysis should cover several important areas which are critical to the implementation of the models.

(a) It is necessary to validate that certain relationships exist and the magnitude of those relationships. For example, for firms within a specific industry, the degree to which the market is responsive to flexible automation and the magnitude of the cost reductions possible should be measured.

(b) Determination of the magnitude, range and functional forms over time of the exogenous cost coefficients should be made.

(c) Given (a) and (b) above, assessment of those exogenous parameters which are of paramount strategic concern for policy formation should be made through statistical analysis.

(d) Consideration of the feasibility of disaggregating the optimal policies from (c) should be given. This may require several iterations of (a)-(d) in order to achieve a feasible operational plan (Starr and Biloski 1983).

(e) Validation of the pragmatic utility of these models (or extensions) as strategic decision aiding tools. In other words, to what extent will managers obtain policy guidance and insight from use of the models?

5.3.3 CONCLUSION

In conclusion, in this research we have assumed the adoption of flexible manufacturing systems technology is more than a simple replacement of old machines for new. FMS not only provides certain production efficiencies but also has the more far-reaching strategic potential to define the firm's production capabilities and serve as a competitive weapon. In particular, FMS technology is deemed to have the largest payoff in mid-volume, mid-variety batch manufacturing environments.

Development of a manufacturing process strategy should be of paramount importance to manufacturers. In particular, the manufacturing process choice should support the business units statement of the firm's competitive advantage. In this dissertation, three goals were met:

(a) Development of a conceptual framework depicting linkages between corporate, business unit and manufacturing strategy;

(b) Development of two normative dynamic decision models to assist firms in the development of a manufacturing process technology strategy;

(c) Performance of sensitivity analysis of key exogenous variables as illustrative examples.

As delineated in Chapter 5, much further research is needed. The author believes that both normative and descriptive research in the area of manufacturing strategy are necessary to refine the modeling approaches contained in this research and to assure the validity and usefulness of this approach. Possible research extensions were covered in Section 5.3.1. Clearly, this research represents a pioneer effort with respect to strategic planning for the acquisition of manufacturing technology. The dynamic decision support models developed in this research serve as an impetus for continued work in normative modeling efforts related to the development of manufacturing policy in support of the firm's competitive advantage.

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APPENDIX A

Numerical Solution Algorithm: Model I of Chapter 3

ALGORITHM 1

Step 0. Initialization. For t=0, 1,...,T set:

a. $m(t)=m_0$, $b(t)=b_0$, $y(t)=y_0$ and $k(t)=k_0$,

b. a(t)=0, h(t)=0, p(t)=0,

c. $SAVE\lambda_i(t)=0$, i=1,2,3

d. Input values for all exogenous parameters

e. $t^*=0$, and compute $\lambda_i(t)$, i=1,2,3 and t=T, T-1,...,0 from Equations (3.30), (3.31) and (3.32) respectively.

Step 1. For $t=t^*$:

a. compute a(t), h(t) and p(t) from Equations (3.18), (3.20), and (3.22), respectively.

b. set $t=t^*+1$ and compute state variables m(t), y(t), b(t), and k(t) from Equations (3.26) through (3.29), respectively.

Step 2. If y(t)<0 then call Algorithm 2; otherwise proceed to Step 3.

Step 3. If k(t)-m(t)N<0, then call Algorithm 3 or if k(t)-m(t)N=0 retain $\mu_2(t)$ from previous iteration.

Step 4. If t=T go to Step 5; otherwise, return to Step 1.

Step 5. Compute $\lambda_i(t-1)$, i=1,2,3 and t=T, T-1,...,0 from Equations (3.30), (3.31), and (3.32), respectively.

If $| SAVE\lambda_i(t)-\lambda_i(t) | \leq \xi$ for all t=0, 1,...,T and i=1,2,3 then convergence has been achieved and stop. Note that $SAVE\lambda_i(t)$

represents the values of the corresponding adjoint variables obtained in the previous iteration and ξ is a prespecified maximum allowable difference level. Otherwise, proceed to Step 6.

<u>Step 6</u>. Exponentially smooth $\lambda_i(t)$ for $t=0,1,\ldots,T$ and $i=1,2,3$ as in Equation (A.1) where $0<\theta<1$.

$$\lambda_i(t)=\theta SAVE\ \lambda_i(t)+(1-\theta)\lambda_i(t) \qquad (A.1)$$

Save the values of $\lambda_i(t)$ as $SAVE\lambda_i(t)$ for $t=1,2,\ldots T$.

Set $t^*=0$ and return to Step 1.

ALGORITHM 2.

<u>Step 0</u>. Set:

a. $p(t-1)=y(t-1)-r(t-1)$ (A.2)

b. $y(t)=y(t-1)+h(t-1)-p(t-1)-r(t-1)$ (A.3)

c. $r(t)=0$ (A.4)

d. $k(t)=k(t-1)+a(t-1)+h(t-1)-p(t-1)-r(t-1)$ (A.5)

<u>Step 1</u>. Return to Algorithm 1, Step 3.

ALGORITHM 3

<u>Step 0</u>. Solve for μ_2(t, case) such that $k(t)=m(t)N$ where case = 1,2,...,15. (Note the permissible ranges of the control variables for each of the 15 cases are depicted in Table 1).

<u>Step 1</u>. Determine which of the computed values of $\mu 2_2$(t, case) where case = 1,2,...,15 is feasible. A feasible μ_2(t,

case) (a) is nonnegative, (b) causes the control variable computed at time t-1 to hold within its permissible ranges as designated in Table 1, and (c) effects changes in controls at time t-1 such that the resultant state variables time t produce k(t)=m(t)N exactly. Set $\mu_2(t)$ equal to the smallest value $\mu_2(t, \text{case})$ in the feasible set.

Step 2. Given $\mu_2(t)$, recompute the adjoint variables at time t-1 using Equations (3.30), (3.31), and (3.32). Compute the controls at time t-1 from Equations (3.18), (3.20), and (3.22) and the state variables at time t from Equations (3.26)-(3.29).

Step 3. Return to Algorithm 1, Step 4.

APPENDIX B

Computer Program: Model I of Chapter 3

```
C
C***********************************************************************
C
C THE STRATEGIC ADOPTION OF FLEXIBLE TECHNOLOGY FOR THE COMPETITIVE ADVANTAGE
C
                              MODEL I OF CHAPTER 3
C
C
C***********************************************************************
C***********************************************************************
C
C DEFINITION OF VARIABLES
C
C
C STATE VARIABLES
C
C       MS(T)-LEVEL OF MARKET SHARE AT TIME T
C       K(T)-LEVEL OF CAPACITY AT TIME T
C       Y(T)-LEVEL OF CONVENTIONAL TECHNOLOGY AT TIME T
C       B(T)-ONE OF TWO COMPONENTS OF THE PER UNIT PRODUCTION PLUS
C            IN PROCESS INVENTORY COSTS THAT CAN BE REDUCED DUE TO
C            ACQUIRING NEW TECHNOLOGY AT TIME T
C
C INTERMEDIATE STATE VARIABLES USED FOR TEMPORARY COMPUTATIONS
C
C       NEWMS(T)-MARKET SHARE CORRESPONDING TO MS(T)
C       NEWK(T)-CAPACITY CORRESPONDING TO K(T)
C       NEWY(T)-CONVENTIONAL TECHNOLOGY CORRESPONDING TO Y(T)
C       NEWB(T)-PER UNIT PRODUCTION COST CORRESPONDING TO B(T)
C
C
C CONTROL VARIABLES
C
C       A(T)-RATE OF ACQUIRING FLEXIBLE AUTOMATION AT TIME T
C       H(T)-RATE OF ACQUIRING CONVENTIONAL TECHNOLOGY AT TIME T
C       L(T)-RATE OF REDUCING CONVENTIONAL TECHNOLOGY AT TIME T
C
C
C INTERMEDIATE CONTROL VARIABLES USED FOR TEMPORARY  COMPUTATIONS
C
C      AA(T)-TEMPORARY VARIABLE CORRESPONDING TO A(T)
C      HH(T)-TEMPORARY VARIABLE CORRESPONDING TO H(T)
C      LL(T)-TEMPORARY VARIABLE CORRESPONDING TO L(T)
C
C
C ADJOINT VARIABLES
C
C
C      LL1(T)-ADJOINT VARIABLE CORRESPONDING TO MARKET SHARE
C      LL2(T)-ADJOINT VARIABLE CORRESPONDING TO PER UNIT PRODUCTION COSTS
C      LL3(T)-ADJOINT VARIABLE CORRESPONDING TO CAPACITY
C      LL4(T)-ADJOINT VARIABLE CORRESPONDING TO CONVENTIONAL CAPACITY
C
C
```

```
C INTERMEDIATE ADJOINT VARIABLES USED FOR TEMPORARY COMPUTATIONS
C
C
C      NEWLL1(T)-TEMPORARY VARIABLE CORRESPONDING TO LL1(T)
C      NEWLL2(T)-TEMPORARY VARIABLE CORRESPONDING TO LL2(T)
C      NEWLL3(T)-TEMPORARY VARIABLE CORRESPONDING TO LL3(T)
C      NEWLL4(T)-TEMPORARY VARIABLE CORRESPONDING TO LL4(T)
C      SL1(T)-SAVED VALUE OF LL1(T)
C      SL2(T)-SAVED VALUE OF LL2(T)
C      SL3(T)-SAVED VALUE OF LL3(T)
C      SL4(T)-SAVED VALUE OF LL4(T)
C
C
C LAGRANGE MULTIPLIERS
C
C
C      MU1(T)-LAGRANGE MULTIPLIER FOR STATE CONTRAINT Y(T)>0
C      MU2(T)-LAGRANGE MULTIPLIER FOR STATE CONSTRAINT K(T)>MS(T)N
C      MU2AO(T)-VALUE OF MU2(T) SUCH THAT A(T)=0
C      MU2AMAX(T)-VALUE OF MU2(T) SUCH THAT AT(T)=AMAX(T)
C      M2HO(T)-VALUE OF MU2(T) SUCH THAT H(T)=0
C      M2HMAX(T)-VALUE OF MU2(T) SUCH THAT H(T)=HMAX(T)
C      MU2SAV(T)-SAVED VALUE OF MU2(T)
C
C
C EXOGENOUS VARIABLES
C
C       AMAX(T)-MAXIMUM RATE OF ACQUIRING FLEXIBLE TECHNOLOGY
C       HMAX(T)-MAXIMUM RATE OF ACQUIRING CONVENTIONAL TECHNOLOGY
C       LMAX(T)-MAXIMUM RATE OF REDUCING CONVENTIONAL TECHNOLOGY
C       C1(T)-COST OF ACQUIRING FLEXIBLE AUTOMATION
C       C2(T)-COST OF ACQUIRING CONVENTIONAL TECHNOLOGY
C       C3(T)-COST OF REDUCING CONVENTIONAL TECHNOLOGY
C       C4(T)-COST OF HOLDING CAPACITY
C       V1(T)-PENALTY COST OF DEVIATIONS BETWEEN ACTUAL AND GOAL
C             MARKET SHARE
C       RHO-DISCOUNT FACTOR
C       EX(T)-EXPONENTIAL FUNCTION OF RHO
C       G1(T)-2*DISCOUNTED COSTS OF ACQUIRING FLEXIBLE TECHNOLOGY
C       G2(T)-2*DISCOUNTED COSTS OF ACQUIRING CONVENTIONAL TECHNOLOGY
C       G3(T)-2*DISCOUNTED COSTS OF REDUCING CONVENTIONAL TECHNOLOGY
C       G4(T)-DISCOUNTED COST OF HOLDING CAPACITY
C       BB-COMPONENT OF THE PER UNIT PRODUCTION PLUS IN-PROCESS INVENTORY
C          COST WHICH IS UNAFFECTED BY ACQUIRING FLEXIBLE AUTOMATION
C       OBJ-VALUE OF OBJECTIVE FUNCTION AT CONVERGENCE
C       NEWOBJ-VALUE OF OBJECTIVE FUNCTION AT AN INTERMEDIATE PERIOD
C
C       POP(T)-MARKET SATURATION LEVEL AT TIME T
C       PROD(T)-LEVEL OF PRODUCTION AT TIME T
C       NPROD(T)-DIFFERENCE BETWEEN CAPACITY AND PRODUCTION
C       GOALMS(T)-PLANNED LEVEL OF MARKET SHARE
C       DELTA(T)-EXOGENOUS MARKET GROWTH/DECAY FACTOR
C       GAMMA(T)-PER UNIT EFFECTIVENESS OF FLEXIBLE TECHNOLOGY
C                IN CAPTURING COMPETITOR'S MARKET
```

```
C       ALPHA(T)-EFFICIENCY FACTOR CORRESPONDING TO THE REDUCTION
C                IN THE PER UNIT PRODUCTION COSTS DUE TO
C                   ACQUIRING AUTOMATION
C       R(T)-EXOGENOUS ATTRITION
C       COUNT-NUMBER OF ITERATIONS
C       STOPIT-MAXIMUM NUMBER OF ITERATIONS PERMITTED
C       ERR-MAXIMUM TOLERANCE IN CHECKING FOR CONVERGENCE
C       CVG1-CONVERGENCE ON LL1(T)
C       CVG2-CONVERGENCE ON LL2(T)
C       CVG3-CONVERGENCE ON LL3(T)
C       CVG4-CONVERGENCE ON LL4(T)
C       NCASE-NUMBER OF CASES
C       FEASOL-FEASIBLE SOLUTION
C       NOFEASOL-NO FEASIBLE SOLUTION
C
C
C***********************************************************************
C
C MAIN PROGRAM
C
C***********************************************************************
C
C COMMON BLOCK OF VARIABLES USED BY THE FORTRAN COMPILER FOR SHARING
C COMMON DATA AMONG SUBROUTINES.  USE IN PROGRAM WHERE <INSERT COMMON>
C IS OBSERVED.
C
       COMMON/GRP1/ MS(0:100),K(0:100),Y(0:100),B(0:100),
     1NEWMS(0:100),NEWB(0:100),NEWY(0:100),
     2NEWK(0:100),
     3A(0:100),H(0:100),L(0:100),AA(0:100),LL(0:100),HH(0:100),
     4LMAX(0:100),HMAX(0:100),AMAX(0:100)
C
      COMMON/GRP2/MU1(0:100),MU2(0:100,0:100),MU2SAV(0:100),
     1LL1(0:100),LL2(0:100),LL3(0:100),LL4(0:100),
     2SL1(0:100),SL2(0:100),SL3(0:100),SL4(0:100),
     3M2A0(0:100),M2AMAX(0:100),M2L0(0:100),M2LMAX(0:100),M2H0(0:100),
     4M2HMAX(0:100),NEWLL1(0:100),NEWLL2(0:100),NEWLL3(0:100)
C
      COMMON/GRP3/ EX(0:100),G1(0:100),G2(0:100),G3(0:100),G4(0:100),
     1C1(0:100),C2(0:100),C3(0:100),C4(0:100),V1(0:100),
     2SAVEMU2,OBJ,NEWOBJ(0:100),BB,S1,S2,
     4RHO,POP(0:100),ERR,PHI,AA1,BB1,CC1,
     5 PROD(0:100),NPROD(0:100)
C
      COMMON/GRP4/Q,Q1,U(0:100), W(0:100), X(0:100),Z(0:100),
     1UU(0:100),WW(0:100),XX(0:100),ZZ(0:100),FF(0:100),F(0:100),
     2GOALMS(0:100),DELTA(0:100),ALPHA(0:100),GAMMA(0:100),R(0:100),
     3ATTR(0:100)
C
      COMMON/GRP5/ T,TM,SCRIPT,LLL,KKK,I,J,CASE,CAPCNT,NUMBER,
     1CASES(0:100),CVG1,CVG2,CVG3,CVG4,COUNT,TT,STOPIT,CHECK1,
     2CHECK2,CHECK3,CHECK4,TT1,NCASE,TB1,KK,TB2,FEASOL(0:100),NOFEAS

C
```

```
      DOUBLE PRECISION  MS,K,Y,B,
     1NEWMS,NEWB,NEWY,NEWK,A,H,L,AA,LL,HH,LMAX,HMAX,AMAX,
     2MU1,MU2,MU2SAV,
     3LL1,LL2,LL3,LL4,SL1,SL2,SL3,SL4,M2A0,M2AMAX,M2L0,M2LMAX,M2H0,
     4M2HMAX,NEWLL1,NEWLL2,NEWLL3,
     5EX,G1,G2,G3,G4,C1,C2,C3,C4,V1,SAVEMU2,OBJ,NEWOBJ,BB,S1,S2,
     6RHO,POP,ERR,PHI,AA1,BB1,CC1,PROD,NPROD,
     7Q,Q1,U,W,X,Z,UU,WW,XX,ZZ,FF,F,GOALMS,DELTA,ALPHA,GAMMA,R,ATTR
C
      INTEGER T,TM,SCRIPT,LLL,KKK,I,J,CASE,CAPCNT,CASES,CVG1,CVG2,CVG3,
     1CVG4,COUNT,TT,STOPIT,CHECK1,CHECK2,CHECK3,CHECK4,
     2TT1,NUMBER,NCASE,TB1,KK,TB2,FEASOL,NOFEAS
C
C
       CALL START
       CALL READY
   5   CONTINUE
       CALL INITIAL
       CALL COMPUTE
       CALL LAMBDA
C
C CHECK FOR CONVERGENCE.  IF CONVERGENCE NOT ATTAINED REPEAT.
C
       IF ((CVG1.EQ.1).AND.(CVG2.EQ.1).AND.(CVG3.EQ.1)) CALL PSTATE
       IF ((CVG1.EQ.1).AND.(CVG2.EQ.1).AND.(CVG3.EQ.1))  CALL PCONT
       IF((CVG1.EQ.1).AND.(CVG2.EQ.1).AND.(CVG3.EQ.1))  CALL POBJ
       IF ((CVG1.EQ.1).AND.(CVG2.EQ.1).AND.(CVG3.EQ.1)) CALL PLAMB
       IF ((CVG1.EQ.1).AND.(CVG2.EQ.1).AND.(CVG3.EQ.1)) STOP 5555
C
       CALL READY
       GO TO 5
C
       END
C
C  END MAIN PROGRAM
C
C
C ***********************************************************************
C
       SUBROUTINE START
C
C************************************************************************
C
C IN THIS ROUTINE ALL VARIABLES ARE INITIALIZED
C
C  <INSERT COMMON>
C
      TM=10
      TB1=0
      TB2=5
      MS(0)=.10
      B(0)=20
      K(0)=65
      Y(0)=65
```

```
      S1=1000000
      S2=10
      CASE=0
      SCRIPT=0
      NCASE=15
      RHO=.150000
C
      DO 100 T=0,TM
C
         MS(T)=MS(0)
         B(T)=B(0)
         Y(T)=Y(0)
         K(T)=K(0)
         MU2SAV(T)=0.0
C
         DO 90 I=1,NCASE
            MU2(T,I)=0.0
 90      CONTINUE
C
         MU1(T)=0.0
         EX(T)=DEXP(-RHO*T)
 100  CONTINUE
C
      DO 200 T=0,TM
         HMAX(T)=30
         H(T)=0.0
         AMAX(T)=10
         A(T)=0.0
         LMAX(T)=20
         L(T)=0.0
 200  CONTINUE
C
      CVG1=0
      CVG2=0
      CVG3=0
      CVG4=0
      ERR=.5
      COUNT=0
      BB=10
      PHI=.8
      STOPIT=300
C
      DO 300 T=0,TM
         C1(T)=40-0*T
         C2(T)=10 + .0*T
         C3(T)=10
         C4(T)=25
         IF (T.GT.0) THEN
           GOALMS(T)=GOALMS(T-1) + .01
         ELSE
            GOALMS(T)=0.10
         END IF
         IF(T.GT.5) GOALMS(T)=GOALMS(5)
         V1(T)=100000
```

```
         ALPHA(T)=0.002 + .0000*T
         GAMMA(T)=.005 + .000*T
         DELTA(T)=+.000000
         POP(T)=500
         G1(T)=2*C1(T)*EX(T)
         G2(T)=2*C2(T)*EX(T)
         G3(T)=2*C3(T)*EX(T)
         G4(T)=C4(T)*EX(T)
         R(T)=0.00
 300  CONTINUE
C
C COMPUTE ADJOINT VARIABLES GIVEN INITIAL STATE AND CONTROL VARIABLES
C
      CALL LAMBDA
C
C SAVE THE VALUES OF LAMBDA
C
      DO 311 T=0,TM
         SL1(T)=LL1(T)
         SL2(T)=LL2(T)
         SL3(T)=LL3(T)
 311  CONTINUE
C
C WRITE OUT THE INPUT DATA
C
      WRITE(6,10) TB1,TB2,MS(0),K(0),Y(0),B(0)
 10   FORMAT('1',///,T35,'TABLE',I4,'.  INPUT DATA EXAMPLE',I3,
     1/////,T2,'STATE VARIABLES AT TIME 0',//,
     1T6,'MS0',T19,'K0',T31,'Y0',T43,'B0',/,T4,F10.6,T16,F10.4,
     1T28,F10.4,T40,F10.4,///,T2,'EXOGENOUS VARIABLES',
     1//,T3,'T',T8,'GOALMS',T19,'C1',T31,'C2',T43,'C3',T55,'C4',
     1T65,'BB',T76,'R',T86,'ALPHA')
      DO 12 T=0,TM
      WRITE(6,13)T,GOALMS(T),C1(T),C2(T),C3(T),C4(T),BB,R(T),ALPHA(T)
 13   FORMAT(T2,I2,T4,F10.4,T16,F10.4,T28,F10.4,T40,F10.4,T52,F10.4,
     13F10.4)
 12   CONTINUE
C
      WRITE(6,14)
 14   FORMAT(//,T5,'V1',T20,'GAMMA',T30,'DELTA',T41,'HMAX',
     1T53,'AMAX',T66,'LMAX')
      DO 16 T=0,TM
      WRITE(6,17) T,V1(T),GAMMA(T),DELTA(T),HMAX(T),AMAX(T),LMAX(T)
 17   FORMAT(T2,I2,T5,F9.2,T16,F10.4,T28,F10.6,T40,F10.6,T52,F10.6,
     1T65,F10.6)
 16   CONTINUE
C
      WRITE(6,18) S1,S2,RHO,PHI,POP(0),STOPIT,TM
 18   FORMAT(//,T5,'S1',T20,'S2',T30,'RHO',T43,'PHI',T55,'POPO',
     1T65,'STOPIT',T75,'TM',/,T3,F10.1,T14,F10.1,T26,F10.4,T39,F10.4,
     1T54,F5.0,T65,I3,T75,I2,///'1',T4,'BOUNDS ON CONTROLS',//,T4,'T',
     1T6,'HMAX',T16,'AMAX',T28,'LMAX',/)
C
      DO 19 T=0,TM
```

```
      WRITE(6,21) T,HMAX(T),AMAX(T),LMAX(T)
 21   FORMAT(T4,I2,T6,F10.4,T16,F10.4,T28,F10.4)
 19   CONTINUE
C
      RETURN
      END
C
C
C ***********************************************************************
C
       SUBROUTINE READY
C
C************************************************************************
C
C IN THIS SUBROUTINE A CHECK IS MADE TO DETERMINE IF BOTH AMAX(T)
C AND GAMMA(T) ARE WITHIN THEIR BOUNDS
C
C <INSERT COMMON>
C
      INTEGER ERROR1,ERROR2,ERROR3
C
      ERROR1=0
      ERROR2=0
      ERROR3=0
C
      DO 2080 T=1,TM
         IF (ALPHA(T).LE.1/AMAX(T)) GO TO 2010
         WRITE(6,2000) ALPHA(T),AMAX(T),T
 2000    FORMAT(' ','ALPHA(T)=',F10.4,2X,'AMAX(T)=',F10.4,
     1   2X,'TIME=',I3,'***ERROR ALERT-ALPHA(T) TOO BIG')
         ERROR1=ERROR1+1
 2010    CONTINUE
C
 2030   IF (GAMMA(T).LE.1/AMAX(T)) GO TO 2050
        WRITE(6,2040) GAMMA(T),AMAX(T),T
 2040   FORMAT(' ','GAMMA(T)=',F10.4,'AMAX(T)=',F10.4,2X,
     1  'TIME=',I3,'***ERROR ALERT-GAMMA(T) TOO BIG')
        ERROR2=ERROR2+1
 2050   CONTINUE
C
 2080 CONTINUE
      IF((ERROR1.EQ.0).AND.(ERROR2.EQ.0))
     1RETURN
C
      STOP
      END
C
C
C ***********************************************************************
C
       SUBROUTINE INITIAL
C
C************************************************************************
C
```

```
C REINITIALIZTION AFTER EACH COMPLETE ITERATION
C CHECK NUMBER OF ITERATIONS IS LESS THAN MAXIMUM
C
C <INSERT COMMON>
C
      COUNT=COUNT + 1
C
      IF (COUNT.GE.STOPIT) THEN
         CALL PSTATE
         CALL PCONT
         CALL PLAMB
         CALL POBJ
         STOP
      ELSE
         CHECK1=0
         CHECK2=0
         CHECK3=0
         CHECK4=0
         CVG1=0
         CVG2=0
         CVG3=0
         CVG4=0
       END IF
C
       RETURN
       END
C
C
C ************************************************************************
C
      SUBROUTINE COMPUTE
C
C*************************************************************************
C
C IN THIS SUBROUTINE VALUES OF STATE AND CONTROL VARIABLES ARE COMPUTED
C
C <INSERT COMMON>
C
C INITIAL COMPUTATION OF CONTROLS AT TIME 0
C
      T=0
      TT=0
      NEWLL1(TT)=LL1(TT)
      NEWLL2(TT)=LL2(TT)
      NEWLL3(TT)=LL3(TT)
C
      CALL CONTROL
C
      A(T)=AA(TT)
      H(T)=HH(TT)
      L(T)=LL(TT)
C
      DO 400 T=1,TM
          TT=T
```

```
          SAVEMS(T)=MS(T)
          SAVEB(T)=B(T)
          B(T)=B(T-1)-ALPHA(T-1)*A(T-1)*B(T-1)
          IF (B(T).LE.0.0)  B(T)=0.0
          MS(T)=MS(T-1) + GAMMA(T-1)*A(T-1)*(1.0-MS(T-1))
     1          +DELTA(T-1)*MS(T-1)
          IF (MS(T).LE.0.0) MS(T)=0.0
          Y(T)=Y(T-1)+H(T-1)-L(T-1)-R(T-1)
          K(T)=K(T-1)+A(T-1)+H(T-1)-L(T-1)-R(T-1)
C
C CHECK STATE CONSTRAINT ON LEVEL OF CONVENTIONAL OUTPUT
C
          IF (Y(T).LT.0.0) CALL MANUAL
C
C CHECK THAT CAPACITY AT T EXCEEDS PRODUCTION AT T
C
          NPROD(T)=K(T)-MS(T)*POP(T)
          IF (NPROD(T).LT.-0.0000005) THEN
            CALL CHECK
          ELSE
            IF(NPROD(T).GT.0.0000005) MU2SAV(T)=0.0
          END IF
          IF (Y(T).LT.0.0) CALL MANUAL
C
C ASSIGN LAMBDAS FOR COMPUTATION OF CONTROLS
C
          NEWLL1(TT)=LL1(T)
          NEWLL2(TT)=LL2(T)
          NEWLL3(TT)=LL3(T)
C
          CALL CONTROL
C
          A(T)=AA(TT)
          H(T)=HH(TT)
          L(T)=LL(TT)
 400  CONTINUE
C
      RETURN
      END
C
C
C **************************************************************************
C
          SUBROUTINE CHECK
C
C***************************************************************************
C
C IN THIS SUBROUTINE A COMPUTATION IS MADE FOR THE LAGRANGE
C MULTIPLIER,MU2>0,SINCE THE STATE CONSTRAINT THAT CAPACITY
C MUST EQUAL OR EXCEED PRODUCTION HAS BEEN VIOLATED
C
C THE PROGRAM RETURNS TO SUBROUTINE COMPUTE A VALUE OF
C MU2 AND THE UPDATED STATE,CONTROL AND ADJOINT VARIABLES
C
```

```
C <INSERT COMMON>
C
C COMPUTATION OF TEMPORARY VARIABLES USED IN CALCULATION OF MU2
C
      EXP1=LL2(T-1)*ALPHA(T-1)*B(T-1)
      EXP2=((2*V1(T)*(SAVEMS(T)-GOALMS(T))+(BB+SAVEB(T))*POP(T)))*EX(T)
      E=(K(T-1)-R(T-1)-POP(T-1)*MS(T-1)-DELTA(T-1)*MS(T-1)*POP(T-1))
      EE=1-GAMMA(T-1)*POP(T-1)+GAMMA(T-1)*POP(T-1)*MS(T-1)
      EXP3=GAMMA(T-1)-GAMMA(T-1)*MS(T-1)
      EXP4=LL1(T)-EXP2-LL1(T)*(GAMMA(T)*A(T)-DELTA(T))
      EXP5=G1(T-1)/(G3(T-1)*EE)
      EXP6=G1(T-1)/(G2(T-1)*EE)
      M2A0(T)=(EXP1+G4(T)-LL3(T)-EXP3*EXP4)/(1-EXP3*POP(T))
      M2AMAX(T)=(AMAX(T-1)*G1(T-1))/(1-POP(T)*EXP3)
      M2AMAX(T)=M2AMAX(T)+M2A0(T)
      M2HO(T)=G4(T)-LL3(T)
      M2HMAX(T)=M2HO(T)*HMAX(T-1)*G2(T-1)
      M2LO(T)=M2HO(T)
      M2LMAX(T)=M2LO(T)-(LMAX(T-1)*G3(T-1))
C
C COMPUTATION OF MU2 FOR EACH CASE
C
C     CASE 1,8,11

      MU2(T,1)=G4(T)-LL3(T)
      MU2(T,8)=G4(T)-LL3(T)
      MU2(T,11)=G4(T)-LL3(T)
C
C     CASE 2,4
C
      CASE=2
C
      DO 6000 CASE=2,5,2
         IF (CASE.EQ.2) THEN
           COST=EXP5
         ELSE
           COST=EXP6
         END IF
C
         MU2(T,CASE)=(EXP1-(E*G1(T-1)/EE)-EXP4*EXP3-(LL3(T)-G4(T))*
     1(1+COST))/(1+COST-POP(T)*EXP3)
C
 6000 CONTINUE
C
C     CASE 3,5
C
      CASE=3
C
      DO 6010 CASE=3,6,2
      IF (CASE.EQ.3) THEN
        SPEC=(LMAX(T-1)*G1(T-1))/EE
      ELSE
        SPEC=(-HMAX(T-1)*G1(T-1))/EE
      END IF
```

```
C
      MU2(T,CASE)=(SPEC+EXP1-(E*G1(T-1)/EE)-EXP4*EXP3
     1  -(LL3(T)-G4(T)))/( 1-POP(T)*EXP3)
C
 6010 CONTINUE
C
C CASES 6,9,12,14
C
      MU2(T,6)=MU2(T,1)-E*G3(T-1)
      MU2(T,9)=MU2(T,1)-E*G2(T-1)
      MU2(T,12)=MU2(T,6)-AMAX(T-1)*EE*G3(T-1)
      MU2(T,14)=MU2(T,9)-AMAX(T-1)*EE*G2(T-1)
C
C CASES 7,10,13,15
C
      MU2(T,7)=DMAX1(M2A0(T),M2LMAX(T))
      MU2(T,10)=DMAX1(M2A0(T),M2HMAX(T))
      MU2(T,13)=DMIN1(M2AMAX(T),M2LMAX(T))
      IF (M2AMAX(T).GE.M2HMAX(T)) THEN
        MU2(T,15)=M2HMAX(T)
      ELSE
        MU2(T,15)=-999
      END IF
C
C RECOMPUTE CONTROLS FOR EACH CASE WITH NEW MU2
C
      CASE=0
C
      DO 7000 I=1,NCASE
C
          CASE=CASE+1
          CASES(I)=0
          IF (MU2(T,I).GE.0.0) THEN /* COMPUTE NEW LAMBDAS*/
            CASES(I)=I
            TT=T-1
            NEWLL1(TT)=EXP4-MU2(T,I)*POP(T)
            NEWLL2(TT)=LL2(TT)
            NEWLL3(TT)=LL3(T)-G4(T)+MU2(T,I)
C
            CALL CONTROL
C
            AA(T-1)=AA(TT)
            LL(T-1)=LL(TT)
            HH(T-1)=HH(TT)
C
C COMPUTE STATES AT T FOR EACH CASE I GIVEN CONTROLS AT T-1
C
            NEWMS(I)=MS(T-1)+GAMMA(T-1)*AA(T-1)*(1.0-MS(T-1))
     1               +DELTA(T-1)*MS(T-1)
            NEWB(I)=B(T-1)-ALPHA(T-1)*AA(T-1)*B(T-1)
            NEWY(I)=Y(T-1)+HH(T-1)-LL(T-1)-R(T-1)
            NEWK(I)=K(T-1)+AA(T-1)+HH(T-1)-LL(T-1)-R(T-1)
C
            NPROD(I)=NEWMS(I)*POP(T)
```

```
          IF (DABS(NEWK(I)-NEWMS(I)*POP(T)).LE.0.000005) THEN
            FEASOL(I)=1
          ELSE
            FEASOL(I)=0
          END IF
        ELSE
         FEASOL(I)=0
        END IF
C
 7000 CONTINUE
C
      IF(M2A0(T).GT.M2AMAX(T)) THEN
        NUMB=1
      ELSE
        NUMB=0
      END IF
C THE ABOVE IS A SPECIAL CHECK ON THE VALUES OF MU2
C WHICH CAUSE A(T) TO BE AT THE BOUNDS
C
      DO 7601 J=1,5
         IF(MU2(T,J).GE.M2A0(T).AND.NUMB.EQ.1) FEASOL(J)=0
         IF(MU2(T,J).LE.M2A0(T).AND.NUMB.EQ.0) FEASOL(J)=0
         IF(MU2(T,J).LE.M2AMAX(T).AND.NUMB.EQ.1)FEASOL(J)=0
         IF(MU2(T,J).GE.M2AMAX(T).AND.NUMB.EQ.0)FEASOL(J)=0
 7601 CONTINUE
C
      DO 7602 J=6,10
         IF(MU2(T,J).LT.M2A0(T).AND.NUMB.EQ.1) FEASOL(J)=0
         IF(MU2(T,J).GT.M2A0(T).AND.NUMB.EQ.0) FEASOL(J)=0
 7602 CONTINUE
C
      DO 7603 J=11,15
         IF(MU2(T,J).GT.M2AMAX(T).AND.NUMB.EQ.1) FEASOL(J)=0
         IF(MU2(T,J).LT.M2AMAX(T).AND.NUMB.EQ.0) FEASOL(J)=0
 7603 CONTINUE
C
      IF(MU2(T,2).LE.M2LMAX(T).OR.MU2(T,2).GE.M2LO(T))
     1 FEASOL(2)=0
      IF(MU2(T,3).GT.M2LMAX(T)) FEASOL(3)=0
      IF(MU2(T,4).LE.M2HO(T).OR.MU2(T,4).GE.M2HMAX(T))
     1 FEASOL(4)=0
      IF(MU2(T,5).LT.M2HMAX(T)) FEASOL(5)=0
      IF((MU2(T,6).GE.M2LO(T)).OR.(MU2(T,6).LE.M2LMAX(T)))
     1 FEASOL(6)=0
      IF(MU2(T,7).GT.M2LMAX(T)) FEASOL(7)=0
      IF((MU2(T,9).LE.M2HO(T)).OR.(MU2(T,9).GE.M2HMAX(T)))
     1 FEASOL(9)=0
      IF(MU2(T,10).LT.M2HMAX(T)) FEASOL(10)=0
      IF(MU2(T,12).GE.M2LO(T).OR.MU2(T,12).LE.M2LMAX(T))
     1 FEASOL(12)=0
      IF(MU2(T,13).GT.M2LMAX(T)) FEASOL(13)=0
      IF((MU2(T,14).LE.M2HO(T)).OR.(MU2(T,14).GE.M2HMAX(T)))
     1 FEASOL(14)=0
      IF(MU2(T,15).LT.M2HMAX(T)) FEASOL(15)=0
```

```
C
C   COMPUTE NEWOBJ(I) AT T FOR ALL CASES
C
      DO 7013 I=1,NCASE
         IF (FEASOL(I).EQ.1) THEN
           AA1=0.0
           BB1=0.0
           CC1=0.0
           NEWOBJ(I)=0.0
           AA1=(V1(T)*(NEWMS(I)-GOALMS(T))**2+(BB+NEWB(I))*
     1     NEWMS(I)*POP(T) +C1(T)*AA(T)**2+C2(T)*HH(T)**2
     2     +C3(T)*LL(T)**2+C4(T)*NEWK(I))
     3     +MU2(T,I)*DABS(K(T)-MS(T)*POP(T))
           NEWOBJ(I)=AA1*EX(T)
         ELSE
           NEWOBJ(I)=-9999999999999
         END IF
 7013 CONTINUE
C
      DO 7800 I=1,NCASE
         NPROD(I)=NEWMS(I)*POP(T)
         IF(DABS(NEWK(I)-NPROD(I))-.000005) 7852,7852,7851
 7851    FEASOL(I)=0
         NEWOBJ(I)=-9999999999999
 7852    CONTINUE
C
 7800 CONTINUE
C
C   FIND THE FIRST CASE IN WHICH THE SOLUTION IF FEASIBLE
C
      CASE=0
      NOFEAS=0
      DO 8000 I=1,NCASE
      IF(FEASOL(15-I+1).EQ.1.AND.NEWOBJ(15-I+1).GE.-99999999999999)
     1THEN
      CASE=NCASE-I+1
      NOFEAS=NOFEAS +1
      ELSE
      CONTINUE
      END IF
 8000 CONTINUE
C
C   FIND THE VALUE OF THE  WHICH IS THE LOWEST FEASIBLE VALUE
C
      IF (NOFEAS.LT.1) THEN
        WRITE(6,9010) T
        STOP  9999
      ELSE
        CONTINUE
      END IF
      SAVEMU2=MU2(T,CASE)
      SCRIPT=CASE
      DO 9000 I=CASE,NCASE-1
      IF((SAVEMU2.GE.MU2(T,I+1)).AND.(NEWOBJ(I+1).GE.-999999999).AND.
```

```
     1FEASOL(I+1).EQ.1.AND.MU2(T,I+1).GT.0.0) THEN
         SAVEMU2=MU2(T,I+1)
         SCRIPT=I+1
       ELSE
         CONTINUE
       END IF
 9000 CONTINUE
C
C NO FEASIBLE VALUES
C
 9010 FORMAT(/,' ','NO FEASIBLE SOLUTION WITH RESPECT OF
     1CAPACITY CONSTRAINT AT TIME T=',I3,//)
      WRITE(6,8002)T,SCRIPT,NEWOBJ(SCRIPT),SAVEMU2,MU2(T,SCRIPT)
 8002 FORMAT(/,T2,'T,SCRIPT,NEWOBJ(SCRIPT),SAVEMU2,MU2(T,SCRIPT)',/,
     1T3,2(I3,2X),3(F20.5,2X))
C
C NOTE:   SCRIPT REPRESENTS THE CASE WITH THE LOWEST FEASIBLE MU2
C
       IF(MU2(T,SCRIPT).GT.0.0) THEN
         TT=T-1
         NEWLL1(TT)=EXP4-MU2(T,SCRIPT)*POP(T)
         NEWLL2(TT)=LL2(T-1)
         NEWLL3(TT)=LL3(T)-G4(T)+MU2(T,SCRIPT)
         LL1(TT)=NEWLL1(TT)
         LL2(TT)=NEWLL2(TT)
         LL3(TT)=NEWLL3(TT)
         MU2SAV(T)=MU2(T,SCRIPT)
         CALL CONTROL
         A(T-1)=AA(TT)
         L(T-1)=LL(TT)
         H(T-1)=HH(TT)
         MS(T)=NEWMS(SCRIPT)
         B(T)=NEWB(SCRIPT)
         Y(T)=NEWY(SCRIPT)
         K(T)=NEWK(SCRIPT)
         NPROD(T)=NPROD(SCRIPT)
         RETURN
       ELSE
         WRITE(6,9020) MU2(T,SCRIPT)
 9020    FORMAT(//,2X,'NO FEASIBLE SOLUTION MU2=', F15.4)
         STOP 9999
       END IF
C
       RETURN
       END
C
C
C***************************************************************************
C
        SUBROUTINE MANUAL
C
C***************************************************************************
C
C THIS SUBROUTINE HANDLES THE VIOLATION OF STATE CONTRAINTS ON
```

```
C THE LEVEL OF CONVENTIONAL OUTPUT, Y(T)>0
C
C <INSERT COMMON>
C
C
      L(T-1)=Y(T-1)-R(T-1)
      Y(T)=Y(T-1)+H(T-1)-L(T-1)-R(T-1)
      R(T)=0.0
      K(T)=K(T-1)+A(T-1)+H(T-1)-L(T-1)-R(T-1)
C
      RETURN
      END
C
C **********************************************************************
C
        SUBROUTINE CONTROL
C
C***********************************************************************
C
C IN THIS SUBROUTINE THE CONTROL VARIABLES ARE COMPUTED
C
C <INSERT COMMON>
C
      AA(TT)=((NEWLL1(TT)*GAMMA(TT)*(1.0-MS(TT)))
     1      -(NEWLL2(TT)*ALPHA(TT)*B(TT))+NEWLL3(TT))/G1(TT)
C
      IF (AA(TT).LE.0.0)  AA(TT)=0.0
      IF (AA(TT).GE.AMAX(TT))AA(TT)=AMAX(TT)
C
      HH(TT)=(NEWLL3(TT))/G2(TT)
C
      IF (HH(TT).LE.0.0) HH(TT)=0.0
      IF (HH(TT).GE.HMAX(TT))HH(TT)=HMAX(TT)
C
      LL(TT)=(-NEWLL3(TT))/G3(TT)
C
      IF (LL(TT).LE.0.0) LL(TT)=0.0
      IF (LL(TT).GE.LMAX(TT))LL(TT)=LMAX(TT)
C
      RETURN
      END
C
C
C***********************************************************************
C
      SUBROUTINE PSTATE
C
C***********************************************************************
C
C THIS SUBROUTINE WRITES OUT THE VALUES OF THE STATE VARIABLES OVER TIME
C
C <INSERT COMMON>
C
      WRITE(6,1000) TB1,TB2
```

```
      LLL=TM
      DO 900 J=0,TM
         KK=LLL-J
         PROD(KK)=POP(KK)*MS(KK)
         WRITE(6,1010) KK,GOALMS(KK),MS(KK),K(KK),PROD(KK),
     1   B(KK),Y(KK)
 900  CONTINUE
C
 1000 FORMAT('1',////,T23,'TABLE',I4,'.  OPTIMAL SOLUTION EXAMPLE',
     1I3,/////,T25,'GOAL MARKET SHARE AND STATE VARIABLES'///,
     2 T14,'GOAL',T26,'ACTUAL',T60,'PER UNIT',T73,'LEVEL OF',
     3/T13,'MARKET',T26,'MARKET',T36,'CAPACITY',T47,
     4 'PRODUCTION',T59,'PRODUCTION',T70,'CONVENTIONAL',/,' ',T4,
     5 'TIME',T13,'SHARE',T26,'SHARE',T38,'LEVEL',T50,'LEVEL',
     6 T62,'COST',T73,'OUTPUT',////)
 1010  FORMAT(' ',T5,I3,T10,F10.6,T22,F10.6,T34,F10.4,T46,
     1 F10.4,T58,F10.4,T70,F10.4)
C
      RETURN
      END
C
C
C *********************************************************************
C
       SUBROUTINE PCONT
C
C************************************************************************
C
C THIS SUBROUTINE WRITES OUT THE CONTROL VARIABLES OVER TIME
C
C <INSERT COMMON>
C
      LLL=TM
      WRITE(6,5020)
      DO 5010 J=0,TM
         KK=LLL-J
         WRITE (6,5030) KK, A(KK), H(KK), L(KK)
 5010 CONTINUE
C
 5020 FORMAT(////,T35,'CONTROL VARIABLES'
     1//,T21,'INCREASE IN',T41,'INCREASE IN',T61,'DECREASE IN',
     2/,T22,'LEVEL OF',T41,'CONVENTIONAL',T61,'CONVENTIONAL',/,
     3T3,'TIME',T21,'AUTOMATION',T44,'OUTPUT',T64,'OUTPUT',//)
 5030 FORMAT(' ',T4,I3,T20,F10.4,T40,F10.4,T60,F10.4)
C
      RETURN
      END
C
C
C *********************************************************************
C
       SUBROUTINE LAMBDA
C
C************************************************************************
```

```
C
C COMPUTATION OF ADJOINT VARIABLES AND TEST FOR CONVERGENCE
C
C <INSERT COMMON>
C
C COMPUTATION OF LAMBDA 1 BACKWARDS
C
      LL1(TM)=S1*DEXP(-RHO*TM)
C
      DO 820 T=1,TM
         LL1(TM-T)=2*V1(TM-T+1)*(MS(TM-T+1)-GOALMS(TM-T+1))
         LL1(TM-T)=LL1(TM-T)+(BB+B(TM-T+1))*POP(TM-T+1)
         LL1(TM-T)=LL1(TM-T)*DEXP(-RHO*(TM-T+1))
         LL1(TM-T)=LL1(TM-T+1)*GAMMA(TM-T+1)*A(TM-T+1)
     2            -LL1(TM-T+1)*DELTA(TM-T+1) +LL1(TM-T)
         LL1(TM-T)=LL1(TM-T+1)-LL1(TM-T)-MU2SAV(TM-T+1)*POP(TM-T+1)
 820 CONTINUE
C
C
C COMPUTATION OF LAMBDA2 BACKWARDS
C
      LL2(TM)=0.0
C
      DO 825 T=1,TM
         LL2(TM-T)=LL2(TM-T+1)-( LL2(TM-T+1)*ALPHA(TM-T+1)*
1        A(TM-T+1)+MS(TM-T+1)*POP(TM-T+1)*DEXP(-RHO*(TM-T+1)))
 825 CONTINUE
C
C COMPUTATION OF LAMBDA3 BACKWARDS
C
      LL3(TM)=S2*DEXP(-RHO*TM)
C
      DO 830 T=1,TM
         LL3(TM-T)=LL3(TM-T+1)-(C4(TM-T+1)*
     1   DEXP(-RHO*(TM-T+1)))+MU2SAV(TM-T+1)
830   CONTINUE
C
C
C CHECK FOR CONVERGENCE OF ADJOINT VARIABLES
C
 840 DO 845 T=0,TM
         IF (DABS(LL1(T)-SL1(T))-ERR) 842,842,850
 842     CHECK1=CHECK1+1
C        CONVERGENCE ATTAINED ON LL1(T)
         IF (CHECK1.EQ.TM) CVG1=1
 845 CONTINUE
 850 CONTINUE
C
 855    DO 858 T=0,TM
          IF (DABS(LL2(T)-SL2(T))-ERR) 856,856,860
 856      CHECK2=CHECK2+1
C         CONVERGENCE ATTAINED ON LL2(T)
          IF (CHECK2.EQ.TM) CVG2=1
 858  CONTINUE
```

```
  860  CONTINUE
C
  865  DO 868 T=0,TM
          IF (DABS(LL3(T)-SL3(T))-ERR) 867,867,870
  867     CHECK3=CHECK3+1
          IF (CHECK3.EQ.TM) CVG3=1
  868 CONTINUE
  870 CONTINUE
C
      IF ((CVG1.EQ.1).AND.(CVG2.EQ.1).AND.(CVG3.EQ.1)) RETURN
C
C IF CONVERGENCE NOT ATTAINED SMOOTH ADJOINT VARIABLES
C
C SMOOTH ADJOINT VARIABLES
C
      DO 880 T=0,TM
              LL1(T)=PHI*SL1(T)+(1-PHI)*LL1(T)
              LL2(T)=PHI*SL2(T)+(1-PHI)*LL2(T)
              LL3(T)=PHI*SL3(T)+(1-PHI)*LL3(T)
              SL1(T)=LL1(T)
              SL2(T)=LL2(T)
              SL3(T)=LL3(T)
  880  CONTINUE
C
      IF (COUNT.LT.STOPIT) RETURN
      WRITE (6,8880) COUNT, CVG1,CVG2,CVG3
 8880 FORMAT(' ',T3,'NUMBER OF ITERATIONS=',I3,//,
     1T3,'CONVERGENCE NOT ATTAINED. CVG1=',I3,'CVG2=',
     2I3,'CVG3=',I3)
C
      STOP
      END
C
C
C ***********************************************************************
C
       SUBROUTINE PLAMB
C
C***********************************************************************
C
C THE SUBROUTINE WRITES THE VALUES OF THE ADJOINT VARIABLES OVER TIME
C
C <INSERT COMMON>
C
      WRITE(6,3000) TB1,TB2
 3000 FORMAT('1',/////,T35,'TABLE',I4,'.  ADJOINT VARIABLES EXAMPLE',
     1I3,/////,T2,'TIME',
     1T31,'MARKET',T55,'PRODUCTION COSTS',T83,'CAPACITY',T104,
     1'LAGRANGE MULTIPLIER',/2X)
C
      DO 3200 J=0,TM
         KK=TM-J
         WRITE(6,3100) KK,LL1(KK),LL2(KK),LL3(KK),MU2SAV(KK)
 3100     FORMAT(T3,I3,T15,F25.5,T41,F25.5,T66,F25.5,T91,F25.5)
```

```
 3200 CONTINUE
C
        RETURN
        END
C
C
C ***************************************************************************
C
      SUBROUTINE POBJ
C
C****************************************************************************
C
C THIS SUBROUTINE COMPUTES THE OBJECTIVE FUNCTION AND PRINTS IT OUT
C
C <INSERT COMMON>
C
      AA1=0.0
      BB1=0.0
      CC1=0.0
      OBJ=0.0
C
      DO 1300 J=0,TM
         AA1=(V1(J)*(MS(J)-GOALMS(J))**2+(BB+B(J))*
     1       MS(J)*POP(J)+C1(J)*A(J)**2 +C2(J)*H(J)**2
     2       +C3(J)*L(J)**2+C4(J)*K(J))
C
         BB1=AA1*EX(J)
         CC1=CC1+BB1
 1300 CONTINUE
C
      OBJ=-CC1+S1*MS(TM)*DEXP(-RHO*TM)+
     1    (S2*K(TM)*DEXP(-RHO*TM))
C
      WRITE(6,1350) OBJ,COUNT,CVG1,CVG2,CVG3
 1350 FORMAT(' ',////,2X,'THE VALUE OF THE OBJECTIVE FUNCTION IS',
     1F15.4,2X,'AT ITERATION=',I3,///,2X,'CVG1=',I3,
     2'CVG2=',I3,'CVG3=',I3)
C
        RETURN
        END
```

APPENDIX C

Exogenous Input Parameters: Model I of Chapter 3

TABLE 4. INPUT DATA EXAMPLE 1

STATE VARIABLES AT TIME 0

MBO	KO	YO	BO
0.100000	65.0000	65.0000	20.0000

EXOGENOUS VARIABLES

T	GOALMS	C1	C2	C3	C4	BB	R	ALPHA
0	0.1000	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
1	0.1100	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
2	0.1200	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
3	0.1300	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
4	0.1400	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
5	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
6	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
7	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
8	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
9	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
10	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010

	V1	GAMMA	DELTA	HMAX	AMAX	LMAX
0	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
1	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
2	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
3	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
4	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
5	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
6	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
7	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
8	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
9	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
10	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000

S1	S2	RHO	PHI	POPO	STOPIT	TM
100000.0	10.0	0.1500	0.8000	500.	300	10

TABLE 5. INPUT DATA EXAMPLE 2

STATE VARIABLES AT TIME 0

MBO	KO	YO	BO
0.100000	65.0000	65.0000	20.0000

EXOGENOUS VARIABLES

T	GOALMB	C1	C2	C3	C4	BB	R	ALPHA
0	0.1000	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
1	0.1100	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
2	0.1200	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
3	0.1300	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
4	0.1400	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
5	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
6	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
7	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
8	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
9	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
10	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010

	V1.	GAMMA	DELTA	HMAX	AMAX	LMAX
0	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
1	100000.00	0.0060	0.000000	30.000000	10.000000	20.000000
2	100000.00	0.0070	0.000000	30.000000	10.000000	20.000000
3	100000.00	0.0080	0.000000	30.000000	10.000000	20.000000
4	100000.00	0.0090	0.000000	30.000000	10.000000	20.000000
5	100000.00	0.0100	0.000000	30.000000	10.000000	20.000000
6	100000.00	0.0110	0.000000	30.000000	10.000000	20.000000
7	100000.00	0.0120	0.000000	30.000000	10.000000	20.000000
8	100000.00	0.0130	0.000000	30.000000	10.000000	20.000000
9	100000.00	0.0140	0.000000	30.000000	10.000000	20.000000
10	100000.00	0.0150	0.000000	30.000000	10.000000	20.000000

S1	S2	RHO	PHI	POPO	STOPIT	TM
100000.0	10.0	0.1500	0.8000	500.	300	10

TABLE 6. INPUT DATA EXAMPLE 3

STATE VARIABLES AT TIME 0

MS0	K0	Y0	B0
0.100000	65.0000	65.0000	20.0000

EXOGENOUS VARIABLES

T	GOALMS	C1	C2	C3	C4	BB	R	ALPHA
0	0.1000	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
1	0.1100	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
2	0.1200	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
3	0.1300	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
4	0.1400	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
5	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
6	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
7	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
8	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
9	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
10	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010

	V1	GAMMA	DELTA	HMAX	AMAX	LMAX
0	300000.00	0.0050	0.000000	30.000000	10.000000	20.000000
1	300000.00	0.0050	0.000000	30.000000	10.000000	20.000000
2	300000.00	0.0050	0.000000	30.000000	10.000000	20.000000
3	300000.00	0.0050	0.000000	30.000000	10.000000	20.000000
4	300000.00	0.0050	0.000000	30.000000	10.000000	20.000000
5	300000.00	0.0050	0.000000	30.000000	10.000000	20.000000
6	300000.00	0.0050	0.000000	30.000000	10.000000	20.000000
7	300000.00	0.0050	0.000000	30.000000	10.000000	20.000000
8	300000.00	0.0050	0.000000	30.000000	10.000000	20.000000
9	300000.00	0.0050	0.000000	30.000000	10.000000	20.000000
10	300000.00	0.0050	0.000000	30.000000	10.000000	20.000000

S1	S2	RHO	PHI	POPO	STOPIT	TM
100000.0	10.0	0.1500	0.8000	500.	300	10

TABLE 7. INPUT DATA EXAMPLE 4

STATE VARIABLES AT TIME 0

MBO	KO	YO	BO
0.100000	65.0000	65.0000	20.0000

EXOGENOUS VARIABLES

T	GOALMS	C1	C2	C3	C4	BB	R	ALPHA
0	0.1000	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
1	0.1100	37.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
2	0.1200	34.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
3	0.1300	31.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
4	0.1400	28.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
5	0.1500	25.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
6	0.1500	22.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
7	0.1500	19.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
8	0.1500	16.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
9	0.1500	13.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
10	0.1500	10.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010

	V1	GAMMA	DELTA	HMAX	AMAX	LMAX
0	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
1	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
2	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
3	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
4	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
5	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
6	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
7	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
8	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
9	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
10	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000

S1	S2	RHO	PHI	POPO	STOPIT	TM
100000.0	10.0	0.1500	0.8000	500.	300	10

TABLE 8. INPUT DATA EXAMPLE 5

STATE VARIABLES AT TIME 0

MBO	KO	YO	BO
0.100000	65.0000	65.0000	20.0000

EXOGENOUS VARIABLES

T	GOALMS	C1	C2	C3	C4	BB	R	ALPHA
0	0.1000	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0500
1	0.1100	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0500
2	0.1200	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0500
3	0.1300	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0500
4	0.1400	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0500
5	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0500
6	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0500
7	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0500
8	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0500
9	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0500
10	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0500

	V1	GAMMA	DELTA	HMAX	AMAX	LMAX
0	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
1	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
2	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
3	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
4	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
5	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
6	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
7	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
8	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
9	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000
10	100000.00	0.0050	0.000000	30.000000	10.000000	20.000000

S1	S2	RHO	PHI	POPO	STOPIT	TM
100000.0	10.0	0.1500	0.9000	500.	300	10

TABLE 9. INPUT DATA EXAMPLE 6

STATE VARIABLES AT TIME 0

MSO	KO	YO	SO
0.100000	65.0000	65.0000	20.0000

EXOGENOUS VARIABLES

T	GOALMS	C1	C2	C3	C4	SB	R	ALPHA
0	0.1000	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
1	0.1100	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
2	0.1200	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
3	0.1300	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
4	0.1400	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
5	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
6	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
7	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
8	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
9	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
10	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010

T	V1	GAMMA	DELTA	HMAX	AMAX	LMAX
0	100000.00	0.0050	0.050000	30.000000	10.000000	20.000000
1	100000.00	0.0050	0.050000	30.000000	10.000000	20.000000
2	100000.00	0.0050	0.050000	30.000000	10.000000	20.000000
3	100000.00	0.0050	0.050000	30.000000	10.000000	20.000000
4	100000.00	0.0050	0.050000	30.000000	10.000000	20.000000
5	100000.00	0.0050	0.050000	30.000000	10.000000	20.000000
6	100000.00	0.0050	0.050000	30.000000	10.000000	20.000000
7	100000.00	0.0050	0.050000	30.000000	10.000000	20.000000
8	100000.00	0.0050	0.050000	30.000000	10.000000	20.000000
9	100000.00	0.0050	0.050000	30.000000	10.000000	20.000000
10	100000.00	0.0050	0.050000	30.000000	10.000000	20.000000

S1	S2	RHO	PHI	POPO	STOPIT	TM
100000.0	10.0	0.1500	0.8000	500.	300	10

TABLE 10. INPUT DATA EXAMPLE 7

STATE VARIABLES AT TIME 0

MSO	KO	YO	BO
0.100000	65.0000	65.0000	20.0000

EXOGENOUS VARIABLES

T	GOALMS	C1	C2	C3	C4	BB	R	ALPHA
0	0.1000	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
1	0.1100	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
2	0.1200	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
3	0.1300	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
4	0.1400	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
5	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
6	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
7	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
8	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
9	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010
10	0.1500	40.0000	10.0000	10.0000	25.0000	10.0000	0.0000	0.0010

	V1	GAMMA	DELTA	HMAX	AMAX	LMAX
0	100000.00	0.0050	-0.050000	30.000000	10.000000	20.000000
1	100000.00	0.0050	-0.050000	30.000000	10.000000	20.000000
2	100000.00	0.0050	-0.050000	30.000000	10.000000	20.000000
3	100000.00	0.0050	-0.050000	30.000000	10.000000	20.000000
4	100000.00	0.0050	-0.050000	30.000000	10.000000	20.000000
5	100000.00	0.0050	-0.050000	30.000000	10.000000	20.000000
6	100000.00	0.0050	-0.050000	30.000000	10.000000	20.000000
7	100000.00	0.0050	-0.050000	30.000000	10.000000	20.000000
8	100000.00	0.0050	-0.050000	30.000000	10.000000	20.000000
9	100000.00	0.0050	-0.050000	30.000000	10.000000	20.000000
10	100000.00	0.0050	-0.050000	30.000000	10.000000	20.000000

S1	S2	RHO	PHI	POPO	STOPIT	TM
100000.0	10.0	0.1500	0.8000	500.	300	10

APPENDIX D

Detailed Results: Model I of Chapter 3

TABLE 11. OPTIMAL SOLUTION EXAMPLE 1

GOAL MARKET SHARE AND STATE VARIABLES

TIME	GOAL MARKET SHARE	ACTUAL MARKET SHARE	CAPACITY LEVEL	PRODUCTION LEVEL	PER UNIT PRODUCTION COST	LEVEL OF CONVENTIONAL OUTPUT
10	0.150000	0.124396	62.1978	62.1978	19.8908	56.7307
9	0.150000	0.111950	55.9748	55.9748	19.9468	53.3107
8	0.150000	0.104279	52.1395	52.1395	19.9810	51.1881
7	0.150000	0.100514	50.2568	50.2568	19.9977	50.1427
6	0.150000	0.100000	50.0000	50.0000	20.0000	50.0000
5	0.150000	0.100000	50.3669	50.0000	20.0000	50.3669
4	0.140000	0.100000	51.7585	50.0000	20.0000	51.7585
3	0.130000	0.100000	54.0322	50.0000	20.0000	54.0322
2	0.120000	0.100000	57.0650	50.0000	20.0000	57.0650
1	0.110000	0.100000	60.7513	50.0000	20.0000	60.7513
0	0.100000	0.100000	65.0000	50.0000	20.0000	65.0000

CONTROL VARIABLES

TIME	INCREASE IN LEVEL OF AUTOMATION	INCREASE IN CONVENTIONAL OUTPUT	DECREASE IN CONVENTIONAL OUTPUT
10	4.8848	0.4304	0.0000
9	2.8030	3.4200	0.0000
8	1.7127	2.1226	0.0000
7	0.8372	1.0454	0.0000
6	0.1141	0.1427	0.0000
5	0.0000	0.0000	0.3669
4	0.0000	0.0000	1.3916
3	0.0000	0.0000	2.2737
2	0.0000	0.0000	3.0328
1	0.0000	0.0000	3.6863
0	0.0000	0.0000	4.2487

THE VALUE OF THE OBJECTIVE FUNCTION IS -15541.1038 AT ITERATION= 77

TABLE 12. ADJOINT VARIABLES EXAMPLE 1

TIME	MARKET	PRODUCTION COSTS	CAPACITY	LAGRANGE MULTIPLIER
10	22313.01601	0.00000	2.23130	21.07919
9	9036.29309	-13.87821	17.73224	1.53500
8	6233.28647	-28.35023	12.78624	2.06042
7	3388.83200	-44.00577	7.31681	2.59171
6	293.55602	-61.55568	1.16007	5.53844
5	-4508.67898	-81.87714	-3.46573	0.00000
4	-6870.51185	-105.49547	-15.27489	0.00000
3	-10712.19340	-132.93605	-28.99518	0.00000
2	-16450.84685	-164.81746	-44.93589	0.00000
1	-24599.84735	-201.85837	-63.45634	0.00000
0	-35789.05108	-244.89377	-84.97404	0.00000

TABLE 13. OPTIMAL SOLUTION EXAMPLE 2

GOAL MARKET SHARE AND STATE VARIABLES

TIME	GOAL MARKET SHARE	ACTUAL MARKET SHARE	CAPACITY LEVEL	PRODUCTION LEVEL	PER UNIT PRODUCTION COST	LEVEL OF CONVENTIONAL OUTPUT
10	0.150000	0.128211	64.1053	64.1053	19.9543	61.8203
9	0.150000	0.105694	56.8132	52.8470	19.9903	56.3265
8	0.150000	0.100000	52.6739	50.0000	20.0000	52.6739
7	0.150000	0.100000	50.6060	50.0000	20.0000	50.6060
6	0.150000	0.100000	50.0000	50.0000	20.0000	50.0000
5	0.150000	0.100000	50.3668	50.0000	20.0000	50.3668
4	0.140000	0.100000	51.7585	50.0000	20.0000	51.7585
3	0.130000	0.100000	54.0321	50.0000	20.0000	54.0321
2	0.120000	0.100000	57.0650	50.0000	20.0000	57.0650
1	0.110000	0.100000	60.7513	50.0000	20.0000	60.7513
0	0.100000	0.100000	65.0000	50.0000	20.0000	65.0000

CONTROL VARIABLES

TIME	INCREASE IN LEVEL OF AUTOMATION	INCREASE IN CONVENTIONAL OUTPUT	DECREASE IN CONVENTIONAL OUTPUT
10	10.0000	0.4304	0.0000
9	1.7984	5.4937	0.0000
8	0.4867	3.6526	0.0000
7	0.0000	2.0680	0.0000
6	0.0000	0.6060	0.0000
5	0.0000	0.0000	0.3668
4	0.0000	0.0000	1.3916
3	0.0000	0.0000	2.2737
2	0.0000	0.0000	3.0329
1	0.0000	0.0000	3.6863
0	0.0000	0.0000	4.2487

THE VALUE OF THE OBJECTIVE FUNCTION IS -16142.7700 AT ITERATION= 45

TABLE 14 ADJOINT VARIABLES EXAMPLE 2

TIME	MARKET	PRODUCTION COSTS	CAPACITY	LAGRANGE MULTIPLIER
10	22313.01601	0.00000	2.23130	31.83089
9	681.13567	-14.30383	28.48393	0.00000
8	-926.17160	-27.97817	22.00293	0.00000
7	-2426.28324	-43.02426	14.47307	0.00000
6	-4175.97207	-60.52115	5.72463	0.97389
5	-6695.76312	-80.84963	-3.46573	0.00000
4	-9057.59598	-104.46796	-15.27489	0.00000
3	-12899.27734	-131.90854	-28.99518	0.00000
2	-18637.93099	-163.78995	-44.93589	0.00000
1	-26786.93148	-200.83086	-63.45634	0.00000
0	-37976.13521	-243.86626	-84.97404	0.00000

TABLE 15. OPTIMAL SOLUTION EXAMPLE 3

GOAL MARKET SHARE AND STATE VARIABLES

TIME	GOAL MARKET SHARE	ACTUAL MARKET SHARE	CAPACITY LEVEL	PRODUCTION LEVEL	PER UNIT PRODUCTION COST	LEVEL OF CONVENTIONAL OUTPUT
10	0.150000	0.141665	70.8324	70.8324	19.8119	61.3915
9	0.150000	0.129470	64.7351	64.7351	19.8676	58.0958
8	0.150000	0.121215	60.6076	60.6076	19.9050	55.8471
7	0.150000	0.115623	57.8117	57.8117	19.9302	54.3157
6	0.150000	0.111822	55.9111	55.9111	19.9473	53.2711
5	0.150000	0.108782	54.8278	54.3909	19.9609	52.8700
4	0.140000	0.105204	54.7589	52.6022	19.9768	53.6008
3	0.130000	0.101995	55.7491	50.9976	19.9911	55.3057
2	0.120000	0.100000	57.8490	50.0000	20.0000	57.8490
1	0.110000	0.100000	61.1140	50.0000	20.0000	61.1140
0	0.100000	0.100000	65.0000	50.0000	20.0000	65.0000

CONTROL VARIABLES

TIME	INCREASE IN LEVEL OF AUTOMATION	INCREASE IN CONVENTIONAL OUTPUT	DECREASE IN CONVENTIONAL OUTPUT
10	4.7905	0.4304	0.0000
9	2.8017	3.2957	0.0000
8	1.8787	2.2488	0.0000
7	1.2646	1.5313	0.0000
6	0.8560	1.0447	0.0000
5	0.6823	0.4010	0.0000
4	0.7996	0.0000	0.7308
3	0.7147	0.0000	1.7049
2	0.4434	0.0000	2.5433
1	0.0000	0.0000	3.2649
0	0.0000	0.0000	3.8860

THE VALUE OF THE OBJECTIVE FUNCTION IS -16535.2665 AT ITERATION= 62

TABLE 16. ADJOINT VARIABLES EXAMPLE 3

TIME	MARKET	PRODUCTION COSTS	CAPACITY	LAGRANGE MULTIPLIER
10	22313.01601	0.00000	2.23130	20.43435
9	9351.30927	-15.80485	17.08740	2.93991
8	7072.21488	-32.54251	13.54630	4.70070
7	5353.71404	-50.73603	10.71715	6.52635
6	4037.63190	-70.90237	8.49506	5.45700
5	4517.19552	-93.57344	3.78781	0.00000
4	9107.58337	-119.20204	-8.02135	0.00000
3	12303.11009	-147.97540	-21.74164	0.00000
2	13411.52625	-180.38716	-37.68235	0.00000
1	11159.33908	-217.34809	-56.20280	0.00000
0	3412.96718	-260.38349	-77.72050	0.00000

TABLE 17. OPTIMAL SOLUTION EXAMPLE 4

GOAL MARKET SHARE AND STATE VARIABLES

TIME	GOAL MARKET SHARE	ACTUAL MARKET SHARE	CAPACITY LEVEL	PRODUCTION LEVEL	PER UNIT PRODUCTION COST	LEVEL OF CONVENTIONAL OUTPUT
10	0.150000	0.141135	70.5677	70.5677	19.8155	61.3195
9	0.150000	0.114733	59.2681	57.3665	19.9344	55.9848
8	0.150000	0.103285	53.1989	51.6424	19.9854	52.4689
7	0.150000	0.100000	50.5187	50.0000	20.0000	50.5187
6	0.150000	0.100000	50.0000	50.0000	20.0000	50.0000
5	0.150000	0.100000	50.3668	50.0000	20.0000	50.3668
4	0.140000	0.100000	51.7585	50.0000	20.0000	51.7585
3	0.130000	0.100000	54.0321	50.0000	20.0000	54.0321
2	0.120000	0.100000	57.0650	50.0000	20.0000	57.0650
1	0.110000	0.100000	60.7513	50.0000	20.0000	60.7513
0	0.100000	0.100000	65.0000	50.0000	20.0000	65.0000

CONTROL VARIABLES

TIME	INCREASE IN LEVEL OF AUTOMATION	INCREASE IN CONVENTIONAL OUTPUT	DECREASE IN CONVENTIONAL OUTPUT
10	10.0000	0.4304	0.0000
9	5.9648	5.3348	0.0000
8	2.5534	3.5158	0.0000
7	0.7300	1.9502	0.0000
6	0.0000	0.5187	0.0000
5	0.0000	0.0000	0.3668
4	0.0000	0.0000	1.3916
3	0.0000	0.0000	2.2737
2	0.0000	0.0000	3.0329
1	0.0000	0.0000	3.6863
0	0.0000	0.0000	4.2487

THE VALUE OF THE OBJECTIVE FUNCTION IS -15387.5968 AT ITERATION= 51

TABLE 18. ADJOINT VARIABLES EXAMPLE 4

TIME	MARKET	PRODUCTION COSTS	CAPACITY	LAGRANGE MULTIPLIER
10	22313.01601	0.00000	2.23130	31.00683
9	2763.17305	-15.74579	27.65988	0.00000
8	629.18813	-30.52358	21.17888	0.00000
7	-1080.49183	-46.00004	13.64902	0.00000
6	-2826.23706	-63.46335	4.90058	1.79794
5	-5758.05451	-83.79183	-3.46573	0.00000
4	-8119.88738	-107.41016	-15.27489	0.00000
3	-11961.56893	-134.85074	-28.99518	0.00000
2	-17700.22238	-166.73215	-44.93589	0.00000
1	-25849.22288	-203.77306	-63.45634	0.00000
0	-37038.42661	-246.80846	-84.97404	0.00000

TABLE 19. OPTIMAL SOLUTION EXAMPLE 5

GOAL MARKET SHARE AND STATE VARIABLES

TIME	GOAL MARKET SHARE	ACTUAL MARKET SHARE	CAPACITY LEVEL	PRODUCTION LEVEL	PER UNIT PRODUCTION COST	LEVEL OF CONVENTIONAL OUTPUT
10	0.150000	0.148571	74.2853	74.2853	11.1770	63.2448
9	0.150000	0.134845	67.4227	67.4227	13.2845	59.5552
8	0.150000	0.124495	62.2473	62.2473	15.0656	56.7443
7	0.150000	0.116928	58.4641	58.4641	16.4775	54.6748
6	0.150000	0.111678	55.8388	55.8388	17.5126	53.2316
5	0.150000	0.107577	54.5281	53.7885	18.3560	52.8399
4	0.140000	0.104038	54.4770	52.0192	19.1108	53.5786
3	0.130000	0.101403	55.6021	50.7013	19.6883	55.2904
2	0.120000	0.100000	57.8396	50.0000	20.0000	57.8396
1	0.110000	0.100000	61.1096	50.0000	20.0000	61.1096
0	0.100000	0.100000	65.0000	50.0000	20.0000	65.0000

CONTROL VARIABLES

TIME	INCREASE IN LEVEL OF AUTOMATION	INCREASE IN CONVENTIONAL OUTPUT	DECREASE IN CONVENTIONAL OUTPUT
10	4.7616	0.4304	0.0000
9	3.1729	3.6897	0.0000
8	2.3645	2.8108	0.0000
7	1.7137	2.0695	0.0000
6	1.1822	1.4432	0.0000
5	0.9190	0.3917	0.0000
4	0.7899	0.0000	0.7388
3	0.5867	0.0000	1.7118
2	0.3117	0.0000	2.5492
1	0.0000	0.0000	3.2700
0	0.0000	0.0000	3.8904

• THE VALUE OF THE OBJECTIVE FUNCTION IS -15261.0887 AT ITERATION=226

TABLE 20 ADJOINT VARIABLES EXAMPLE 5

TIME	MARKET	PRODUCTION COSTS	CAPACITY	LAGRANGE MULTIPLIER
10	22313.01601	0.00000	2.23130	22.47730
9	8244.31802	-16.57528	19.13034	4.28270
8	3739.77574	-31.42439	16.93204	5.08183
7	-1083.75148	-46.45777	14.48401	5.99950
6	-6392.33677	-62.93595	11.73507	2.12975
5	-9896.17030	-81.91823	3.70058	0.00000
4	-12540.07662	-103.56212	-8.10858	0.00000
3	-16531.49846	-128.02075	-21.82888	0.00000
2	-22301.15220	-156.59400	-37.76958	0.00000
1	-30415.39913	-191.19459	-56.29004	0.00000
0	-41604.60286	-234.22999	-77.80773	0.00000

TABLE 21. OPTIMAL SOLUTION EXAMPLE 6

GOAL MARKET SHARE AND STATE VARIABLES

TIME	GOAL MARKET SHARE	ACTUAL MARKET SHARE	CAPACITY LEVEL	PRODUCTION LEVEL	PER UNIT PRODUCTION COST	LEVEL OF CONVENTIONAL OUTPUT
10	0.150000	0.172735	86.3675	86.3675	19.9539	84.0618
9	0.150000	0.157258	78.6289	78.6289	19.9900	78.1302
8	0.150000	0.147746	73.8728	73.8728	20.0000	73.8728
7	0.150000	0.140710	70.3550	70.3550	20.0000	70.3550
6	0.150000	0.134010	67.0048	67.0048	20.0000	67.0048
5	0.150000	0.127628	63.8141	63.8141	20.0000	63.8141
4	0.140000	0.121551	61.6557	60.7753	20.0000	61.6557
3	0.130000	0.115762	60.8739	57.8812	20.0000	60.8739
2	0.120000	0.110250	61.2768	55.1250	20.0000	61.2768
1	0.110000	0.105000	62.6996	52.5000	20.0000	62.6996
0	0.100000	0.100000	65.0000	50.0000	20.0000	65.0000

CONTROL VARIABLES

TIME	INCREASE IN LEVEL OF AUTOMATION	INCREASE IN CONVENTIONAL OUTPUT	DECREASE IN CONVENTIONAL OUTPUT
10	4.6411	0.4304	0.0000
9	1.8070	5.9316	0.0000
8	0.4987	4.2575	0.0000
7	0.0000	3.5178	0.0000
6	0.0000	3.3502	0.0000
5	0.0000	3.1907	0.0000
4	0.0000	2.1584	0.0000
3	0.0000	0.7818	0.0000
2	0.0000	0.0000	0.4030
1	0.0000	0.0000	1.4227
0	0.0000	0.0000	2.3004

THE VALUE OF THE OBJECTIVE FUNCTION IS -16685.2087 AT ITERATION= 80

TABLE 22 ADJOINT VARIABLES EXAMPLE 6

TIME	MARKET	PRODUCTION COSTS	CAPACITY	LAGRANGE MULTIPLIER
10	22313.01601	0.00000	2.23130	34.10104
9	1503.98190	-19.27120	30.75409	1.37333
8	-3384.68584	-39.62015	25.64641	6.50332
7	-11179.24618	-61.85044	24.61987	11.37073
6	-22022.46035	-86.47032	27.24216	13.06552
5	-34454.64383	-113.71243	30.14344	5.35697
4	-43827.81881	-143.85607	23.69125	0.00000
3	-52226.33806	-177.21027	9.97096	0.00000
2	-62586.43116	-214.11698	-5.96974	0.00000
1	-75383.43056	-254.95459	-24.49020	0.00000
0	-91202.51380	-300.14176	-46.00790	0.00000

TABLE 23. OPTIMAL SOLUTION EXAMPLE 7

GOAL MARKET SHARE AND STATE VARIABLES

TIME	GOAL MARKET SHARE	ACTUAL MARKET SHARE	CAPACITY LEVEL	PRODUCTION LEVEL	PER UNIT PRODUCTION COST	LEVEL OF CONVENTIONAL OUTPUT
10	0.150000	0.099051	49.5257	49.5257	19.8188	40.4348
9	0.150000	0.087951	44.4068	43.9757	19.8864	38.7143
8	0.150000	0.081032	41.6141	40.5158	19.9340	38.3094
7	0.150000	0.077416	40.7186	38.7079	19.9664	39.0367
6	0.150000	0.076506	41.3951	38.2531	19.9869	40.7387
5	0.150000	0.077922	43.3978	38.9610	19.9976	43.2794
4	0.140000	0.081451	46.5421	40.7253	20.0000	46.5421
3	0.130000	0.085737	50.4262	42.8687	20.0000	50.4262
2	0.120000	0.090250	54.8451	45.1250	20.0000	54.8451
1	0.110000	0.095000	59.7245	47.5000	20.0000	59.7245
0	0.100000	0.100000	65.0000	50.0000	20.0000	65.0000

CONTROL VARIABLES

TIME	INCREASE IN LEVEL OF AUTOMATION	INCREASE IN CONVENTIONAL OUTPUT	DECREASE IN CONVENTIONAL OUTPUT
10	5.0139	0.4304	0.0000
9	3.3984	1.7205	0.0000
8	2.3878	0.4049	0.0000
7	1.6229	0.0000	0.7274
6	1.0254	0.0000	1.7019
5	0.5380	0.0000	2.5407
4	0.1184	0.0000	3.2627
3	0.0000	0.0000	3.8841
2	0.0000	0.0000	4.4190
1	0.0000	0.0000	4.8793
0	0.0000	0.0000	5.2755

THE VALUE OF THE OBJECTIVE FUNCTION IS -15550.4644, AT ITERATION= 50

TABLE 24. ADJOINT VARIABLES EXAMPLE 7

TIME	MARKET	PRODUCTION COSTS	CAPACITY	LAGRANGE MULTIPLIER
10	22313.01601	0.00000	2.23130	12.26737
9	13451.19867	-11.05069	8.92042	0.00000
8	11893.29901	-22.41340	2.43941	0.00000
7	10803.25216	-34.56300	-5.09044	0.00000
6	10012.22930	-48.05226	-13.83889	0.00000
5	9340.47361	-63.55555	-24.00313	0.00000
4	8572.84026	-81.92520	-35.81229	0.00000
3	6333.46380	-104.26603	-49.53258	0.00000
2	2096.97146	-131.60035	-65.47329	0.00000
1	-4712.28207	-165.02977	-83.99374	0.00000
0	-14805.16373	-205.91340	-105.51144	0.00000

APPENDIX E

Numerical Solution Algorithm: Model II of Chapter 4

Closed form solutions to the model do not exist; therefore, discrete approximations are made to optimal control, state and adjoint variables in the continuous model defined in Chapter 4.3.

The following numerical solution algorithm is used to solve the numerical examples presented in Chapter 4.6.

<u>Step</u> 1. For $t=0,1,\ldots,T$, initialize the exogenous functions, state variables and save the values of the adjoint variables as $S\lambda_i(t)$, $i=1,2,\ldots,5$ and $t=1,2,\ldots,T$. Set $t^*=0$.

<u>Step</u> 2. Compute $a(t)$ and $r(t)$ from Equations (4.27) and (4.29) respectively for $t=t^*$. If $t^*=T$, go to Step 3, otherwise, proceed. Compute the state variables for t+1 as follows:

$$s(t+1)=s(t)+\gamma_1(t)[a(t)+\alpha(t)k(t)][N-s(t)]+\gamma_2(t)s(t) \quad \text{(E.1)}$$

$$x(t+1)=x(t)+a(t) \quad \text{(E.2)}$$

$$k(t+1)=k(t)+a(t)-r(t)+\alpha(t)k(t) \quad \text{(E.3)}$$

$$\alpha(t+1)=\alpha(t)-\psi(t)\alpha t)[1-\phi(t)a(t)/x(t)] \quad \text{(E.4)}$$

$$c_3(t+1)=-\beta(t)a(t)c_3(t) \quad \text{(E.5)}$$

If for some t+1, it is found $k(t+1)<0$ or $s(t+1)<0$, STOP; otherwise continue. Set $t^*=t+1$. Go to beginning of Step 2.

<u>Step</u> 3. Compute backwards in time the new values of $\lambda_i(t)$ for $i=1,2,\ldots,5$ and for $t=T-1, T-2,\ldots,0$ using the Equations (A.19)-(A.23) and $\lambda_1(T)=G_1e^{-\rho T}$, $\lambda_2(T)=0$, $\lambda_3(T)=G_2e^{-\rho T}\lambda_4(T)=G_3e^{-\rho T}$ and $\lambda_5(T)=0$:

$$\lambda_1(t)=\lambda_1(t+1)-\{2v(t+1)[s(t+1)-\hat{s}(t+1)]$$

$$-2c_4(t+1)[dk(t+1)$$

$$+[B(t+1)+c_3(t+1)]-s(t+1)]+c_5(t+1)\}e^{-\rho(t+1)}$$

$$-\lambda_1(t+1)\{\gamma_1(t+1)[a(t+1)+\alpha(t+1)k(t+1)]-\gamma_2(t+1)\} \qquad (E.6)$$

$$\lambda_2(t)=\lambda_2(t+1)-\lambda_4(t+1)\psi(t+1)\alpha(t+1)\phi(t+1)a(t+1)/x^2(t+1) \qquad (E.7)$$

$$\lambda_3(t)=\lambda_3(t+1)-\{2c_4(t+1)d[dk(t+1)-s(t+1)]$$

$$-c_5(t+1)d\}e^{-\rho(t+1)}+\lambda_3(t+1)\alpha(t+1) \qquad (E.8)$$

$$+\lambda_1(t+1)\gamma_1(t+1)\alpha(t+1)[N-s(t+1)]$$

$$\lambda_4(t)=\lambda_4(t+1)+\lambda_3(t+1)k(t+1)$$

$$-\lambda_4(t+1)\psi(t+1)[1-\phi(t+1)a(t+1)/x(t+1)] \qquad (E.9)$$

$$+\lambda_1(t+1)\gamma_1(t+1)k(t+1)[N-s(t+1)]$$

$$\lambda_5(t)=\lambda_5(t+1)-s(t+1)e^{-\rho(t+1)}-\lambda_5(t+1)\beta(t+1)a(t+1) \qquad (E.10)$$

Step 4. Check for convergence of adjoint variables by comparing the newly computed value with their respective values in a previous iteration using Equation (24).

$$|S\lambda_i(t)-\lambda_i(t)| < Err_i \qquad (E.11)$$

If for all $i=1,2,\ldots,5$ and $t=0,1,\ldots,T$ Equation (24) holds, where Err is a prespecified tolerance level, convergence has been achieved and STOP; otherwise, proceed to Step 5.

Step 5. Derive the exponentially smoothed values of $\lambda_i(t)$, $i=1,2,\ldots,5$ and $t=0,1,\ldots,T$ as follows:

$$\lambda_i(t)=\Omega S\lambda_i(t)+(1-\Omega)\lambda_i(t) \quad \text{(E.12)}$$

where $0<\Omega<1$.

Save the values of $\lambda_i(t)$ as $S\lambda_i(t)$ for the next iteration. (Step 5 aids in obtaining a fast convergence to the optimal solution). Set $t^*=0$. Go to Step 2.

APPENDIX F

Computer Program: Model II of Chapter 4

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C
C
C***************************************************************************
C
C OPTIMAL ACQUSITION OF FMS TECHNOLOGY SUBJECT TO TECHNOLOGICAL PROGRESS
C
C                        MODEL II OF CHAPTER 4
C
C***************************************************************************
C
C DEFINITION OF VARIABLES
C
C
C STATE VARIABLES
C
C       S(T)-LEVEL OF DEMAND AT TIME T
C       K(T)-LEVEL OF CAPACITY AT TIME T
C       ALPHA(T)-TECHNOLOGICAL PROGRESS FACTOR
C       C3(T)-ONE OF TWO COMPONENTS OF THE PER UNIT PRODUCTION PLUS
C            IN PROCESS INVENTORY COSTS THAT CAN BE REDUCED DUE TO
C            ACQUIRING NEW TECHNOLOGY AT TIME T
C       X(T)-ACCUMULATED LEVEL OF FLEXIBLE TECHNOLOGY ACQUIRED OVER THE
C            PLANNING HORIZON
C
C INTERMEDIATE STATE VARIABLES USED FOR TEMPORARY COMPUTATIONS
C
C       NEWS(T)-DEMAND CORRESPONDING TO MS(T)
C       NEWK(T)-CAPACITY CORRESPONDING TO K(T)
C       NALPHA(T)-TECHNOLOGICAL PROGRESS FACTOR CORRESPONDING
                   TO ALPHA(T)
C       NEWC3(T)-PER UNIT PRODUCTION COST CORRESPONDING TO C3(T)
C       NEWX(T)-ACCUMULATED LEVEL OF FLEXIBLE TECHNOLOGY CORRESPONDING
                TO X(T)
C
C
C CONTROL VARIABLES
C
C       A(T)-RATE OF ACQUIRING FLEXIBLE AUTOMATION AT TIME T
C       R(T)-RATE OF REDUCING EXISTING CAPACITY AT TIME T
C
C
C INTERMEDIATE CONTROL VARIABLES USED FOR TEMPORARY  COMPUTATIONS
C
C       AA(T)-TEMPORARY VARIABLE CORRESPONDING TO A(T)
C       RR(T)-TEMPORARY VARIABLE CORRESPONDING TO R(T)
C
C
C ADJOINT VARIABLES
C
C
C       LL1(T)-ADJOINT VARIABLE CORRESPONDING TO DEMAND
C       LL2(T)-ADJOINT VARIABLE CORRESPONDING TO CAPACITY
C       LL3(T)-ADJOINT VARIABLE CORRESPONDING TO TECHNOLOGICAL
                PROGRESS FACTOR
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C       LL4(T)-ADJOINT VARIABLE CORRESPONDING TO CONVENTIONAL
C             ACCUMULATED LEVEL OF NEW FLEXIBLE TECHNOLOGY
C       LL5(T)-ADJOINT VARIABLE CORRESPONDING TO PER UNIT
              PRODUCTION COSTS
C
C
C INTERMEDIATE ADJOINT VARIABLES USED FOR TEMPORARY COMPUTATIONS
C
C
C       NEWLL1(T)-TEMPORARY VARIABLE CORRESPONDING TO LL1(T)
C       NEWLL2(T)-TEMPORARY VARIABLE CORRESPONDING TO LL2(T)
C       NEWLL3(T)-TEMPORARY VARIABLE CORRESPONDING TO LL3(T)
C       NEWLL4(T)-TEMPORARY VARIABLE CORRESPONDING TO LL4(T)
C       NEWLL5(T)-TEMPORARY VARIABLE CORRESPONDING TO LL5(T)
C       SL1(T)-SAVED VALUE OF LL1(T)
C       SL2(T)-SAVED VALUE OF LL2(T)
C       SL3(T)-SAVED VALUE OF LL3(T)
C       SL4(T)-SAVED VALUE OF LL4(T)
C       SL5(T)-SAVED VALUE OF LL5(T)
C
C
C EXOGENOUS VARIABLES
C
C
C       AMAX(T)-MAXIMUM RATE OF ACQUIRING FLEXIBLE TECHNOLOGY
C       RMAX(T)-MAXIMUM RATE OF REDUCING EXISTING VINTAGE CAPACITY
C       C1(T)-COST OF ACQUIRING FLEXIBLE AUTOMATION
C       C2(T)-COST OF REDUCING EXISTING VINTAGE CAPACITY
C       C4(T)-COST PER UNIT SQUARED DEVIATION BETWEEN
C            DEMAND AND THE DESIRED LEVEL OF CAPACITY UTILIZATION
C       C5(T)-COST PER UNIT DEVIATION BETWEEN DEMAND AND THE DESIRED
C            LEVEL OF CAPACITY UTILIZATION
C       D1-A COEFFICIENT REFLECTING THE MOST EFFECTIVE (DESIRED) LEVEL
C          OF OPERATING CAPACITY UTILIZATION
C       S1-VALUE PER UNIT DEMAND AT THE TERMINAL TIME
C       S2-VALUE PER UNIT CAPACITY  AT THE TERMINAL TIME
C       S3-VALUE PER UNIT TECHNOLOGICAL PROGRESS FACTOR AT THE
           TERMINAL TIME
C       V1(T)-PENALTY COST OF DEVIATIONS BETWEEN ACTUAL AND GOAL
C            MARKET SHARE
C       RHO-DISCOUNT FACTOR
C       EX(T)-EXPONENTIAL FUNCTION OF RHO
C       G1(T)-2*DISCOUNTED COSTS OF ACQUIRING FLEXIBLE TECHNOLOGY
C       G2(T)-2*DISCOUNTED COSTS OF ACQUIRING CONVENTIONAL TECHNOLOGY
C       G3(T)-2*DISCOUNTED COSTS OF REDUCING CONVENTIONAL TECHNOLOGY
C       G4(T)-DISCOUNTED COST OF HOLDING CAPACITY
C       B(T)-COMPONENT OF THE PER UNIT PRODUCTION
C           COST WHICH IS UNFAFFECTED BY ACQUIRING FLEXIBLE AUTOMATION
C       OBJ-VALUE OF OBJECTIVE FUNCTION AT CONVERGENCE
C       NEWOBJ-VALUE OF OBJECTIVE FUNCTION AT AN INTERMEDIATE PERIOD
C       POP(T)-MARKET SATURATION LEVEL OF DEMAND AT TIME T
C       PROD(T)-LEVEL OF PRODUCTION AT TIME T
C       NPROD(T)-DIFFERENCE BETWEEN CAPACITY AND PRODUCTION
C       GOALS(T)-PLANNED LEVEL OF DEMAND
```

```
C       GAMMA2(T)-EXOGENOUS MARKET GROWTH/DECAY FACTOR
C       GAMMA1(T)-PER UNIT EFFECTIVENESS OF FLEXIBLE TECHNOLOGY
C                IN CAPTURING COMPETITOR'S MARKET
C       BETA(T)-EFFICIENCY FACTOR CORRESPONDING TO THE REDUCTION
C                IN THE PER UNIT PRODUCTION COSTS DUE TO
C                   ACQUIRING AUTOMATION
C        PSI(T)-PERCENT REDUCTION IN THE TECHNOLOGICAL PROGRESS FACTOR
C        PHI(T)-EFFECTIVENESS FO FLEXIBLE TECHNOLOGY TO IMPROVE
C               TECHNOLOGICAL PROGRESS FACTOR
C       COUNT-NUMBER OF ITERATIONS
C       STOPIT-MAXIMUM NUMBER OF ITERATIONS PERMITTED
C       ERR-MAXIMUM TOLERANCE IN CHECKING FOR CONVERGENCE
C       CVG1-CONVERGENCE ON LL1(T)
C       CVG2-CONVERGENCE ON LL2(T)
C       CVG3-CONVERGENCE ON LL3(T)
C       CVG4-CONVERGENCE ON LL4(T)
C       CVG5-CONVERGENCE ON LL5(T)
C       FEASOL-FEASIBLE SOLUTION
C       NOFEASOL-NO FEASIBLE SOLUTION
C       TB1-TABLE NUMBER
C       TB2-EXAMPLE NUMBER
C
C
C***********************************************************************
C
C MAIN PROGRAM
C
C************************************************************************
C
C COMMON BLOCK OF VARIABLES USED BY THE FORTRAN COMPILER
C FOR SHARING OF COMMON DATA AMONG SUBROUTINES.  USE IN PROGRAM WHERE
C <INSERT COMMON> IS OBSERVED
C
C
        COMMON/GRP1/ S(0:100),K(0:100),NEWK(0:100),B(0:100),
      1NEWS(0:100),NALPHA(0:100),NEWX(0:100),
      3A(0:100),AA(0:100),R(0:100),RR(0:100),
      4NEWC3(0:100),RMAX(0:100),AMAX(0:100),
      1LL1(0:100),LL2(0:100),LL3(0:100),LL4(0:100),LL5(0:100),SL5(0:100),
      2SL1(0:100),SL2(0:100),SL3(0:100),SL4(0:100),
      4M1RMAX(0:100),NEWLL1(0:100),NEWLL2(0:100),NEWLL3(0:100),
      5NEWLL4(0:100),NEWLL5(0:100),D1(0:100),D2(0:100)
C
       COMMON/GRP2/ EX(0:100),G1(0:100),G2(0:100),G3(0:100),G4(0:100),
      1C1(0:100),C2(0:100),C3(0:100),C5(0:100),C4(0:100),V1(0:100),
      2OBJ,NEWOBJ(0:100),S1,S2,S3,
      4RHO,POP(0:100),ERR,PHI(0:100),BETA(0:100),THETA,AA1,BB1,CC1,
      5PROD(0:100),NPROD(0:100),PSI(0:100),
      2GOALS(0:100),GAMMA2(0:100),ALPHA(0:100),GAMMA1(0:100)
C
       COMMON/GRP3/ T,TM,SCRIPT,LLL,KKK,I,J,JJ,TB1,TB2,NUMBER,
      1CVG1,CVG2,CVG3,CVG4,CVG5,COUNT,TT,STOPIT,CHECK1,
      2CHECK2,CHECK3,CHECK4,CHECK5,TT1,NTB1,KK,FEASOL(0:100),NOFEAS
```

```
C
      DOUBLE PRECISION  S,K,X,Y,B,PSI,BETA,ALPHA,GAMMA1,
     1GAMMA2,NEWS,NALPHA,NEWX,NEWK,A,AA,R,RR,NEWC3,RMAX,AMAX,
     2TOL,D1,D2,GOALS,LL5,SL5,PHI,
     3LL1,LL2,LL3,LL4,SL1,SL2,SL3,SL4,
     4NEWLL1,NEWLL2,NEWLL3,NEWLL4,NEWLL5,
     5EX,G1,G2,G3,G4,C1,C2,C3,C4,C5,V1,OBJ,NEWOBJ,BB,S1,S2,
     6RHO,POP,ERR,THETA,AA1,BB1,CC1,PROD,NPROD,S3,
C
      INTEGER T,TM,SCRIPT,LLL,KKK,I,J,TB1,TB2,CVG1,CVG2,CVG3,
     1CVG4,JJ,COUNT,TT,STOPIT,CHECK1,CHECK2,CHECK3,CHECK4,
     2TT1,NTB1,KK,FEASOL,NOFEAS,CHECK5,CVG5
C
C REINITIALIZE PROGRAM VARIABLES
C
      CALL INITIAL
      CALL READY
    5  CONTINUE
      CALL RESTRT
       CALL COMPUTE
      CALL LAMBDA
C
C CHECK FOR CONVERGENCE.  IF CONVERGENCE NOT ATTAINED REPEAT.
C
      IF((CVG1.EQ.1).AND.(CVG2.EQ.1).AND.(CVG3.EQ.1)
     1.AND.(CVG4.EQ.1).AND.(CVG5.EQ.1)) THEN
        CALL PSTATE
        CALL PCONT
        CALL POBJ
        CALL PLAMB
        STOP 5555
      END IF
      CALL READY
      GO TO 5
C
       END
C
C  END MAIN PROGRAM
C
C
C ***********************************************************************
C
       SUBROUTINE INITIAL
C
C************************************************************************
C
C IN THIS ROUTINE ALL VARIABLES ARE REINITIALIZED
C
C <INSERT COMMON>
C
      TM=10
      S(0)=50
      B(0)=0
      K(0)=40
```

```
      X(0)=.0005
      S1=500
      S2=100
      S3=500
      TB2=7
      TB1=0
      SCRIPT=0
      RHO=.250000
C
      DO 100 T=0,TM
         S(T)=S(0)
         K(T)=K(0)
         X(T)=X(0)
         PSI(T)=0.50
         ALPHA(T)=.001
         EX(T)=DEXP(-RHO*T)
C
  100 CONTINUE
C
      DO 200 T=0,TM
         RMAX(T)=10
         R(T)=0.0
         AMAX(T)=12
         A(T)=0.0
         AA(T)=0.0
         RR(T)=0.0
  200 CONTINUE
C
       CVG1=0
       CVG2=0
       CVG3=0
       CVG4=0
       CVG=0
       NUMBER=0
       ERR=.5
       COUNT=0
       THETA=.8
C
       STOPIT=3000
       DO 300 T=0,TM
          B(T)=0.0
          D1(T)=1.0
          D2(T)=D1(T)
          C1(T)=100-0*T
          C2(T)=40+0*T
          C3(T)=20
          C4(T)=20
          C5(T)=0000
          IF(T.GT.0)THEN
            GOALS(T)=GOALS(T-1)+5
          ELSE
            GOALS(T)=50
          END IF
          IF(T.GT.8)GOALS(T)=GOALS(8)
```

```
         V1(T)=50
         BETA(T)=.001+00*T
         GAMMA1(T)=.001+.000*T
         GAMMA2(T)=.02000
         PHI(T)=.001+.0*T
         POP(T)=500
         G1(T)=C1(T)*EX(T)
         G2(T)=C2(T)*EX(T)
         G3(T)=C3(T)*EX(T)
         G4(T)=C4(T)*EX(T)
  300 CONTINUE
C
      CALL LAMBDA
C
      DO 311 T=0,TM
         SL1(T)=0
         SL2(T)=0
         SL3(T)=0
         SL4(T)=0
         SL5(T)=0
 311    CONTINUE
C
      IF (NUMBER.EQ.0) THEN
      WRITE(6,10) TB1,TB2,S(0),K(0),ALPHA(0),X(0),C3(0)
 10   FORMAT('1',///,T35,'TABLE',I4,'.  INPUT DATA EXAMPLE',I3,
     1/////,T2,'STATE VARIABLES AT TIME 0',//,
     1T5,'S0',T20,'K0',T30,'ALPHA',T40,'X0',T50,'C3',/,T5,F7.4,T17,
     2F10.4,T26,F10.4,T36,F10.4,T47,F10.4///,T2,'EXOGENOUS VARIABLES',
     2//,T3,'T',T7,'GOAL S',T18,'C1',T31,'C2',T43,'C4',T56,'C5',
     3T65,'BETA',T74,'D1',T84,'D2')
      DO 12 T=0,TM
      WRITE(6,13) T,GOALS(T),C1(T),C2(T),C4(T),C5(T),BETA(T),
     2D1(T),D2(T)
 13   FORMAT(T2,I2,T4,F10.4,T16,F10.4,T28,F10.4,T40,F10.4,T52,F10.4,
     1T62,F10.5,T72,F10.6,T82,F10.6)
 12   CONTINUE
      WRITE(6,14)
  14  FORMAT(//,T3,'T',T7,'V1',T18,'EX',T31,'GAMMA1',T43,'GAMMA2',
     1T56,'PHI',T65,'B',T75,'PSI',T84,'RMAX',T94,'AMAX')
      DO 16 T=0,TM
      WRITE(6,17) T,V1(T),EX(T),GAMMA1(T),GAMMA2(T),PHI(T),B(T),
     1PSI(T),RMAX(T),AMAX(T)
 17   FORMAT(T2,I2,T4,F10.4,T14,F10.4,T29,F10.6,T41,F10.6,T54,F10.6,
     1T62,F15.10,T72,F10.5,T81,F10.4,T91,F10.4)
 16   CONTINUE
C
      WRITE(6,18) S1,S2,S3,ALPHA(0),RHO,THETA,POP(0),STOPIT,TM
 18   FORMAT(//,T7,'S1',T18,'S2',T31,'S3',T43,'ALPHA0',T55,'RHO',
     1T65,'THETA',T75,'POPO',T85,'STOPIT',T95,'TM',/T2,F10.1,T16,
     2F10.4,T29,F10.4,
     2T39,F10.4,T51,F10.4,T62,F10.4,T74,F10.5,T83,I6,T93,I4,/
     2'1'//,T4,'BOUNDS ON CONTROLS',//,T4,'T',
     3T6,'RMAX',T16,'AMAX',/)
      DO 19 T=0,TM
```

```
      WRITE(6,21) T,RMAX(T),AMAX(T)
 21   FORMAT(T4,I2,T6,F10.4,T16,F10.4)
 19   CONTINUE
      END IF
C
      RETURN
      END
C
C
C ***********************************************************************
C
       SUBROUTINE READY
C
C************************************************************************
C
C IN THIS SUBROUTINE A CHECK IS MADE TO DETERMINE IF BOTH GAMMA1(T)
C AND BETA(T) ARE WITHIN THEIR UPPER BOUNDS
C
C <INSERT COMMON>
C
      INTEGER ERROR1,ERROR2,ERROR3
C
      ERROR1=0
      ERROR2=0
      ERROR3=0
C
      DO 2080 T=1,TM
         IF (BETA(T).LE.1/AMAX(T)) GO TO 2010
         WRITE(6,2000) BETA(T),AMAX(T),T
2000     FORMAT(' ','BETA(T)=',F10.4,2X,'AMAX(T)=',F10.4,
     1   2X,'TIME=',I3,'***ERROR ALERT-BETA(T) TOO BIG')
         ERROR1=ERROR1+1
 2010    CONTINUE
C
  2030   IF (GAMMA1(T).LE.1/AMAX(T)) GO TO 2050
         WRITE(6,2040) GAMMA1(T),AMAX(T),T
  2040   FORMAT(' ','GAMMA1(T)=',F10.4,'AMAX(T)=',F10.4,2X,
     1   'TIME=',I3,'***ERROR ALERT-GAMMA1(T) TOO BIG')
          ERROR2=ERROR2+1
 2050     CONTINUE
C
 2080 CONTINUE
C
      IF((ERROR1.EQ.0).AND.(ERROR2.EQ.0)) RETURN
C
      STOP
C
C
C ***********************************************************************
C
       SUBROUTINE RESTRT
C
C************************************************************************
C
```

```
C REINITIALIZTION AFTER EACH COMPLETE ITERATION
C
C CHECK NUMBER OF ITERATIONS IS LESS THAN MAXIMUM
C
C <INSERT COMMON>
C
      COUNT=COUNT+1
      IF (COUNT.GE.STOPIT) THEN
        CALL PSTATE
        CALL PCONT
        CALL PLAMB
        CALL POBJ
        STOP
      ELSE
        CHECK1=0
        CHECK2=0
        CHECK3=0
        CHECK4=0
        CHECK5=0
        CVG1=0
        CVG2=0
        CVG3=0
        CVG4=0
        CVG5=0
      END IF
C
      RETURN
      END
C
C
C ********************************************************************
C
      SUBROUTINE COMPUTE
C
C***********************************************************************
C
C IN THIS SUBROUTINE VALUES OF STATE VARIABLES ARE COMPUTED
C USING COMPUTED CONTROL VARIABLE VALUES
C
C <INSERT COMMON>
C
C COMPUTATION OF CONTROLS AT TIME 0
C
      T=0
      TT=0
      NEWLL1(TT)=LL1(TT)
      NEWLL2(TT)=LL2(TT)
      NEWLL3(TT)=LL3(TT)
      NEWLL4(TT)=LL4(TT)
      NEWLL5(TT)=LL5(TT)
C
      CALL CONTROL
C
      A(T)=AA(TT)
```

```
      R(T)=RR(TT)
C
C COMPUTE STATE VARIABLES AT T+1
C
      DO 400 T=1,TM
         TT=T
         CALL STATE
C
         S(T)=NEWS(TT)
         K(T)=NEWK(TT)
         ALPHA(T)=NALPHA(TT)
         X(T)=NEWX(TT)
         C3(T)=NEWC3(TT)
C
C CHECK THAT DEMAND IS NONNEGATIVE
C
      IF (S(T).LT.0.0)  STOP 8888
C
C CHECK THAT CAPACITY AT T EXCEEDS 0
C
      IF(K(T).LT.0.0) STOP 7777
C
C CHECK THAT NO NEW ACQUISITIONS ARE REDUCED
C
      IF((K(T)*(1-ALPHA(T)-AA(T)-RR(T)).LT.0.0) STOP  6666
C
C ASSIGN LAMBDAS FOR COMPUTATION OF CONTROLS
C
      NEWLL1(TT)=LL1(T)
      NEWLL2(TT)=LL2(T)
      NEWLL3(TT)=LL3(T)
      NEWLL4(TT)=LL4(T)
      NEWLL5(TT)=LL5(T)
C
      CALL CONTROL
C
      A(T)=AA(TT)
      R(T)=RR(TT)
C
  400 CONTINUE
C
 875  CONTINUE
C
      RETURN
      END
C
C
C*****************************************************************************
C
       SUBROUTINE STATE
C
C*****************************************************************************
C
C THIS SUBROUTINE COMPUTES THE STATE VARIABLES
```

```
C
C <INSERT COMMON>
C
      J=TT-1
      NEWS(TT)=S(J)+GAMMA1(J)*(AA(J)+ALPHA(J)*K(J))*(POP(J)-S(J))
     1+GAMMA2(J)*S(J)
C
      NEWK(TT)=K(J)+AA(J)-RR(J)+ALPHA(J)*K(J)
C
      NALPHA(TT)=ALPHA(J)-PSI(J)*ALPHA(J)*(1-PHI(J)*AA(J)/X(J))
C
      NEWX(TT)=X(J)+AA(J)
C
      NEWC3(TT)=C3(J)-BETA(J)*AA(J)*C3(J)
C
      RETURN
      END
C
C
C ***************************************************************************
C
        SUBROUTINE CONTROL
C
C****************************************************************************
C
C IN THIS SUBROUTINE THE CONTROL VARIABLES ARE COMPUTED
C
C <INSERT COMMON>
C
      AA(TT)=(+(NEWLL1(TT)*GAMMA1(TT)*(POP(TT)-S(TT)))
     1      -(NEWLL5(TT)*BETA(TT)*C3(TT))+NEWLL2(TT)
     2      +(PSI(TT))*NEWLL3(TT)*PHI(TT)*ALPHA(TT)/X(TT)+NEWLL4(TT))/
     3      (2*G1(TT))
C
      IF (AA(TT).LT.0.0)  AA(TT)=0.0
      IF (AA(TT).GE.AMAX(TT)) AA(TT)=AMAX(TT)
C
      RR(TT)=(-NEWLL2(TT))/(G2(TT)*2)
C
      IF (RR(TT).LE.0.0) RR(TT)=0.0
      IF (RR(TT).GE.RMAX(TT)) RR(TT)=RMAX(TT)
C
       RETURN
       END
C
C
C**************************************************************************
C
      SUBROUTINE PSTATE
C
C**************************************************************************
C
C THIS SUBROUTINE PRINTS THE STATE VARIABLES OVER TIME
C
```

```
C <INSERT COMMON>
C
      WRITE(6,1000)  TB1,TB2
      LLL=TM
      DO 900 J=0,TM
          KK=LLL-J
          WRITE(6,1010) KK,GOALS(KK),S(KK),
     1    K(KK),X(KK),C3(KK),ALPHA(KK)
 900  CONTINUE
C
 1000 FORMAT('1',////,T20,'TABLE',I4,'.  OPTIMAL SOLUTION EXAMPLE',
     1I3,/////,T26,'GOAL DEMAND AND STATE VARIABLES'///,
     2T13,'GOAL',T25,'ACTUAL',T60,'PER UNIT',T71,'LEVEL OF',
     3/,T12,'DEMAND',T25,'DEMAND',T36,'CAPACITY',T47,
     4'AUTOMATION',T59,'PRODUCTION',T71,'PROGRESS',/,' ',T3,
     5'TIME',T12,'LEVEL',T25,'LEVEL',T38,'LEVEL',T49,'LEVEL',
     6T62,'COST',T72,'FACTOR'//)
 1010 FORMAT(' ',T3,I3,T10,F10.6,T22,F10.6,T34,F10.4,T46,
     1F10.4,T58,F10.4,T70,F10.9)
C
       RETURN
       END
C
C
C ***********************************************************************
C
       SUBROUTINE PCONT
C
C************************************************************************
C
C THIS ROUTINE WRITES OUT THE LEVELS OF THE CONTROL VARIABLES
C
C <INSERT COMMON>
C
      LLL=TM
C
      WRITE(6,5020)
      DO 5010 J=0,TM
         KK=LLL-J
         WRITE (6,5030) KK, A(KK), R(KK)
 5010 CONTINUE
C
 5020 FORMAT(//,T30,'CONTROL VARIABLES',//,
     1T23,'INCREASE IN',T47,'REDUCTION IN',
     2/,T24,'LEVEL OF',T49,'EXISTING',/,
     3T3,'TIME',T23,'TECHNOLOGY',T49,'CAPCITY',//)
 5030 FORMAT(' ',T3,I3,T21,F10.4,T46,F10.4)
C
       RETURN
       END
C
C
C*********************************************************************
C
```

```
      SUBROUTINE LAMBDA
C
C***********************************************************************
C
C COMPUTATION OF ADJOINT VARIABLES AND TEST FOR CONVERGENCE
C
C <INSERT COMMON>
C
C COMPUTATION OF LAMBDAS BACKWARDS
C
      LL1(TM)=S1*EX(TM)
      LL2(TM)=S2*EX(TM)
      LL3(TM)=S3*EX(TM)
      LL4(TM)=0.0
      LL5(TM)=0.0
C
      DO 820 T=1,TM
         JJ=TM-T
         J=JJ+1
         LL1(JJ)=LL1(J)-(2*V1(J)*(S(J)-GOALS(J))+B(J)+C3(J)
     1   -2*C4(J)*(D1(J)*K(J)-S(J))+C5(J))*EX(J)
     1   -LL1(J)*(GAMMA1(J)*(A(J)+ALPHA(J)*K(J))-GAMMA2(J))
C
         LL2(JJ)=LL2(J)+LL2(J)*ALPHA(J)+LL1(J)*GAMMA1(J)*ALPHA(J)
     1   *(POP(J)-S(J))
     1   -(2*C4(J)*D1(J)*(D1(J)*K(J)-S(J))-C5(J)*D2(J))*EX(J)
C
         LL3(JJ)=LL3(J)+LL2(J)*K(J)-LL3(J)*(PSI(J))*(1-PHI(J)*A(J)/X(J))
     1   +LL1(J)*GAMMA1(J)*K(J)*(POP(J)-S(J))
C
         LL4(JJ)=LL4(J)-LL3(J)*PHI(J)*(PSI(J))*ALPHA(J)*A(J)/X(J)**2
C
         LL5(JJ)=LL5(J) -S(J)*EX(J)-LL5(J)*BETA(J)*A(J)
C
 820  CONTINUE
C
C CHECK FOR CONVERGENCE OF ADJOINT VARIABLES
C
 840  DO 845 T=0,TM
         IF (DABS(LL1(T)-SL1(T))-ERR) 842,842,850
 842     CHECK1=CHECK1+1
C
C CONVERGENCE ATTAINED ON LL1(T)
C
         IF (CHECK1.EQ.TM) CVG1=1
 845  CONTINUE
 850  CONTINUE
C
 855  DO 858 T=0,TM
         IF (DABS(LL2(T)-SL2(T))-ERR) 856,856,860
 856     CHECK2=CHECK2+1
C
C CONVERGENCE ATTAINED ON LL2(T)
C
```

```
         IF (CHECK2.EQ.TM) CVG2=1
 858   CONTINUE
 860   CONTINUE
C
 865   DO 868 T=0,TM
         IF (DABS(LL3(T)-SL3(T))-ERR) 867,867,870
 867     CHECK3=CHECK3+1
C
C CONVERGENCE ATTAINED ON LL3(T)
C
         IF (CHECK3.EQ.TM) CVG3=1
  868 CONTINUE
  870 CONTINUE
C
      DO 873 T=0,TM
         IF(DABS(LL4(T)-SL4(T))-ERR) 871,871,872
 871     CHECK4=CHECK4+1
C
C CONVERGENCE ATTAINED ON LL4(T)
C
         IF(CHECK4.EQ.TM)CVG4=1
 873  CONTINUE
 872  CONTINUE
C
      DO 875 T=0,TM
         IF(DABS(LL5(T)-SL5(T))-ERR) 874, 874, 876
 874      CHECK5=CHECK5+1
C
C CONVERGENCE ATTAINED ON LL5(T)
C
          IF (CHECK5.EQ.TM)CVG5=1
 875  CONTINUE
 876  CONTINUE
C
      IF((CVG1.EQ.1).AND.(CVG2.EQ.1).AND.(CVG3.EQ.1)
     1.AND.(CVG4.EQ.1).AND.(CVG5.EQ.1))RETURN
C
C CONVERGENCE ATTAINED ON LL5(T)
C IF CONVERGENCE NOT ATTAINED SMOOTH ADJOINT VARIABLES
C
      DO 880 T=0,TM
         LL1(T)=THETA*SL1(T)+(1-THETA)*LL1(T)
         LL2(T)=THETA*SL2(T)+(1-THETA)*LL2(T)
         LL3(T)=THETA*SL3(T)+(1-THETA)*LL3(T)
         LL4(T)=THETA*SL4(T)+(1-THETA)*LL4(T)
         LL5(T)=THETA*SL5(T)+(1-THETA)*LL5(T)
         SL1(T)=LL1(T)
         SL2(T)=LL2(T)
         SL3(T)=LL3(T)
         SL4(T)=LL4(T)
         SL5(T)=LL5(T)
  880 CONTINUE
C
      IF (COUNT.LT.STOPIT) RETURN
```

```
      WRITE (6,8880) COUNT, CVG1,CVG2,CVG3
 8880 FORMAT(' ',T3,'NUMBER OF ITERATIONS=',I3,//,
     1T3,'CONVERGENCE NOT ATTAINED. CVG1=',I3,'CVG2=',
     2I3,'CVG3=',I3)
C
      STOP
      END
C
C
C *****************************************************************************
C
      SUBROUTINE PLAMB
C
C******************************************************************************
C
C <INSERT COMMON>
C
      WRITE(6,3000) TB1,TB2
 3000 FORMAT('1',////,T30,'TABLE',I4,'.  ADJOINT VARIABLES EXAMPLE',
     1I3,/////,T2,'TIME',
     1T18,'DEMAND',T39,'CAPACITY',T59,'PROGRESS',T76,
     2'TECHNOLOGY',T89,'PRODUCTION COSTS',//)
C
      DO 3200 J=0,TM
         KK=TM-J
      WRITE(6,3100) KK,LL1(KK),LL2(KK),LL3(KK),LL4(KK),LL5(KK)
 3100 FORMAT(T2,I3,T6,F20.5,T27,F20.5,T48,F20.5,T68,F16.5,T86,F15.5)
 3200 CONTINUE
C
      RETURN
      END
C
C
C *****************************************************************************
C
      SUBROUTINE POBJ
C
C******************************************************************************
C THIS SUBROUTINE COMPUTES THE OBJECTIVE FUNCTION AND WRITES IT OUT
C
C <INSERT COMMON>
C
      AA1=0.0
      BB1=0.0
      CC1=0.0
      OBJ=0.0
      DO 1300 J=0,TM
         AA1=(V1(J)*(S(J)-GOALS(J))**2+(B(J)+C3(J))*S(J)
     1   +C1(J)*A(J)**2+C2(J)*R(J)**2
     2   +C4(J)*(D1(J)*K(J)-S(J))**2-C5(J)*(D2(J)*K(J)-S(J)))
C
         BB1=AA1*EX(J)
         CC1=CC1+BB1
 1300 CONTINUE
```

```
C
      OBJ=-CC1 +(S1*S(TM)+S2*K(TM)+S3*ALPHA(TM))*EX(TM)
C
      WRITE(6,1350) OBJ,COUNT,CVG1,CVG2,CVG3,CVG4,CVG5
 1350 FORMAT(//,' ',2X,'THE VALUE OF THE OBJECTIVE FUNCTION IS',
     1F15.4,2X,'AT ITERATION=',I3,///,2X,'CVG1=',I3,
     2'CVG2=',I3,'CVG3=',I3,'CVG4=',I3,'CVG5=',I3)
C
      RETURN
      END
```

APPENDIX G

Exogenous Input Parameters: Model II of Chapter 4

TABLE 25. INPUT DATA EXAMPLE 1

STATE VARIABLES AT TIME 0

S0	K0	ALPHA	X0	C3
50.0000	40.000	0.0001	0.0005	20.0000

EXOGENOUS VARIABLES

T	GOAL S	C1	C2	C4	C5	BETA	D1	D2
0	50.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
1	55.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
2	60.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
3	65.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
4	70.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
5	75.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
6	80.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
7	85.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
8	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
9	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
10	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000

T	V1	EX	GAMMA1	GAMMA2	PHI	S	PSI	RMAX	AMAX
0	50.0000	1.0000	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
1	50.0000	0.7788	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
2	50.0000	0.6065	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
3	50.0000	0.4724	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
4	50.0000	0.3679	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
5	50.0000	0.2865	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
6	50.0000	0.2231	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
7	50.0000	0.1738	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
8	50.0000	0.1353	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
9	50.0000	0.1054	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
10	50.0000	0.0821	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000

S1	S2	S3	ALPHA0	RHO	THETA	POPO	STOPIT	TM
500.0	100.0000	500.0000	0.0001	0.2500	0.8000	500.0000	3000	10

TABLE 26. INPUT DATA EXAMPLE 2

STATE VARIABLES AT TIME 0

S0	K0	ALPHA	X0	C3
50.0000	40.000	0.0001	0.0005	20.0000

EXOGENOUS VARIABLES

T	GOAL S	C1	C2	C4	C5	BETA	D1	D2
0	50.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
1	55.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
2	60.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
3	65.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
4	70.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
5	75.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
6	80.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
7	85.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
8	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
9	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
10	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000

T	V1	EX	GAMMA1	GAMMA2	PHI	B	PSI	RMAX	AMAX
0	50.0000	1.0000	0.000050	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
1	50.0000	0.7788	0.000050	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
2	50.0000	0.6065	0.000050	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
3	50.0000	0.4724	0.000050	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
4	50.0000	0.3679	0.000050	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
5	50.0000	0.2865	0.000050	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
6	50.0000	0.2231	0.000050	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
7	50.0000	0.1738	0.000050	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
8	50.0000	0.1353	0.000050	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
9	50.0000	0.1054	0.000050	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
10	50.0000	0.0821	0.000050	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000

S1	S2	S3	ALPHAO	RHO	THETA	POPO	STOPIT	TM
500.0	100.0000	500.0000	0.0001	0.2500	0.8000	500.0000	3000	10

TABLE 27. INPUT DATA EXAMPLE 3

STATE VARIABLES AT TIME 0

S0	K0	ALPHA	X0	C3
50.0000	40.000	0.0001	0.0005	20.0000

EXOGENOUS VARIABLES

T	GOAL S	C1	C2	C4	C5	BETA	D1	D2
0	50.0000	100.0000	40.0000	20.0000	0.0000	0.04000	1.000000	1.000000
1	55.0000	100.0000	40.0000	20.0000	0.0000	0.04000	1.000000	1.000000
2	60.0000	100.0000	40.0000	20.0000	0.0000	0.04000	1.000000	1.000000
3	65.0000	100.0000	40.0000	20.0000	0.0000	0.04000	1.000000	1.000000
4	70.0000	100.0000	40.0000	20.0000	0.0000	0.04000	1.000000	1.000000
5	75.0000	100.0000	40.0000	20.0000	0.0000	0.04000	1.000000	1.000000
6	80.0000	100.0000	40.0000	20.0000	0.0000	0.04000	1.000000	1.000000
7	85.0000	100.0000	40.0000	20.0000	0.0000	0.04000	1.000000	1.000000
8	90.0000	100.0000	40.0000	20.0000	0.0000	0.04000	1.000000	1.000000
9	90.0000	100.0000	40.0000	20.0000	0.0000	0.04000	1.000000	1.000000
10	90.0000	100.0000	40.0000	20.0000	0.0000	0.04000	1.000000	1.000000

T	V1	EX	GAMMA1	GAMMA2	PHI	B	PSI	RMAX	AMAX
0	50.0000	1.0000	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
1	50.0000	0.7788	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
2	50.0000	0.6065	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
3	50.0000	0.4724	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
4	50.0000	0.3679	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
5	50.0000	0.2865	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
6	50.0000	0.2231	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
7	50.0000	0.1738	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
8	50.0000	0.1353	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
9	50.0000	0.1054	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
10	50.0000	0.0821	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000

S1	S2	S3	ALPHAO	RHO	THETA	POPO	STOPIT	TM
500.0	100.0000	500.0000	0.0001	0.2500	0.8000	500.0000	3000	10

TABLE 28. INPUT DATA EXAMPLE 4

STATE VARIABLES AT TIME 0

S0	K0	ALPHA	X0	C3
50.0000	40.000	0.0001	0.0005	20.0000

EXOGENOUS VARIABLES

T	GOAL S	C1	C2	C4	C5	BETA	D1	D2
0	50.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
1	55.0000	95.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
2	60.0000	90.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
3	65.0000	85.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
4	70.0000	80.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
5	75.0000	75.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
6	80.0000	70.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
7	85.0000	65.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
8	90.0000	60.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
9	90.0000	55.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
10	90.0000	50.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000

T	V1	EX	GAMMA1	GAMMA2	PHI	B	PSI	RMAX	AMAX
0	50.0000	1.0000	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
1	50.0000	0.7788	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
2	50.0000	0.6065	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
3	50.0000	0.4724	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
4	50.0000	0.3679	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
5	50.0000	0.2865	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
6	50.0000	0.2231	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
7	50.0000	0.1738	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
8	50.0000	0.1353	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
9	50.0000	0.1054	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
10	50.0000	0.0821	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000

S1	S2	S3	ALPHA0	RHO	THETA	POPO	STOPIT	TM
500.0	100.0000	500.0000	0.0001	0.2500	0.8000	500.0000	3000	10

TABLE 29. INPUT DATA EXAMPLE 5.

STATE VARIABLES AT TIME 0

S0	K0	ALPHA	X0	C3
50.0000	40.000	0.0001	0.0005	20.0000

EXOGENOUS VARIABLES

T	GOAL S	C1	C2	C4	C5	BETA	D1	D2
0	50.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
1	55.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
2	60.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
3	65.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
4	70.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
5	75.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
6	80.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
7	85.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
8	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
9	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
10	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000

T	V1	EX	GAMMA1	GAMMA2	PHI	B	PSI	RMAX	AMAX
0	100.0000	1.0000	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
1	100.0000	0.7788	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
2	100.0000	0.6065	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
3	100.0000	0.4724	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
4	100.0000	0.3679	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
5	100.0000	0.2865	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
6	100.0000	0.2231	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
7	100.0000	0.1738	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
8	100.0000	0.1353	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
9	100.0000	0.1054	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000
10	100.0000	0.0821	0.001000	0.000000	0.0010	0.00000	0.5000	10.0000	12.0000

S1	S2	S3	ALPHA0	RHO	THETA	POPO	STOPIT	TM
500.0	100.0000	500.0000	0.0001	0.2500	0.8000	500.0000	3000	10

TABLE 30. INPUT DATA EXAMPLE 6

STATE VARIABLES AT TIME 0

S0	K0	ALPHA	X0	C3
50.0000	40.000	0.0001	0.0005	20.0000

EXOGENOUS VARIABLES

T	GOAL S	C1	C2	C4	C5	BETA	D1	D2
0	50.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
1	55.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
2	60.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
3	65.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
4	70.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
5	75.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
6	80.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
7	85.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
8	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
9	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
10	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000

T	V1	EX	GAMMA1	GAMMA2	PHI	B	PSI	RMAX	AMAX
0	50.0000	1.0000	0.001000	-0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
1	50.0000	0.7788	0.001000	-0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
2	50.0000	0.6065	0.001000	-0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
3	50.0000	0.4724	0.001000	-0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
4	50.0000	0.3679	0.001000	-0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
5	50.0000	0.2865	0.001000	-0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
6	50.0000	0.2231	0.001000	-0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
7	50.0000	0.1738	0.001000	-0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
8	50.0000	0.1353	0.001000	-0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
9	50.0000	0.1054	0.001000	-0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
10	50.0000	0.0821	0.001000	-0.020000	0.0010	0.00000	0.5000	10.0000	12.0000

S1	S2	S3	ALPHAO	RHO	THETA	POPO	STOPIT	TM
500.0	100.0000	500.0000	0.0001	0.2500	0.8000	500.0000	3000	10

TABLE 31. INPUT DATA EXAMPLE 7

STATE VARIABLES AT TIME 0

S0	K0	ALPHA	X0	C3
50.0000	40.000	0.0001	0.0005	20.0000

EXOGENOUS VARIABLES

T	GOAL S	C1	C2	C4	C5	BETA	D1	D2
0	50.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
1	55.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
2	60.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
3	65.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
4	70.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
5	75.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
6	80.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
7	85.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
8	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
9	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
10	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000

T	V1	EX	GAMMA1	GAMMA2	PHI	B	PSI	RMAX	AMAX
0	50.0000	1.0000	0.001000	0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
1	50.0000	0.7788	0.001000	0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
2	50.0000	0.6065	0.001000	0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
3	50.0000	0.4724	0.001000	0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
4	50.0000	0.3679	0.001000	0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
5	50.0000	0.2865	0.001000	0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
6	50.0000	0.2231	0.001000	0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
7	50.0000	0.1738	0.001000	0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
8	50.0000	0.1353	0.001000	0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
9	50.0000	0.1054	0.001000	0.020000	0.0010	0.00000	0.5000	10.0000	12.0000
10	50.0000	0.0821	0.001000	0.020000	0.0010	0.00000	0.5000	10.0000	12.0000

S1	S2	S3	ALPHA0	RHO	THETA	POPO	STOPIT	TM
500.0	100.0000	500.0000	0.0001	0.2500	0.8000	500.0000	3000	10

TABLE 32. INPUT DATA EXAMPLE B

STATE VARIABLES AT TIME 0

SO	KO	ALPHA	XO	C3
50.0000	40.000	0.0001	0.0005	20.0000

EXOGENOUS VARIABLES

T	GOAL S	C1	C2	C4	C5	BETA	D1	D2
0	50.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
1	55.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
2	60.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
3	65.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
4	70.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
5	75.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
6	80.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
7	85.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
8	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
9	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000
10	90.0000	100.0000	40.0000	20.0000	0.0000	0.00100	1.000000	1.000000

T	V1	EX	GAMMA1	GAMMA2	PHI	B	PSI	RMAX	AMAX
0	50.0000	1.0000	0.001000	0.000000	0.0500	0.00000	0.5000	10.0000	12.0000
1	50.0000	0.7788	0.001000	0.000000	0.0500	0.00000	0.5000	10.0000	12.0000
2	50.0000	0.6065	0.001000	0.000000	0.0500	0.00000	0.5000	10.0000	12.0000
3	50.0000	0.4724	0.001000	0.000000	0.0500	0.00000	0.5000	10.0000	12.0000
4	50.0000	0.3679	0.001000	0.000000	0.0500	0.00000	0.5000	10.0000	12.0000
5	50.0000	0.2865	0.001000	0.000000	0.0500	0.00000	0.5000	10.0000	12.0000
6	50.0000	0.2231	0.001000	0.000000	0.0500	0.00000	0.5000	10.0000	12.0000
7	50.0000	0.1738	0.001000	0.000000	0.0500	0.00000	0.5000	10.0000	12.0000
8	50.0000	0.1353	0.001000	0.000000	0.0500	0.00000	0.5000	10.0000	12.0000
9	50.0000	0.1054	0.001000	0.000000	0.0500	0.00000	0.5000	10.0000	12.0000
10	50.0000	0.0821	0.001000	0.000000	0.0500	0.00000	0.5000	10.0000	12.0000

S1	S2	S3	ALPHAO	RHO	THETA	POPO	STOPIT	TM
500.0	100.0000	500.0000	0.0001	0.2500	0.8000	500.0000	3000	10

APPENDIX H

Detailed Results: Model II of Chapter 4

TABLE 33. OPTIMAL SOLUTION EXAMPLE 1

GOAL DEMAND AND STATE VARIABLES

TIME	GOAL DEMAND LEVEL	ACTUAL DEMAND LEVEL	CAPACITY LEVEL	AUTOMATION LEVEL	PER UNIT PRODUCTION COST	LEVEL OF PROGRESS FACTOR
10	90.000000	76.471472	81.0652	60.3664	18.8248	.000001246
9	90.000000	75.190144	78.8643	57.3504	18.8817	.000002493
8	90.000000	73.287008	76.4699	52.8908	18.9663	.000004985
7	85.000000	70.726542	73.3534	46.9269	19.0801	.000009969
6	80.000000	67.790161	69.8005	40.1344	19.2106	.000019935
5	75.000000	64.672978	65.9465	32.9765	19.3491	.000039862
4	70.000000	61.514203	61.8132	25.7776	19.4894	.000079701
3	65.000000	58.414621	57.3006	18.7675	19.6270	.000159343
2	60.000000	55.444228	52.1351	12.1024	19.7587	.000318510
1	55.000000	52.640343	45.8674	5.8639	19.8827	.000636343
0	50.000000	50.000000	40.0000	0.0005	20.0000	.000100000

CONTROL VARIABLES

TIME	INCREASE IN LEVEL OF TECHNOLOGY	REDUCTION IN EXISTING CAPCITY
10	1.5588	0.0000
9	3.0160	0.8153
8	4.4596	2.0657
7	5.9639	2.8481
6	6.7925	3.2409
5	7.1579	3.3066
4	7.1989	3.0705
3	7.0101	2.5066
2	6.6651	1.5162
1	6.2384	0.0000
0	5.8634	0.0000

THE VALUE OF THE OBJECTIVE FUNCTION IS -33458.7476 AT ITERATION= 54

TABLE 34. ADJOINT VARIABLES EXAMPLE 1

TIME	DEMAND	CAPACITY	PROGRESS	TECHNOLOGY	PRODUCTION COSTS
10	41.04250	8.20850	41.04250	0.00000	0.00000
9	165.56531	-6.87458	2095.07544	0.00000	-6.27716
8	334.66059	-22.36448	6032.25661	0.00000	-14.18321
7	574.01751	-39.59443	12236.38827	0.00000	-24.03828
6	833.57291	-57.85171	21289.63601	0.00000	-36.18535
5	1114.00394	-75.78803	31756.14113	0.00000	-51.06559
4	1410.95220	-90.36635	42864.70484	-0.00001	-69.22918
3	1710.19264	-94.72365	54095.23308	-0.00002	-91.36062
2	1978.93925	-73.56908	64903.17257	-0.00011	-118.31329
1	2149.76936	6.97216	74499.68700	-0.00058	-151.15334
0	2093.59097	218.57861	81720.89157	-0.00468	-191,20672

TABLE 35. OPTIMAL SOLUTION EXAMPLE 2

GOAL DEMAND AND STATE VARIABLES

TIME	GOAL DEMAND LEVEL	ACTUAL DEMAND LEVEL	CAPACITY LEVEL	AUTOMATION LEVEL	PER UNIT PRODUCTION COST	LEVEL OF PROGRESS FACTOR
10	90.000000	50.290468	51.8822	12.8799	19.7438	.000000656
9	90.000000	50.278309	51.3415	12.3392	19.7545	.000001313
8	90.000000	50.264609	50.8707	11.7301	19.7666	.000002625
7	85.000000	50.248138	50.4821	10.9979	19.7811	.000005250
6	80.000000	50.229212	49.9994	10.1569	19.7977	.000010500
5	75.000000	50.207759	49.2354	9.2040	19.8166	.000020997
4	70.000000	50.182761	48.1239	8.0945	19.8386	.000041989
3	65.000000	50.152233	46.7667	6.7412	19.8655	.000083961
2	60.000000	50.113783	45.0573	5.0395	19.8993	.000167866
1	55.000000	50.064322	42.8588	2.8553	19.9429	.000335476
0	50.000000	50.000000	40.0000	0.0005	20.0000	.000100000

CONTROL VARIABLES

TIME	INCREASE IN LEVEL OF TECHNOLOGY	REDUCTION IN EXISTING CAPCITY
10	0.5562	0.0000
9	0.5407	0.0000
8	0.6091	0.1385
7	0.7322	0.3438
6	0.8411	0.3589
5	0.9529	0.1899
4	1.1095	0.0000
3	1.3533	0.0000
2	1.7018	0.0000
1	2.1842	0.0000
0	2.8548	0.0000

THE VALUE OF THE OBJECTIVE FUNCTION IS -77559.9942 AT ITERATION= 43

TABLE 36. ADJOINT VARIABLES EXAMPLE 2

TIME	DEMAND	CAPACITY	PROGRESS	TECHNOLOGY	PRODUCTION COSTS
10	41.04250	8.20850	41.04250	0.00000	0.00000
9	370.60259	2.98229	494.27695	0.00000	-4.12809
8	791.65619	-1.49988	828.11360	0.00000	-9.42516
7	1329.99793	-4.78077	1243.36765	0.00000	-16.22199
6	1932.03472	-6.40675	1890.22301	0.00000	-24.94193
5	2589.76055	-4.35488	2797.26034	0.00000	-36.12860
4	3283.12554	6.78979	4051.96319	0.00000	-50.47894
3	3974.38378	37.08976	5906.49466	0.00000	-68.88414
2	4602.11981	101.06971	8869.03428	-0.00001	-92.48116
1	5066.61079	223.77955	13654.35129	-0.00006	-122.71932
0	5210.44530	448.36082	21308.45815	-0.00067	-161.44141

TABLE 37. OPTIMAL SOLUTION EXAMPLE 3

GOAL DEMAND AND STATE VARIABLES

TIME	GOAL DEMAND LEVEL	ACTUAL DEMAND LEVEL	CAPACITY LEVEL	AUTOMATION LEVEL	PER UNIT PRODUCTION COST	LEVEL OF PROGRESS FACTOR
10	90.000000	76.744271	81.3408	61.0034	1.1928	.000001299
9	90.000000	75.467080	79.1487	57.9952	1.3560	.000002597
8	90.000000	73.569761	76.7688	53.5463	1.6495	.000005194
7	85.000000	71.014742	73.6702	47.5911	2.1653	.000010387
6	80.000000	68.080994	70.1371	40.8002	2.9729	.000020771
5	75.000000	64.960617	66.3031	33.6303	4.1683	.000041533
4	70.000000	61.788892	62.1876	26.3976	5.8652	.000083043
3	65.000000	58.661550	57.6873	19.3211	8.1808	.000166026
2	60.000000	55.642252	52.5248	12.5438	11.2234	.000331873
1	55.000000	52.760533	46.1345	6.1310	15.0956	.000663052
0	50.000000	50.000000	40.0000	0.0005	20.0000	.000100000

CONTROL VARIABLES

TIME	INCREASE IN LEVEL OF TECHNOLOGY	REDUCTION IN EXISTING CAPCITY
10	1.5581	0.0000
9	3.0083	0.8164
8	4.4489	2.0694
7	5.9552	2.8573
6	6.7909	3.2592
5	7.1699	3.3387
4	7.2327	3.1224
3	7.0765	2.5858
2	6.7773	1.6322
1	6.4128	0.0530
0	6.1305	0.0000

THE VALUE OF THE OBJECTIVE FUNCTION IS -31209.5929 AT ITERATION= 55

TABLE 38. ADJOINT VARIABLES EXAMPLE 3

TIME	DEMAND	CAPACITY	PROGRESS	TECHNOLOGY	PRODUCTION COSTS
10	41.04250	8.20850	41.04250	0.00000	0.00000
9	164.78252	-6.88370	2101.21706	0.00000	-6.29955
8	332.84139	-22.40522	6042.72310	0.00000	-13.49570
7	570.81424	-39.72251	12197.66867	0.00000	-21.05064
6	828.52367	-58.17849	21212.92268	0.00000	-28.37672
5	1106.53275	-76.52334	31626.67157	0.00000	-35.85951
4	1400.42026	-91.89187	42660.31823	-0.00001	-44.18670
3	1696.06306	-97.71534	53784.72558	-0.00002	-54.13395
2	1961.18010	-79.19988	64446.42653	-0.00011	-66.52063
1	2129.72526	-3.30439	73854.23873	-0.00057	-82.23611
0	2072.24228	203.73879	80756.29285	-0.00475	-102.23165

TABLE 39 OPTIMAL SOLUTION EXAMPLE 4

GOAL DEMAND AND STATE VARIABLES

TIME	GOAL DEMAND LEVEL	ACTUAL DEMAND LEVEL	CAPACITY LEVEL	AUTOMATION LEVEL	PER UNIT PRODUCTION COST	LEVEL OF PROGRESS FACTOR
10	90.000000	79.585041	85.2060	67.7017	18.6864	.000001196
9	90.000000	77.749542	82.0743	63.3549	18.7679	.000002393
8	90.000000	75.287228	78.9072	57.5577	18.8774	.000004785
7	85.000000	72.115550	74.9530	50.1460	19.0183	.000009569
6	80.000000	68.638484	70.6903	42.0866	19.1729	.000019134
5	75.000000	65.094112	66.2973	33.9394	19.3303	.000038259
4	70.000000	61.631616	61.7925	26.0456	19.4841	.000076495
3	65.000000	58.348011	57.0626	18.6195	19.6299	.000152929
2	60.000000	55.303769	51.8210	11.7896	19.7649	.000305681
1	55.000000	52.524901	45.6109	5.6074	19.8879	.000610689
0	50.000000	50.000000	40.0000	0.0005	20.0000	.000100000

CONTROL VARIABLES

TIME	INCREASE IN LEVEL OF TECHNOLOGY	REDUCTION IN EXISTING CAPCITY
10	3.1021	0.0000
9	4.3467	1.2153
8	5.7972	2.6305
7	7.4117	3.4582
6	8.0593	3.7981
5	8.1472	3.7567
4	7.8939	3.3938
3	7.4261	2.7048
2	6.8298	1.6041
1	6.1823	0.0000
0	5.6069	0.0000

THE VALUE OF THE OBJECTIVE FUNCTION IS -31009.8683 AT ITERATION= 54

TABLE 40. ADJOINT VARIABLES EXAMPLE 4

TIME	DEMAND	CAPACITY	PROGRESS	TECHNOLOGY	PRODUCTION COSTS
10	41.04250	8.20850	41.04250	0.00000	0.00000
9	143.32820	-10.24717	2190.15366	0.00000	-6.53274
8	288.07890	-28.48004	5221.29111	0.00000	-14.69908
7	502.56606	-48.07597	10017.98543	0.00000	-24.80289
6	739.15679	-67.79708	17524.19496	0.00000	-37.15086
5	1000.74365	-86.10558	26510.35375	0.00000	-52.16676
4	1284.64714	-99.88131	36404.32708	0.00000	-70.39153
3	1577.55620	-102.21403	46834.15002	-0.00002	-92.50887
2	1846.48443	-77.83501	57351.06476	-0.00010	-119.38354
1	2022.20049	6.88847	67210.15411	-0.00053	-152.11160
0	1971.52917	222.83070	75228.89737	-0.00456	-192.07764

TABLE 41. OPTIMAL SOLUTION EXAMPLE 5

GOAL DEMAND AND STATE VARIABLES

TIME	GOAL DEMAND LEVEL	ACTUAL DEMAND LEVEL	CAPACITY LEVEL	AUTOMATION LEVEL	PER UNIT PRODUCTION COST	LEVEL OF PROGRESS FACTOR
10	90.000000	82.314530	87.5401	74.1395	18.5654	.000001521
9	90.000000	80.967263	85 3862	70.9245	18.6253	.000003042
8	90.000000	78.840742	82.8842	65.8758	18.7198	.000006083
7	85.000000	75.768223	79.1999	58.6343	18.8564	.000012164
6	80.000000	72.177175	74.9133	50.2423	19.0159	.000024324
5	75.000000	68.333449	70.2726	41.3413	19.1867	.000048637
4	70.000000	64.411729	65.3441	32.3444	19.3609	.000097247
3	65.000000	60.535377	60.0584	23.5355	19.5330	.000194421
2	60.000000	56.797835	54.1891	15.1235	19.6987	.000388627
1	55.000000	53.270660	47.2681	7.2646	19.8547	.000776413
0	50.000000	50.000000	40.0000	0.0005	20.0000	.000100000

CONTROL VARIABLES

TIME	INCREASE IN LEVEL OF TECHNOLOGY	REDUCTION IN EXISTING CAPCITY
10	1.5442	0.0000
9	3.2149	1.0613
8	5.0487	2.5472
7	7.2416	3.5582
6	8.3920	4.1072
5	8.9010	4.2637
4	8.9969	4.0748
3	8.8089	3.5348
2	8.4120	2.5638
1	7.8589	0.9745
0	7.2641	0.0000

THE VALUE OF THE OBJECTIVE FUNCTION IS -41214.7451 AT ITERATION= 80

TABLE 42. ADJOINT VARIABLES EXAMPLE 5

TIME	DEMAND	CAPACITY	PROGRESS	TECHNOLOGY	PRODUCTION COSTS
10	41.04250	8.20850	41.04250	0.00000	0.00000
9	182.78526	-8.94919	2239.78249	0.00000	-6.75679
8	389.27341	-27.57922	6895.79232	0.00000	-15.26895
7	708.71176	-49.46745	14750.82281	0.00000	-25.86180
6	1045.00383	-73.31764	27270.58420	0.00000	-38.84106
5	1405.51132	-97.72895	41637.07326	0.00000	-54.62001
4	1791.72185	-119.92729	56590.59644	-0.00001	-73.71170
3	2193.35067	-133.58371	71464.65381	-0.00003	-96.74428
2	2577.55169	-124.40906	85613.12679	-0.00014	-124.48695
1	2869.01956	-60.72349	97993.15552	-0.00075	-157.88939
0	2913.27554	127.21534	106761.68817	-0.00642	-198.13580

TABLE 43. OPTIMAL SOLUTION EXAMPLE 6

GOAL DEMAND AND STATE VARIABLES

TIME	GOAL DEMAND LEVEL	ACTUAL DEMAND LEVEL	CAPACITY LEVEL	AUTOMATION LEVEL	PER UNIT PRODUCTION COST	LEVEL OF PROGRESS FACTOR
10	90.000000	70.034510	77.4540	72.8066	18.5905	.000001357
9	90.000000	69.764969	75.5000	68.9372	18.6627	.000002713
8	90.000000	68.634954	73.4231	63.1357	18.7716	.000005425
7	85.000000	66.696073	70.6353	55.5834	18.9144	.000010849
6	80.000000	64.299381	67.4279	47.1325	19.0756	.000021695
5	75.000000	61.685941	63.9533	38.3581	19.2445	.000043380
4	70.000000	59.027594	60.2597	29.6578	19.4134	.000086734
3	65.000000	56.451318	56.2874	21.3138	19.5767	.000173401
2	60.000000	54.051679	51.8279	13.5267	19.7304	.000346602
1	55.000000	51.892775	46.4284	6.4249	19.8715	.000692439
0	50.000000	50.000000	40.0000	0.0005	20.0000	.000100000

CONTROL VARIABLES

TIME	INCREASE IN LEVEL OF TECHNOLOGY	REDUCTION IN EXISTING CAPCITY
10	1.5749	0.0000
9	3.8694	1.9156
8	5.8014	3.7249
7	7.5524	4.7653
6	8.4509	5.2450
5	8.7744	5.3026
4	8.7003	5.0118
3	8.3440	4.3815
2	7.7871	3.3456
1	7.1018	1.7344
0	6.4244	0.0000

THE VALUE OF THE OBJECTIVE FUNCTION IS -49637.4221 AT ITERATION= 60

TABLE 44 ADJOINT VARIABLES EXAMPLE 6

TIME	DEMAND	CAPACITY	PROGRESS	TECHNOLOGY	PRODUCTION COSTS
10	41.04250	8.20850	41.04250	0.00000	0.00000
9	226.87889	-16.15262	2023.12256	0.00000	-5.74878
8	456.95054	-40.33093	7161.74004	0.00000	-13.07971
7	757.68433	-66.25005	15092.57887	0.00000	-22.29256
6	1078.97664	-93.62837	26057.81793	0.00000	-33.71424
5	1422.27179	-121.54294	38416.66416	0.00000	-47.77646
4	1783.26829	-147.50610	51308.27352	-0.00001	-65.03057
3	2146.71904	-165.58063	64159.50226	-0.00003	-86.17982
2	2477.31754	-162.34654	76367.60295	-0.00013	-112.12645
1	2703.30090	-108.06849	87048.86953	-0.00069	-144.03730
0	2686.23802	62.92219	94796.99081	-0.00588	-183.42852

TABLE 45. OPTIMAL SOLUTION EXAMPLE 7

GOAL DEMAND AND STATE VARIABLES

TIME	GOAL DEMAND LEVEL	ACTUAL DEMAND LEVEL	CAPACITY LEVEL	AUTOMATION LEVEL	PER UNIT PRODUCTION COST	LEVEL OF PROGRESS FACTOR
10	90.000000	83.651366	84.6330	46.8929	19.0816	.000001132
9	90.000000	81.131544	82.4910	44.7512	19.1225	.000002264
8	90.000000	78.294841	79.5464	41.7380	19.1803	.000004527
7	85.000000	75.007483	75.8821	37.5335	19.2613	.000009054
6	80.000000	71.468786	71.7218	32.6125	19.3566	.000018105
5	75.000000	67.814392	67.0960	27.2976	19.4600	.000036203
4	70.000000	64.134438	61.8545	21.8020	19.5675	.000072387
3	65.000000	60.479921	56.2918	16.2475	19.6768	.000144725
2	60.000000	56.883724	50.7436	10.7139	19.7863	.000289300
1	55.000000	53.377823	45.2841	5.2806	19.8944	.000578005
0	50.000000	50.000000	40.0000	0.0005	20.0000	.000100000

CONTROL VARIABLES

TIME #	INCREASE IN LEVEL OF TECHNOLOGY	REDUCTION IN EXISTING CAPCITY
10	1.5408	0.0000
9	2.1418	0.0000
8	3.0131	0.0689
7	4.2046	0.5410
6	4.9209	0.7618
5	5.3150	0.6917
4	5.4955	0.2585
3	5.5546	0.0000
2	5.5336	0.0000
1	5.4334	0.0000
0	5.2801	0.0000

THE VALUE OF THE OBJECTIVE FUNCTION IS -21350.9651 AT ITERATION= 48

TABLE 46. ADJOINT VARIABLES EXAMPLE 7

TIME	DEMAND	CAPACITY	PROGRESS	TECHNOLOGY	PRODUCTION COSTS
10	41.04250	8.20850	41.04250	0.00000	0.00000
9	95.56952	4.98556	2161.43851	0.00000	-6.86652
8	194.46505	-0.74584	4794.23764	0.00000	-15.40302
7	360.35993	-7.52076	8861.31861	0.00000	-25.95266
6	542.42816	-13.59908	15481.83321	0.00000	-38.87789
5	738.90266	-15.85292	23438.26887	0.00000	-54.63341
4	941.81452	-7.60905	32084.39253	0.00000	-73.77219
3	1130.50509	25.96931	40967.14924	-0.00002	-96.96051
2	1271.91275	105.17750	49922.70371	-0.00008	-124.99063
1	1318.33727	254.33849	58910.66990	-0.00043	-158.80071
0	1196.21059	506.96325	67666.30702	-0.00375	-199.50858

TABLE 47. OPTIMAL SOLUTION EXAMPLE 8

GOAL DEMAND AND STATE VARIABLES

TIME	GOAL DEMAND LEVEL	ACTUAL DEMAND LEVEL	CAPACITY LEVEL	AUTOMATION LEVEL	PER UNIT PRODUCTION COST	LEVEL OF PROGRESS FACTOR
10	90.000000	77.051808	81.5703	57.8952	18.8717	.000079084
9	90.000000	75.806920	79.4212	54.9731	18.9270	.000157748
8	90.000000	73.970911	77.1299	50.6877	19.0084	.000314169
7	85.000000	71.303705	74.1714	44.9762	19.1176	.000624373
6	80.000000	68.679909	70.8364	38.5170	19.2419	.001238363
5	75.000000	65.682501	67.2606	31.7805	19.3724	.002450752
4	70.000000	62.625665	63.4440	25.0983	19.5027	.004837112
3	65.000000	59.559636	59.2093	18.7002	19.6283	.009511511
2	60.000000	56.460358	54.0906	12.7179	19.7464	.018585897
1	55.000000	53.217225	47.1494	7.1459	19.8571	.035776942
0	50.000000	50.000000	40.0000	0.0005	20.0000	.000100000

CONTROL VARIABLES

TIME	INCREASE IN LEVEL OF TECHNOLOGY	REDUCTION IN EXISTING CAPCITY
10	1.5574	0.0000
9	2.9222	0.7857
8	4.2854	2.0183
7	5.7115	2.7993
6	6.4591	3.2119
5	6.7366	3.3256
4	6.6822	3.1724
3	6.3981	2.7266
2	5.9823	1.8690
1	5.5720	0.3176
0	7.1454	0.0000

THE VALUE OF THE OBJECTIVE FUNCTION IS -30870.8227 AT ITERATION= 61

TABLE 48. ADJOINT VARIABLES EXAMPLE 8

TIME	DEMAND	CAPACITY	PROGRESS	TECHNOLOGY	PRODUCTION COSTS
10	41.04250	8.20850	41.04250	0.00000	0.00000
9	160.55037	-6.62538	2106.08431	0.00000	-6.32480
8	322.91600	-21.85341	5938.57540	-0.00001	-14.29631
7	552.98306	-38.91813	11907.17537	-0.00009	-24.24592
6	799.55042	-57.33753	20679.77897	-0.00061	-36.53292
5	1061.85529	-76.22897	30793.80729	-0.00340	-51.62150
4	1334.01312	-93.37115	41452.29120	-0.01598	-70.09210
3	1600.84317	-103.04212	52095.43188	-0.06916	-92.66243
2	1830.79185	-90.69562	62139.29142	-0.29580	-120.20354
1	1963.22011	-19.79679	70817.74720	-1.36369	-153.72939
0	1883.32191	199.90148	77212.24694	-8.27538	-194.31843