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OF NEW PROCESS TECHNOLOGY*

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STRATEGIC EVALUATION OF THE OPTIMAL ACQUISITION
OF NEW PROCESS TECHNOLOGY

BY

Hyun Gyu Kim

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ABSTRACT

STRATEGIC EVALUATION OF THE OPTIMAL ACQUISITION OF NEW PROCESS TECHNOLOGY

By

Hyun Gyu Kim

This dissertation focuses on the strategic decisions involved in optimal investment policies for the acquisition of new process technology. Here, optimal investment policies include not only the acquisition of new process technology but also the attrition of existing manual production capacity. This study explores analytically why and how the technology decisions involving these optimal investment policies are related to corporate strategy and external market environment. This dissertation also presents a conceptual framework for investment decisions regarding the acquisition of new process technology. This framework explains the relationships among decision variables and other variables used in the development of a model.

The model developed here is a dynamic optimal control model. It has an objective function which maximizes the long-term value of a firm's strategic business unit (SBU) and also minimizes both tangible and intangible costs associated with the use and acquisition of process technology during the planning horizon. These cost factors include not only the direct costs associated with the acquisition and attrition of process technology but also the cost associated with the flexibility attribute of process technology. It is assumed here that there are two components to process technology, capacity (automation capacity) and flexibility. Capacity refers to the total volume that can be produced by the system, whereas flexibility refers to the variety of product (part) types that the system can handle. Other cost factors in the objective function are related to the penalty costs associated with deviations between an SBU's actual market demand and its goals, as well as deviations between its actual market demand and its production level. These deviations are measured

in terms of both volume and variety. The constraints address the change in market potential for volume and variety, the change in unit production cost due to the acquisition of new process technology and flexibility, and the change in system capacity and flexibility. The optimal solution of the model provides decisions regarding both the acquisition of new process technology affecting the system capacity and flexibility, and the attrition of the conventional (existing) production capacity.

A scenario analysis is conducted to examine several research issues. The results of scenario analysis lead to some insightful conclusions. First, in the long run for the optimal performance of a firm's manufacturing systems it should select a strategic priority which is congruent to external market conditions. Second, the acquisition policy of new process technology is affected by the type of product life cycle (external market conditions).



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Dedicated

to

my father

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CHAPTER I

INTRODUCTION

This dissertation focuses on the strategic decisions involved in optimal investment policies for the acquisition of new process technology. Here, optimal investment policies include not only the acquisition of new process technology¹ but also the attrition of existing manual production capacity. This study explores analytically why and how the technology decisions involving these optimal investment policies are related to corporate strategy and external market environment. This dissertation also presents a conceptual framework for investment decisions regarding the acquisition of new process technology. This framework explains the relationships among decision variables and other variables² used in the development of a model.

The model developed here is a dynamic optimal control model. It has an objective function which maximizes the long-term value of a firm's strategic business unit (SBU) and also minimizes both tangible and intangible costs associated with the use and acquisition of process technology during the planning horizon. These cost factors include not only the direct costs associated with the acquisition and attrition of process technology but also the cost associated with the flexibility attribute of process technology. It is assumed here that there are two components to process technology, capacity (automation capacity) and flexibility. Capacity refers to the total volume that can be produced by the system, whereas flexibility refers to the variety of product (part) types that the system can handle. Other cost factors in the objective function are related to the penalty costs associated with

¹ Hereafter, "new process technology" is sometimes referred to as "new technology."

² In an optimal control model, decision variables are called "control variables," and the other variables are called "state variables."

deviations between an SBU's actual market demand and its goals, as well as deviations between its actual market demand and its production level. These deviations are measured in terms of both volume and variety. The constraints address the change in market potential for volume and variety, the change in unit production cost due to the acquisition of new process technology and flexibility, and the change in system capacity and flexibility. The optimal solution of the model provides decisions regarding both the acquisition of new process technology affecting the system capacity and flexibility, and the attrition of the conventional (existing) production capacity.

From the scenario analysis using the model, this study attempts to evaluate two strategic issues found frequently in the literature. One is the effect of the strategic emphasis on flexibility over cost efficiency on optimal policies, and the other is the effect on the changes in the position of technology choice on the product - technology matrix³ due to technology acquisition. These two issues are evaluated within the framework of the product life cycle (PLC) theory. In doing so, this dissertation attempts to provide insights for both managers and researchers on how to make strategic acquisition decisions for new process technology. This is an important understanding given the current, rapid diffusion of new process technology.

1.1 OBJECTIVES OF RESEARCH

Faced with fierce and ever-rising competition created by the proliferation of new products and shorter or truncated product life cycles, many U.S. manufacturing firms recently began to adopt new process technology, such as the Just-In-Time (JIT), Robots, Computer Integrated Manufacturing (CIM), or Flexible Manufacturing System (FMS), to

³ The product and technology matrix is a slightly different version of the product-process matrix suggested by Hayes and Wheelwright [1984]. In this matrix, a process technology choice is determined by the combination of the degree of automation capacity and the degree of flexibility. The stages of PLC are represented by the third dimension in the matrix.

improve manufacturing flexibility. Although the need for investment in new process technology has been widely recognized by most manufacturing firms as well as academicians there have been few studies concerning the technology acquisition problem in the broad context of manufacturing strategy. This study attempts to respond to this need by exploring the strategic implication of new advanced technology acquisition. Results of this study are expected to offer managers sound guidance for optimizing manufacturing systems' performance potential in the long run (Kantrow 1980).

It has been argued frequently that the relatively weak performance of the U.S. manufacturing industry during the last two decades has been due partly to an obsession with short-term performance and to the attention given solely to cost efficiency by most production managers (DeMeyer et al. 1989; Kaplan 1986). A similar phenomenon can be observed in past analytic studies. Most of the studies employ cost efficiency as the single decision criterion. However, the importance of manufacturing flexibility has become recognized by both practitioners and academicians. In fact, some empirical studies have revealed that manufacturing flexibility is a key ingredient for the survival of manufacturing firms in the fierce competition of the international market (DeMeyer, et al. 1989; see also Buffa 1984; Jaikumar 1986; Goldhar and Jelinek 1983). In addition, manufacturing flexibility is regarded as one of the competitive priorities as opposed to cost efficiency in terms of the capabilities of process technology (Hayes and Wheelwright 1984). A firm with the competitive priority of manufacturing flexibility may focus on improving the flexibility of its process technology to achieve the economies of scope. On the contrary, a firm with the competitive priority of cost efficiency may focus on increasing the automation capacity of its process technology to achieve the economies of scale. Hence, if the objective of technology acquisition is to enhance a firm's overall competitive position in the market, the decision criteria for optimal performance should reflect the trade-offs involved in these two conflicting priorities. This view is shared by many researchers (Kaplan 1983; Jaikumar 1986; Hayes and Jaikumar 1988; Hough 1989) who assert that

the evaluation for new technology acquisition should include its intangible benefits.

As suggested by Kim (1989), the studies in strategy can be placed into three categories: conceptual, empirical, and analytical. Most studies in manufacturing strategy will be categorized as either conceptual or empirical. Few studies will be included in the analytical category. In fact, the analytical study of manufacturing strategy is still in its infancy. One of the important benefits of analytic study is the high controllability of variables. This controllability permits the exploration of many hypothetical scenarios in a given study, which would allow the development of new directions from existing theories. The above view was supported by Robert H. Hayes during his presentation at the 1988 Decision Sciences Institute National Meeting. Hayes asserted that the study of manufacturing strategy should move to a new stage in which transportable and practicable research tools are developed. Many have also argued that analytic tools should be developed to examine the interrelationships among the various components of manufacturing strategy (see also Kim 1989; Adam and Swamidass 1989). In fact, a too simplistic or static representation of a strategic problem such as technology acquisition may distort the analysis of its full impact on overall performance measures, such as ROI, market share, total production cost, etc., and cause the decision maker to reject the proposal. Due to the greater power of computing available with the advancement of personal computers, numerical solutions to the complex model of optimal control theory, such as the one used in this dissertation, can easily be attained.

In summary, the objective of this study is threefold. First, it examines the problem of technology acquisition, taking a broad-based view founded on the conceptual framework identified from the body of literature in manufacturing strategy. Second, this study employs realistic settings in the model that consider the trade-offs between two strategic priorities - flexibility and cost efficiency. Finally, the study develops a dynamic optimal control model to capture the strategic impact of the acquisition of new advanced technology on a SBU's performance in the long run. The purpose of the model is to

determine the strategic mix of automation capacity and degree of flexibility so that not only the SBU's strategic objectives but also its tactical and operational objectives are fulfilled.

1.2 RESEARCH ISSUES

Strategic justification for investment in new process technology is a complex problem. The investment in new process technology is related not only to capacity planning but also to a firm's competitive position in the market. The introduction of new process technologies, such as FMS, CIM, and Robots, is argued to promise great changes in the performance of manufacturing firms and even changes in industry structure (Jaikumar 1986; Hayes and Jaikumar 1988). In particular, many have asserted that investment in new equipment and technology is indispensable for improving the flexibility of a firm (Drucker 1971; Frohman 1982; Goldhar and Jelinek 1983; Hayes and Wheelwright 1984). Accordingly, this dissertation identifies and examines two key issues. The first is the relationship between the relative emphasis on *flexibility* and *cost efficiency* and the optimal acquisition of new process technology, given market conditions of product variety and demand growth along the product life cycle. The second issue is the effect of the optimal acquisition of new process technology on changes in the process technology choice within the product-technology matrix. This dissertation explores the strategic implications of these two issues in a dynamic environment.

1.2.1 Flexibility and Cost Efficiency of New Process Technology

Primarily, this dissertation examines the relationship between a firm's strategic priorities and the optimal acquisition of new process technology along the stages of the product life cycle (PLC). Based on the literature review, this dissertation identifies two major reasons for the lack of strategic perspectives in past analytic studies of the new

process technology investment. The first one is the improper definition of new process technology, and the second is the failure to address the dynamic interaction between technology investment and strategic competitiveness variables, such as degree of automation capacity, level of overall system flexibility, market conditions, and manufacturing cost structure.

Most past analytic studies for technology acquisition problems define process technology in units of output (Bustein 1986; Fine and Freund 1986; Gaimon 1985, 1986, 1989, and 1992; Roth et al. 1991). These studies fail to consider the strategic aspect of new process technology -- flexibility -- and thereby narrow their scope by disregarding the product variety aspect of market demand. In addition, the models in these studies usually have an objective function with a single criterion of cost performance. In this dissertation, however, new process technology is defined as the combination of automation capacity and flexibility. Automation capacity is defined as production capacity in units of output substituted for conventional old capacity (see Groover 1980). Also, flexibility is defined as the capability of the production system to produce a variety of products (parts). Hence, process technology of a manufacturing system is defined here in terms of both the automated capacity (degree of automation) and the level of flexibility (degree of flexibility). The acquisition of new technology, therefore, entails two separate decisions: the acquisition of automation capacity and the acquisition of flexibility. More significantly, this new definition of process technology allows the model here to consider the product variety aspect of market demand as an environmental variable.

Many argue that justifying new technology acquisition based solely on cost savings is incongruous with the surmounting trend of increasing the strategic importance of new technology (Meredith and Hill 1987; Hill 1989; see also Kaplan 1983). Some even assert that the introduction of new process technologies, such as FMS, CIM, or Robots, seems to promise great changes in the performance of manufacturing firms and even in industry structure (Jaikumar 1986; Hayes and Jaikumar 1988). In particular, many have asserted

that investment in new equipment and technology is indispensable for improving the flexibility of a firm (Drucker 1971; Frohman 1982; Goldhar and Jelinek 1983; Hayes and Wheelwright 1984). Accordingly, they argue that intangible benefits of new technology, such as improved flexibility, quality, and delivery dependability, should be considered in the evaluation process for the acquisition of new technology.

This dissertation maintains that the cost-benefit analysis for new technology acquisition should be linked to the strategic priority determined by the corporate strategy. By doing so, the technology acquisition decision can be made consistent with the objectives of the corporate strategy (Frohman 1982; Garrett 1986; Hayes and Wheelwright 1984; Skinner 1974). In this dissertation, the acquisition of automation capacity is assumed to create benefits such as savings in variable costs due to the elimination of direct labor (Hough 1989; Jaikumar 1986) and improved product volume flexibility due to increased production volume capacity. The acquisition of flexibility is also assumed to yield benefits of improved product mix flexibility. However, new technology acquisition accompanies enormous fixed costs of capital investment (see Miller 1985; Smith et al. 1986). Therefore, it can be conjectured that if a firm's strategic priority is cost efficiency, the firm would want to invest less in new process technology than a firm with a strategic priority of flexibility. Hence, the acquisition decisions for new technology have to consider the proper balance between the fixed investment costs of new technology and its long-term benefits in order to be consistent with the firm's choice between cost efficiency and flexibility as its strategic priority.

Accordingly, the model developed in this study considers both cost efficiency and flexibility in the objective function as two conflicting criteria measuring the long-term performance of a manufacturing firm's SBU. Specifically, the strategic priority of a firm is reflected by the values of cost coefficients assigned to measure flexibility in the objective function. Through the scenario analysis using the model, this study attempts to explore the effects of different strategic priorities on the optimal acquisition of new technology by

changing the values of those cost coefficients. In summary, this dissertation extends the analytic models of past studies by defining new process technology with two separate variables -- automation capacity and flexibility -- and attempts to identify the relationship between the relative emphasis placed on two competitive priorities -- cost efficiency and flexibility -- and the optimal acquisition of new process technology.

1.2.2 Acquisition of New Process Technology and Evolution of Technology Choice

According to the normative concept of the conventional product-process matrix theory (Hayes and Wheelwright 1979a), the best "fit" on the matrix is determined by identifying a technology choice which has the optimal operating characteristics for a particular market demand in volume and product (part) variety. One major drawback of this conventional matrix theory is the definition of technology choices identified along the vertical axis of the matrix. This drawback is due to the fact that both automation and flexibility are considered in a single dimension. This theory views each technology choice with a fixed setting, such as a highly flexible system with a low degree of automation (Job Shop) and, conversely, a highly automated system with a low degree of flexibility (Transfer Line). However, it does not consider process technologies with any combination of both flexibility and automation such as a highly automated system with a high degree of flexibility.

As Hayes and Wheelwright (1984) admitted, the product-process matrix is no longer congruous with the current trend of rapid diffusion of new process technologies which have the characteristic of high degrees of both automation and flexibility. Recognizing the inadequacy of the conventional product-process matrix, this study proposes a new matrix called a "Product-Technology Box" in which a technology choice is defined in terms of both the degree of automation along the horizontal axis and the degree of flexibility along the vertical axis. In this box, an additional third dimension is included to represent the dynamic environment of the product life cycle (PLC), reflecting

the changing market requirements in terms of both product volume and variety as does the horizontal axis of the product-process matrix.

This study also recognizes the recent findings of the "Reversal of the Traditional PLC" (The Reversed PLC), in which demand for both product volume and variety continue to increase after the growth stage without making a transition to the maturity stage (Abernathy et al. 1983; Ayres and Steger 1983). Accordingly, the third dimension of the new box can be defined by either the Normal PLC or the Reversed PLC. The premise linking a technology choice and a stage of the PLC in the new box is the same as in the conventional product-process matrix. The process technology choice determines both the manufacturing cost structure and the variety of either products or parts the production system can handle (Hayes and Wheelwright 1984; see also Hill 1989). Meanwhile, market demand for a particular combination of volume and product variety at a certain stage of the PLC requires the proper operating characteristics of process technology. Therefore, this dissertation posits that the best position for a technology choice in the new box is different, depending upon the type of the PLC.

The analysis in this study also considers the interaction between the firm's strategic emphasis on a particular competitive priority and the actual changes in the future market environment, such as aggregate market demand changes and the introduction of new products. For example, Firm A, whose strategic priority is flexibility, may purchase new process technology to improve flexibility. On the contrary, Firm B, whose strategic priority is low cost, may be reluctant to purchase new process technology unless savings from new investment is greater than the fixed investment cost. Since improved flexibility due to the acquisition of new process technology by Firm A may reduce the operating costs by the efficient use of materials, elimination of manual activities, and so forth, its overall cost performance may surpass Firm B's cost performance in the long run. However, the performance of these two firms may be affected by changes in the market environment such as demand volume changes and product mix changes. If future market

demand in volume grows quickly with little introduction of new products, it may not be appropriate for Firm A to assume a burden of excess investment costs for unnecessary flexibility. On the other hand, if the future market demand for product variety increases steadily, Firm A will enjoy the advantage of its flexibility while Firm B may lose its competitiveness in the long run.

In summary, using a dynamic optimal control model, this dissertation explores the difference in the evolution of technology choice under the different market environments encountered in two types of product life cycle. In addition, it explores how the technology choice evolves in the new product-technology box according to the interaction effect between changes in the firm's external market conditions and changes in its relative emphasis on two competitive priorities -- flexibility and cost efficiency.

1.3 RESEARCH QUESTIONS

Based on the issues discussed in the previous section, this section sets forth research questions for this study. According to the discussion in the previous section, the research questions are divided into two categories: (1) the acquisition policy for new technology and (2) the evolution of process choice. There are also subordinate research questions related to the major questions in each category.

1.3.1 Questions for The Acquisition of New Process Technology

The major question for the acquisition of new process technology is, "How do the optimal acquisition policies for the new technology of a firm differ according to the choice of its strategic priority?" Related questions include:

- a) Does a firm purchase more new technology when its strategic priority is flexibility compared to other priorities?
- b) In the long run, can a firm with a competitive priority of cost efficiency

achieve a lower cost performance compared to a firm placing primary emphasis on flexibility?

1.3.2 Questions for The Evolution of Technology Choice

1. One major question concerns how the evolution of process technology choice through the acquisition of new technology is affected by changing market conditions. For example, for a product life cycle characterized by a sustained growth stage and an increasing number of new products instead of the transition from a growth stage to a mature stage in the normal product life cycle, how does the evolution of technology choice relative to this new product life cycle differ from that of the traditional product life cycle?

2. Another major question is, "How do changes in market conditions interact with a firm's strategic (competitive) priority to affect decisions involving the evolution of process technology choice?" Related questions include:

a) For each of the two PLC types described in section 1.2.2, how does the evolution of technology choice differ due to different choices of strategic priority?

b) Which choice of strategic priority is most insensitive to changes in market conditions?

1.4 SUMMARY

In this chapter, the fundamental theme of this dissertation is described. In this dissertation, the problem of new process technology acquisition is evaluated analytically within the context of manufacturing strategy. Two critical issues are identified. First, this study explores the effect of a firm's relative emphasis on two competitive priorities -- flexibility and cost efficiency -- on the optimal acquisition policy for new process technology. Second, the study explores the interaction effect of strategic priority and

external market environmental changes on the evolution of process technology choice along the stages of PLC.

This study develops a dynamic based on the optimal control theory, which considers two conflicting objectives -- maximizing flexibility and minimizing cost efficiency. With factor settings identified in the body of literature, a scenario analysis is conducted to examine the research questions. The results are discussed to find possible extension of and new directions from the existing theories of manufacturing strategy.

CHAPTER II

LITERATURE REVIEW

This chapter reviews the current body of knowledge related to both manufacturing flexibility and new advanced process technology. The major purpose of the literature review is to identify the relevant issues to fill the gap between the current body of knowledge and the desired path of future researches in this field. It is also to identify the relevant variables and concepts built in the theories of manufacturing strategy to extend the researches of the past into a new direction. This chapter reviews the literature related to the research questions raised in Chapter I as well as the research methodologies for the acquisition of new advanced technology.

Section 2.1 reviews the past researches for the definition and the conceptual works of manufacturing flexibility. Through the review, it is possible to identify the definition as well as the measurement of manufacturing flexibility relevant to the research context of this study. Section 2.2 is devoted to review the past researches on the process technology and the product life cycle theory related to the manufacturing strategy. This section allows to identify the gap between the conventional normative consensus applicable to the old operating environment of manufacturing firms and the new perspectives of theory building under the current trend of the operating environment faced by today's manufacturing firms. The major contribution of the literature review in this section is to provide the theoretical background to develop the conceptual frameworks in Chapter III, as the main focus of this dissertation, which links the corporate strategy and the acquisition decision of new advanced technology.

Section 2.3 reviews the past researches for the manufacturing automation. Again,

it attempts to reveal the proper definition of new advanced technology based on the current body of knowledge. This section also provides contributions in developing the conceptual frameworks in Chapter III by identifying the interrelationships among the attributes of new advanced technology and the manufacturing firm's internal and external operating environment. At the end of this section, several analytical research approaches taken by the past studies are reviewed to help developing a new analytic model in Chapter IV based on the conceptual framework developed in Chapter III.

2.1 MANUFACTURING FLEXIBILITY

Flexibility is one of the key objectives of any manufacturing system (Chatterjee et al 1984). Hayes and Wheelwright (1984) also considers flexibility as one of the dimensions of the competitive strategy of a business along with price(cost), quality, and dependability. Some researchers contend that flexibility is the next battle ground in international industrial competition (DeMeyer et al. 1989; see also Stalk 1988). Baranson (1983) argues that the global view held by Japanese companies towards marketing and production explains why Japanese managers there take a long-term and comprehensive view towards capital investments that consider not only cost savings but more significantly the broader strategic implications of increased flexibility.

There are many different versions of the definition of manufacturing flexibility. The dimensions of manufacturing flexibility defined by numerous studies include such factors as volume, mix, machine, design, operation, process, and design. This section reviews the literature on flexibility to identify the proper measure of flexibility as the firm's performance. This section focuses on two key dimensions of manufacturing flexibility -- product mix flexibility and volume flexibility -- which have been regarded as major competitive priorities closely related to manufacturing flexibility at the strategic level.

2.1.1 Definition of Flexibility

Although there are many different versions of the definition of flexibility, the term "manufacturing flexibility" is not well understood (Kumar 1986; Swamidass 1988). The general issue of flexibility can be traced as far back as the early 1920s. In an economic context, flexibility was defined as "the risk arising from the immobility of invested resources" (Lavington 1921), "a relatively flat average cost curve" (Stigler 1939), and "the inverse relationship with the marginal cost" (Nelson 1962). Flexibility has also been examined in the Organizational Behavior literature, e.g., organizational flexibility (Feibleman and Friend, 1945), structural flexibility (Preece, 1986), or labor flexibility (Atkinson 1985).⁴

In the context of manufacturing, flexibility is defined as "the ability to respond effectively to a wide range of possible environments" (Gerwin 1987; Sethi and Sethi 1990; Slack 1983; Zelenovic 1982). Some define it in terms of resource capability, some in terms of constraints on manufacturing environment, and others in terms of both internal and external environmental uncertainties. In view of capability, Sethi et al. (1990) defines manufacturing flexibility as the "ability to reconfigure manufacturing resources so as to produce efficiently different products of acceptable quality." Jaikumar (1984) asserts that manufacturing flexibility should be constrained within a domain defined by the portfolio of products, process, and procedures and the domain should be planned, managed, and with learning expanded. With regard to environmental uncertainties, Garrett (1986) suggests that manufacturing flexibility is required in order for a firm to cope with both internal changes and external forces. The internal disturbances for which flexibility is useful include equipment breakdown, variable task times, queuing delays, rejects, and rework (Buzacott and Mandelbaum 1985). External forces refer largely to the fundamental uncertainties of the competitive environment (Behrbohm 1985; Zelenovic 1982; Garrett 1986; Maier 1982).

⁴ For the details of these definitions, see Sethi and Sethi (1990).

Kim (1989) defines manufacturing flexibility at three different levels, strategic, tactical, and operational. According to his typology, manufacturing flexibility at the strategic level reflects environmental uncertainties (see also Kamarkar and Kekre 1980; Zelenovic 1982; Slack 1983). At the tactical level, manufacturing flexibility is recognized as a concept conflicting with efficiency (see also DeMeyer et al. 1989). Here, manufacturing flexibility is viewed in terms of trade-offs between economies of scale and economies of scope (see also Cohen and Lee 1985; Goldhar and Jelinek 1983). Kim points out that both product mix and volume flexibility are identified as two competitive priorities closely related with manufacturing flexibility in both the strategic and the tactical levels. Kim argues that these two flexibilities well reflect the strategic priorities imposed by a firm's external environments (see also Swamidass 1986). Two of the main external uncertainties faced by manufacturing firms will be the demand changes and the introduction of new products in the market. Accordingly, Kim asserts that the response to these uncertainties is properly captured by the definition of these two flexibilities. Finally, at the operational level, manufacturing flexibility is recognized as operational capabilities provided by a particular process technology (see also Browne et al. 1984).

According to the literature, the definitions of manufacturing flexibility in the strategic context usually imply "responsiveness to uncertainties." Sethi and Sethi (1990) states "The probabilistic nature of these uncertainties may not always be known. Uncertainties may exist for level of demand, product prices, product mix, and availability of resources. Uncertainties may arise out of actions of competitors, changing consumer preferences, technological innovations, new regulations, etc." Hence, manufacturing flexibility has major implications for a firm's competitive strength, and this significant role of manufacturing flexibility makes it a part of the firm's strategy. In this regard, by recognizing demand changes and the variety of new products as two major external uncertainties, this dissertation includes both product mix flexibility and volume flexibility as key competitive priorities of a manufacturing firm in coping with these uncertainties.

2.1.2 Manufacturing Flexibility and Its Strategic Implications

As stated above, there are many dimensions of flexibility identified in the literature. Even the definition for each dimension of flexibility differs among authors. This section traces the proper definitions of product volume and mix flexibilities for the study in this dissertation. Furthermore, manufacturing flexibility entails not only the direct benefits of quick and economic response to environmental uncertainties but also other indirect benefits that might be overlooked. Thus, this section explores the strategic implications of flexibility for a firm's competitiveness in the long run.

2.1.2.1 Definition of Product Mix Flexibility and Volume Flexibility

In this dissertation the main theme is characterized as the strategic analysis of process technology. Accordingly, product mix and volume flexibilities will be defined in the context of manufacturing strategy. In the literature of manufacturing strategy these two flexibilities have been frequently referred as primary types of flexibility at the strategic level (Cox 1989; Kim 1989; Schonberger 1986; Skinner 1974).

Product mix flexibility is "*the ability to respond inexpensively and rapidly to additional or substituted products*" (see also Gupta, et al. 1989). Sethi and Sethi (1990) defines product mix flexibility as the ease with which new parts can be added or substituted for existing parts. This definition is very similar to the definition of product flexibility of Browne et al. (1984), part flexibility of Gerwin (1982) and Falkner (1986), and design adequacy of Zelenovic (1982). According to these definitions, product mix flexibility is referred as "*the capability of process technology to respond to part changes or part addition*." It is important to note that in Lim's survey of FMSs in the United Kingdom (1987), 11 out of 12 reporting companies considered manufacturing flexibility to mean product mix flexibility.

Product volume flexibility is defined as "*the ability to operate profitably at*



different overall output levels" (Gupta, et al 1989, Sethi, et al. 1990). Similar definitions can be found in other studies (Browne et al. 1984; Gerwin 1982; Maier 1982; Kegg 1984). This definition is also similar to the definition of demand flexibility by Son and Park (1987). According to Slack (1987), volume flexibility has two aspects: speed of response and range of variations. He suggests that the former is useful in the short term while the latter is useful in the long run.

Buzacott (1982) defines flexibility with some strategic flavor. He separates flexibility into job and machine flexibility considering the nature of the change and disturbances that the system should be able to cope with. *Job flexibility* is defined as "the ability of the system to cope with external changes such as the type, mix, processing requirements, and quantity of jobs allocated to the system," while *machine flexibility* is related to the internal changes such as machine breakdowns, variability in processing times, and quality problems. According to his definition, both *product volume flexibility* and *product mix flexibility* reflect his definition of job flexibility.

2.1.2.2 Strategic Value of Manufacturing Flexibility

According to a recent research, conducted by The Manufacturing Roundtable of Boston University (Miller and Roth 1988), flexibility was ranked from fourth to eighth in importance for future competitiveness, and first in the size of strategic gap (i.e., the difference between current capability and future needs). However, flexibility did not appear at all in a list of 10 key performance measurements offered by the responding executives. The authors give two primary reasons for this discrepancy. First, in contrast to cost, delivery, and quality, which have been the cornerstones of manufacturing planning and control for many years, the idea of flexibility as a top priority has only recently come to the fore. Consequently, it tends to be treated, even on a conceptual level, less often and usually on a somewhat abstract as opposed to concrete basis. Second, and partly because of the first, the technology for measuring flexibility is poorly developed (see also Cox

1989).

On the contrary, Baranson (1983) argues that the global view held by Japanese firms towards marketing and production explains why Japanese managers take a long-term and comprehensive view towards capital investments considering not only cost savings in labor, material, and space, but more significantly the broader strategic implications of increased flexibility and versatility in designing and producing of products (see also De Myer et al. 1989). Empirical evidence also supports the view that flexibility does not get its proper due at the time of decision making with regard to investment in manufacturing technology (Lim 1987). Hence, it is critical for the evaluation of technology investment to consider the long term strategic implications of enhanced flexibility due to the acquisition of new technology.

The current trend of market and industry structure is being shaped by the adaptation of new advanced manufacturing technologies, rapid-response systems to environmental uncertainties and complexity, expanding variety and increasing innovation. The competitive values of manufacturing flexibility lie in its ability to neutralize the effects of demand uncertainties (Swamidass 1986; Swamidass and Newell 1987), to increase market share through the proliferation of new products, and to achieve low cost production with the economies of scope (Hill 1988). Stalk (1988) asserts that companies adopting strategies based on flexible manufacturing are reducing if not eliminating delays and using their response advantages to attract the most profitable customers. By characterizing the flexible firm as a time-based competitor, Stalk further asserts that the flexible firm achieves lead time reduction with small lot size and, hence, enjoys big advantages in both productivity and time: labor productivity in time-based factories can be as much as 200 percent higher than in conventional plants; time-based factories can respond eight to ten times faster than traditional factories. For example, Toyota had its suppliers reduce production lead time from 6 days to 1 day by reducing lot sizes and the number of inventory holding points (Stalk 1988).

In particular, a firm with high product mix flexibility can simultaneously pursue both a differentiation and a low cost strategy (Hill 1988). High product mix flexibility can allow the firm to introduce more products to the market than can its competitors. In the long run this will increase the brand loyalty of its customers and, consequently, increase the demand (see Roth et al. 1991). Hence, the firm can achieve the objective of the low cost strategy due to the economies of scale with the increased demand. An empirical study by White (1986) shows a significant and positive relationship between differentiation and low cost (see also Phillips et al. 1983). White found that 19 of 69 business units had a competitive advantage based on a combination of both differentiation and low cost. Moreover, his result suggests that business units that successfully combined both low cost and differentiation had the highest return on investment.

The strategic values of both product volume flexibility and mix flexibility referred in the literature can be summarized as follows: first, the ability to neutralize the demand uncertainties; second, lead time reduction; third, low cost production; finally, increased market share. The latter two values explain how firms can pursue both a differentiation strategy and a low cost strategy simultaneously.

2.1.3 Measurement of Manufacturing Flexibility

Since the survival of manufacturing firms will depend on their ability to adapt to rapid change in the market and industry, flexibility plays a key role not only as a strategic goal but also as one of the important means for performance measurement (Gupta and Goyal 1989) reflecting the changing source of competition (Stalk 1988). However, since flexibility, as Slack (1983) points out, is an indication of potential it is difficult to measure (see also Son and Park 1987). This is why there are so many different definitions of flexibility. Before defining the measurement of flexibility it is important to identify the key elements that constitute it. Another important aspect of measurement is how to measure the manufacturing system's overall flexibility as a performance in the dynamic production

environment.

There are two major elements in measuring manufacturing flexibility identified in the literature, *time* and *cost*. Gupta and Goyal (1989) states that manufacturing flexibility has been measured by cost, delivery speed, or lead time (see also Cox 1989). Particularly, product mix flexibility can be measured by time or cost required to switch from one part to another, not necessarily of the same part types (Browne et al. 1984; Buzacott 1982; Zelenovic 1982). Son and Park (1987) suggests a measurement of product mix flexibility as the ratio of the physical output of the system to the setup cost of the equipment, viewing the reduction in setup costs as the way to increase product mix flexibility.

As a generalized measure developed from the definition of *product volume flexibility* of Browne et al. (1984), Gupta and Goyal (1989) suggests "*the range of volumes in which the firm can run profitably.*" Gerwin (1987) measures it by "*the ratio of average volume fluctuations over a given period of time to the production capacity limit.*" Falkner (1986) suggests, as a measure of volume flexibility, "*the stability of manufacturing costs over widely varying levels of total production volume.*" Son and Park (1987) suggest measuring it with "*the ratio of the physical output to the inventory cost of finished product and raw material,*" indicating the difference between supply and demand, that is, response to internal and external demand.

Although a single comprehensive measure of manufacturing flexibility takes into account its direct benefits such as quick and economic response, it should be carefully designed with a broad perspective since the benefits of flexibility are also reflected indirectly by the improvement in other performances, such as inventory cost reduction or improved market position. In the past literature, there are few examples of using a single quantified measure of manufacturing flexibility in researches on manufacturing strategy. Nagarur (1992) presents a simple approach to measuring the flexibility of FMS. He introduces an index, which is called "producibility," which measure the reroutability of any excess load of a machine center to other centers. This flexibility index may be useful in

measuring the overall operational flexibility of production system. A recent study by Ramasesh et al. (1992) employs the ratio of the net revenue generated by the system to the standard deviation of the net revenue distribution as a measure of aggregate flexibility. In their mixed integer stochastic program, the objective function generates optimal production levels for a set of products to maximize the net revenue considering costs associated with product mix and product volume flexibilities. Beside some conceptual drawbacks of this particular model, it is hard to expect that the solution of the model may guide any significant strategic implications, rather it may be suitable for a comparison purpose for different systems under a static environment.

Relevant to the study of this dissertation, Gupta and Goyal (1989) suggests that a single measure for manufacturing flexibility should be concomitant with a given manufacturing strategy. Then, the manufacturing system could be designed and modified accordingly. Importantly, it is necessary to develop a measure of overall manufacturing flexibility under a specific production setting of process technology and production control system, considering the economic consequences of future environmental changes (see Buzacott 1982). As Gupta and Goyal (1989) asserts that flexibility is not a self-contained concept, it may be necessary to relate manufacturing flexibility as a performance measure to the other production objectives related to manufacturing cost and time such as operating cost and lead time. Hence, Gupta and Goyal imply that the system's flexibility will be reflected in the long term performance measured in both operating cost and lead time through constant changes in process technology and control system according to the environmental changes.

2.1.4 Trade-off between Flexibility and Efficiency

The conflict between flexibility and cost efficiency primarily account for by the high initial investment of new technology which enhance flexibility. For example, a numerical controlled turning center costs \$300,000 to \$400,000, whereas an FMS

installation can balloon to \$25 million (Bobrowski and Mabert 1988). For this reason, flexibility and cost efficiency have been considered as conflicting objectives (De Meyer et al. 1989). By defining flexibility with two conflicting factors, "Quick Response to Change" and "Economic Response to Change," Chung and Chen (1989) conceptualize flexibility as the compromise between these two factors. They provide a simple formula for conceptualizing a framework for flexibility evaluation,

$$\text{The Total System Flexibility} = \alpha Q + (1 - \alpha)E,$$

with α for a weight, Q for a factor of the quickness, and E for a factor of the economic response.

However, as discussed before, a firm with high flexibility may pursue successfully both differentiation and low cost strategies simultaneously. In particular, a firm with high product mix flexibility can introduce more new products into the market than can its competitors and, consequently, enjoy the economies of scale through the increased market share (Hill 1988). Hill (1988) suggests that, if the cost reduction due to the increased market share outweighs the increase in the cost related to product variety, the firm can pursue successfully both differentiation and low cost strategies at the same time. In fact, some empirical studies (Newell and Swamidass 1987; Meyer et al. 1989; Phillips, et al. 1983; White 1986) provide evidence that there is a positive relationship between MF and other manufacturing performance measures such as cost reduction and/or quality improvement.

In summary, the cost implication of manufacturing flexibility entails two aspects. On one side, flexibility will increase the cost due to the huge initial capital investment and the potential increase in variety of products. On the other side, however, flexibility will reduce the cost due to the efficient use of labor and materials and the increased market share resulting from a firm's enhanced competitive position in the market. Hence, in developing a model for the study of flexibility it is important to consider not only the fixed investment cost in improving flexibility but also the other benefits related to cost reduction

due to the improvement in flexibility.

2.1.5 Summary and Implications

It seems that the flexibility of advanced process technologies can become easily submerged in technical requirements, thereby disregarding a holistic view (Sethi, et al. 1990). This view is consistent with the result of an empirical study by Slack (1987) in which the managers are found to focus more on flexibility of individual resources than on the flexibility of the production system as a whole. It is also found from the literature that manufacturing flexibility has a significant long-term strategic impact by enhancing a firm's competitive position in the market. However, the literature concerning manufacturing flexibility needs empirical studies with raw data from industries to identify the functional relationships among the means of achieving manufacturing flexibility such as investment in new process technologies and manufacturing parameters such as lead time, fixed and variable costs. These studies are indispensable as research background to aid the conceptual and theoretical studies in analyzing the strategic implications of investment in new process technologies on the firm's competitive position in the market.

In summary, the implication for this dissertation can be summarized in three major points. First, both *product mix flexibility* and *product volume flexibility*, as performance measures for the analysis of strategic issues, are found properly related to and should reflect the contingencies of the corporate strategy. Second, manufacturing flexibility is found to have a significant impact on a firm's market position with potential market share growth and the cost structure of the firm's production system. Finally, it is also found that the variables related to both manufacturing *time* and *cost* representing the long-term effects of flexibility should be used for strategic evaluation of manufacturing flexibility.

2.2 PROCESS TECHNOLOGY AND PRODUCT LIFE CYCLE

The first part of this section will be devoted to exploring the literature related to process technology. The purpose of the review is to find, first, how the past studies categorize different process technologies as defined in the product and process matrix theory (Hayes and Wheelwright 1984) and, second, how this categorization scheme can be applied as a theory of manufacturing strategy in the emergence of new advanced process technologies. The current trend of the international market, characterized by a great variety of custom-made products, shorter or truncated product life cycle, and the expectation of higher standard by customers, is quite different from the conditions in the past, which the theory has been constructed from and applied to. Furthermore, the greater emphasis on flexibility in every aspect of manufacturing process also steers the strategic priority from cost efficiency to flexibility. With the notion of these changing market trends and strategic perspectives, it would be necessary to revisit and reevaluate the conventional theory of manufacturing strategy.

2.2.1 Process Technology in Manufacturing Strategy

Technological change is not important for its own sake, but it is important if it affects competitive advantage and changes industry structure as asserted by Porter (1980). It plays a key role in linking the manufacturing capabilities which it embodies and marketing requirements and, consequently, it determine the company's competitive position in the market. Simmonds (1981) also states, while pointing out the drawbacks of the conventional accounting approach of investment appraisal, that new production investment must imply a change in competitive position and it is this change that should be the focus of the investment review.

2.2.1.1 Characteristics of Process Technology

There are many studies related to the definition of process technology (Buffa 1984; Hayes and Wheelwright 1984; Hill 1989). Buffa (1984) identified four different process technologies as physical systems in positioning strategy -- a product-focused system for high volume, a product-focused system for multiple products in moderate volume, a process-focused system for moderate to low volume, and a process-focused system for custom products. The definition of these processes is not much different from the conventional definition of job shop, batch, line, and continuous processes (Hayes and Wheelwright 1979a). The distinction among these four process technology has been made by the difference in two key aspects -- degree of flexibility and level of investment in hard automation. Buffa explains the rationale for the investment in hard automation as a mean of achieving low cost objectives with high volume products. Buffa also relates flexibility to the product mix to distinguish those four systems. Hence, Buffa identifies flexibility and automation as key dimensions of process technology.

Table 2.1. Characteristics of Process Choice

Process Choice	Process flexibility	Automation	Overhead cost	Direct labor	Direct Material
Job Shop	High	Flexible	Low	High	Low
Batch					
Assembly					
Continuous	Low	Hard	High	Low	High

Source: Buffa (1984) and Hill (1989)

A detailed description of the characteristics of these process choices is provided by Hill (1989). In Table 2.1, an anecdotal summary is presented for some of key characteristics of process choices extracted from two studies (Buffa 1984, Hill 1989).

These studies are related to the study of this dissertation. As shown in Table 2.1, compared to continuous process, job shop process has higher process flexibility. In general, job shop process employs flexible technology, whereas continuous process employs hard automation to lower the variable production cost. In terms of cost structure, job shop tends to have a relatively low fixed cost compared to high variable cost, whereas continuous process tends to have high fixed cost compared to low variable cost. The different cost structures of the four process types are mainly due to the natures of the process technologies they adopt. Hill (1989) maintains that job shop process involves the high content of direct labor, thus making it the highest portion of total costs. On the contrary, due to the high process investment, direct labor costs for continuous process are small and its site/plant overheads are high owing to the need to support the process and handle the high output levels involved. However, an empirical study by Raffi and Swamidass (1987) shows that the ratio of manufacturing overhead costs (MOHC)⁵ to total manufacturing cost is not significantly different among process choices. There are not many studies dealing with the process choices in the past. Nevertheless, it is generally found that the process choices are usually characterized through the relative comparison in terms of cost and flexibility (Buffa 1984; Hayes and Wheelwright 1979a; Hill 1989; Raffi and Swamidass 1987).

2.2.1.2 Process Technology in Capacity Planning

One of the critical issues in the studies of the acquisition of new technology is *the pattern of change*, frequently called as *timing* -- gradual transition, *incremental*, from old to new technology, or upheaval, *radical*, of old technology. Yet, there is no clear-cut conclusion on this issue drawn from the literature. Gaimon(1985) in a study of the

⁵ The major component of MOHCs include, indirect supplies, indirect labor, supervisory salaries, social security taxes, pension payment, health care costs, overtime premiums, idle time costs, vacation pay, depreciation, property taxes, property insurance, repairs and maintenance, power costs, and material handling.

optimal acquisition of automation supports the incremental changes of technology. Gaimon used this view as an assumption in developing her model in the study of the optimal acquisition of automation (see also Roth et al. 1991). On the contrary, Vickson(1985) found in his study that the optimal transition from old to new technology has to be instantaneous. He drew his view from the conclusion in the study of the investment choice between two production technologies. Unfortunately, this conclusion is almost predictable from one of the constraints in his model.

Skinner (1974) also points out that the incremental change in production system and organization structure as one of the major factors causing confusion and inconsistency in making strategic decisions and leading to poor performance. Since both Vickson's and Gaimon's models are too simple, missing the dynamic relationships among many important aspects of manufacturing system, it may not be appropriate to draw any conclusion from their studies. Even though Skinner's assertion is based on broader perspective than Vickson's, it does not reveal the details of strategic implication of investment timing in the process of manufacturing strategy formulation.

The other critical issue is related to the evaluation criteria of technology investment. As Hill(1989) points out, the excessive use of ROI distorts strategy building (see also Madu and Georgantzas 1991). He suggests that only when a company reviews investment in light of its corporate strategy, marketing strategy, and manufacturing strategy, the essential cohesion will be established. Until this happens, the company will be in danger of investing in ways that will not give the necessary synergetic gains of strategic coherence. Hence, the evaluation criteria for technology investment should be concomitant with the congruent objectives of those strategies. Particularly, evaluation criteria should be associated with the firm's competitive priority based on the forecast of the contingencies of the firm's operating environment.

2.2.1.3 Process Technology in Manufacturing Strategy

Good process technology strategy can be characterized by *fit* or consistency, which ensures that the firm's process technology evolves in a directed fashion, so that as technological capabilities are renewed and augmented, they reinforce and expand the firm's competitive position (Hayes and Wheelwright, 1984). This *fit* can be understood by identifying general capabilities of process technology not only with existing products but also with new products to be introduced and the changes to the existing products in the dynamic environment. (Hayes and Wheelwright, 1984). Hence, the analysis of process choice for a firm should be carried out with the understanding of the dynamic changes of the firm's internal and external operating environment.

As discussed in the previous section, another important observation in past studies of the evaluation of process technology is criticism of the use of a single performance criterion (Kaplan 1983; Simmonds 1981). Many of those earlier studies analyze their problems with a single criterion of cost minimization or profit maximization by including variables defined with narrow and abstract perspectives.⁶ As a result, most of these studies fail to characterize adequately the nature of different process choices that are frequently referred in manufacturing strategy literature and, consequently, fail to address the relevant strategic issues related to the acquisition of new advanced process technology.

In particular, more researches is called for in the area of identifying key strategic variables affected by the adaptation of new advanced technology. An effort by Ettlie et al. (1984) shows empirical results identifying the organizational causality of two different innovation processes, radical and incremental. What is needed for the strategic evaluation of new advanced technology is empirical study such as this to identify the critical organizational factors in the causal relationships between decision variables related to the acquisition of new advanced technology -- timing and size -- and a firm's overall

⁶ The detailed review of these studies will be presented later in section 2.3.3.

performance including not only the strategic but the operational.

2.2.2 Product Life Cycle in Manufacturing Strategy

2.2.2.1 Product Volume and Product Mix in the Product Life Cycle

Key elements of the conventional product life cycle relevant in manufacturing strategy are product volume and product mix. Four distinguished stages -- introduction, growth, maturity, and decline -- are characterized by the different ranges of product volume and product mix. Hayes and Wheelwright (1984) summarize the framework of Wasson (1978) with four dimensions that are directly linked to manufacturing: production volume, product variety, industry structure, and the dominant form of competition. They suggest that

while the product life cycle is usually primarily in planning a firm's marketing strategy, it also has great implication to the firm's manufacturing strategy. For example, manufacturing has a major stake in decisions that may affect such variables as product customization (versus standardization), volume per model, and the average time before obsolescence or replacement. Given this perspective, the product life cycle can be used to summarize the customer and product requirements that must be satisfied by the manufacturing function and its production technology.

They also assert that, by identifying the relevant range of product volume and variety for each stage of the *product life cycle*, the stage can be matched to the corresponding stage of the *process life cycle* according to the capability the production system can provide. As a result, they developed the famous "product-process matrix." Hill (1984), in his conceptual framework called "product profiling," also related the relevant range of volume and variety to process choice as one of the many operational aspects as a best fit between the marketing strategy and the manufacturing strategy. Even though the concept of the PLC theory has been well accepted in the area of POM until now, the concept of the traditional product life cycle has been challenged by some researchers in marketing area (Ayres et al. 1983; Dhalla et al 1976). Particularly, Ayres and Steger (1983) asserts that, with the rapid evolution of technology, the product life

cycle can be reversed.

2.2.2.2 Manufacturing Cost in PLC

Stalk (1988) suggests that manufacturing costs fall into two categories: those that respond to volume or scale and those that are driven by variety. He reports that scale-related costs decline as volume increases; usually falling 15 percent to 25 percent per unit each time volume doubles. Variety-related costs, on the other hand, reflect the costs of complexity in manufacturing: setup, material handling, inventory, and many of the overhead costs of a factory. In most cases, as variety increases, costs increase, usually at a rate of 20 percent to 35 percent per unit each time variety doubles. Stalk suggests that the optimum cost point for factories can be decided by the combination of volume and variety (see figure 2.1).

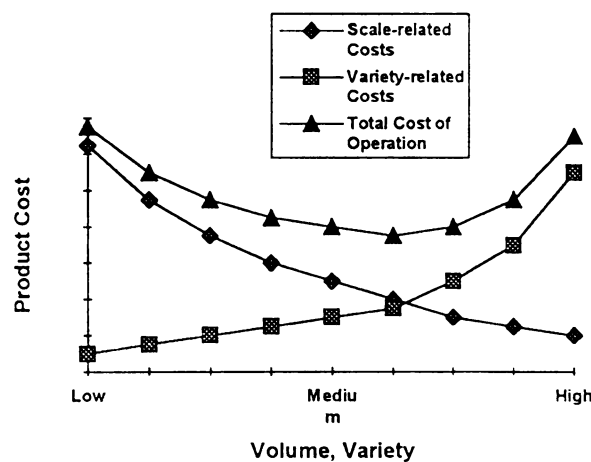


Figure 2.1 Variety-Related Costs and Scale-Related Costs

An empirical study of metalworking industries by Ayres and Miller (1981) shows evidence that the unit production costs increases as the batch size increases. The study

estimates that the unit costs are about ten times higher for custom production in a job shop environment than they are for mass-production operations. It also estimates that the unit costs in the intermediate batch processes range from three to five times higher per pound of material processed than in the most extreme mass production case.

2.2.2.3 Reversal of PLC

In contrast to the traditional product life cycle concept, Ayres and Steger(1983) suggest the reversibility of the biological evolution of the product life cycle. They argue that a "product" may not move through the cycle from birth to death in one direction only and there are a number of historical examples of reversals in the sequence, attributable to technological changes that altered the product significantly but did not replace it. Ayres and Steger also suggest three conditions for the reversal of the product life cycle are potential for accelerated technological change, management flexibility, and manufacturing flexibility. The authors also argue that the evolution process can be accelerated or decelerated depending upon a firm's competitive advantage. If a firm is competent in mass production, it will be beneficial to accelerate the product standardization and maturity. On the contrary, if a firm has competence in technological flexibility, then it will be safe to adopt the deceleration strategy (see also Tombak 1988).

Abernathy, et al. (1983) call this reversal of the life cycle "dematurity" in their framework of the product life cycle. They argue that major technology changes can throw an industry back into a growth stage. After close examination of the US auto industry, the authors found that the auto industry served as a prime example of this process of "dematuration." The immature standardization efforts by the firms lock them into the stage of "rigidity," in which they will ultimately lose their competitiveness in the face of rapid evolution of technology. The "dematuration" process will deter the usual process of product standardization from capturing the advantage of the economies of scale. Rather, it will proliferate the introduction of new products in the market and make the corporate

managers rethink their competitive strategies.

Another interesting empirical study by Dhalla and Yuspeh (1976) suggests that the universal application of the PLC concept may be misleading. They found that, while it is difficult to reverse the trend for the products in a final declining stage, no firm brand behavior can be found with the first three stages of the PLC. The authors give a list of examples that had been for a long time but were still full of vitality and whose sales went up and down but stayed in the growth phase.

These anecdotal and empirical evidences suggest that the evolution of the product life cycle is not given as conventional PLC theory. Instead, the product volume and mix are truly the strategic variables whose behaviors are unpredictable. One interesting inference from the literature is the difference in the width of product variety between the growth stage of the reversed life cycle and that of the usual life cycle. The width of product variety in the growth stage of the reversed life cycle will be much greater than that of the usual life cycle. Hence, as the reversal of the product life cycle will generate more uncertainty into the game of competition a firm must recognize the importance of flexibility in enhancing its strategic competitiveness in the market. Potential reversals will occur with substantial benefits to those who carefully prepare through decisions regarding technology and management planning in a broad strategic fashion.

2.2.3 Integration of Product and Process Decisions

2.2.3.1 Product-Process Matrix

Integration of the product life cycle and the process life cycle has been best described by "fit" (Hayes and Wheelwright 1984) or "alignment" (Pearson et al 1991) based on the market requirements imposed by a stage in the product life cycle and its corresponding process capabilities to generate the optimal performance in meeting those requirements (Pearson et al 1991). Empirical studies (Abernathy 1978b; Hambrick et al.

1982a and b; Shipper 1981) have found that the production process life cycle begins with a fluid, uncoordinated configuration and evolves first into a segmented and finally into a specific, systematic configuration. This transition of the process life cycle corresponds to the evolution from job shop, to batch, to assembly line, and finally to continuous flow production. A conceptual framework to match properly the evolution of the process life cycle by the evolution of the product life cycle is the product and process matrix (Hayes and Wheelwright 1979a and b) as depicted in Figure 2.2.⁷

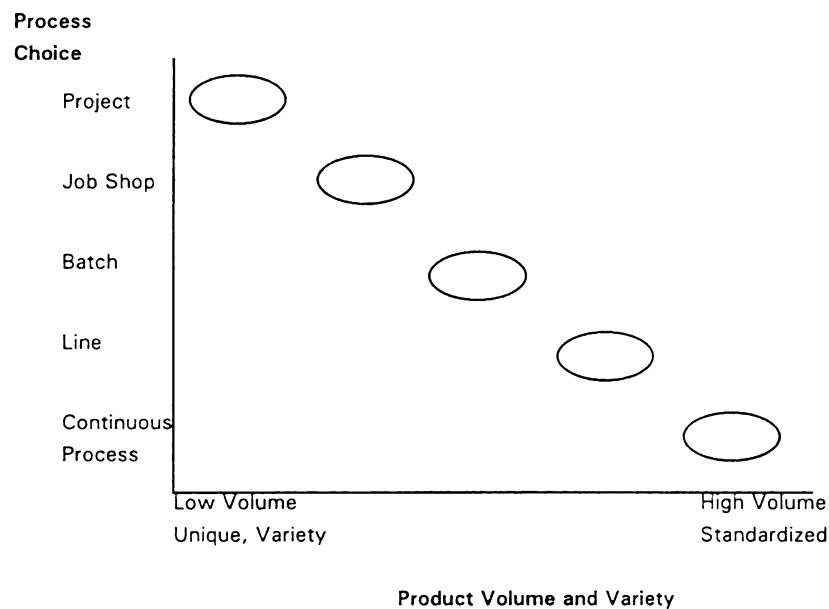


Figure 2.2. Product and Process Matrix

Hill (1989) presented almost the same integration scheme with a different approach, which is called "Product Profiling." He identifies important elements of both marketing strategy and manufacturing capabilities and characterized the process choices according to those elements. The process capabilities are matched with the market requirements prescribed by the business chosen, mainly product range and volume. In this

⁷

For detailed reasonings for the match, refer to Hayes and Wheelwright [1989].

respect, this method is based on the conceptual framework of the product-process matrix. However, he attempts to extend the product and process matrix by linking market requirements and process capabilities through a concept called "order winning criteria," which is similar to the concept of competitive priority. He also asserts that the transition described in the product-process matrix does not appear as a linear sequence (Hill 1989).

Firms may follow an iterative, repetitive course, jumping forwards and backwards at different times according to their perceptions of market demands in the future and the corresponding process design issues (Pearson et al 1991). For example, a firm will have a job shop type of manufacturing process for one of its products. As volume increases a transition to a batch type of process may occur. When volume decreases, towards the end of the product life-cycle, the transition back to job-shop may take place (Hill 1989).

According to Hill's argument and those supporting the reversal of PLC, the process choice may be very much dependent on the future market situation projected by the firm. Based on past studies, it can be presumed that there may be two types of the evolution of process technology. First, given the usual evolution of a product's life cycle as being true and the theory of the product-process matrix as being accepted, the firm's process technology will cycle with the transition from the flexible system, to the dedicated and inflexible system, back to the flexible system, and so on. Second, if the product life cycle stays in the growth stage by the reintroduction or design updates of the product (Smith 1980; Ayres and Steger 1983), the firm may always focus its investment more on the flexible manufacturing technology instead of blindly switching to the dedicated system. According to the current trend of market conditions and technology development, the former is not as persuasive as the latter. Thus, the investment in process technology should be carefully planned according to the dynamic changes of the market requirements in the future.

2.2.3.2 Effect of Flexible Technology on Product-Process Matrix

The recent development of flexible technology allows firms to produce a wider range of product variety and volume at the same or lower cost than does conventional technology (Goldhar and Jelinek 1983; Jelinek and Goldhar 1984; see also Suresh and Meredith 1985). Hence, flexible automation has challenged the managerial wisdom of the past decades that was captive to in the paradigm of product-process matrix theory (Adler 1988). It seems that the matrix's normative implication is no longer applicable to any process choice with the higher level of flexible automation.

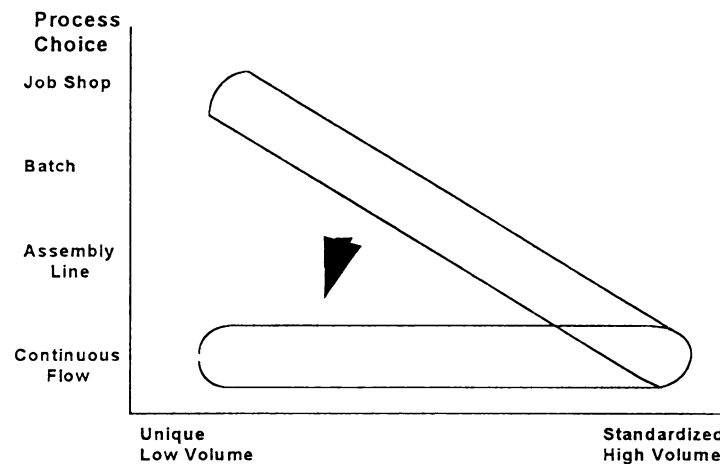


Figure 2.3. Effect of Flexible Automation on the Product-Process Matrix

In a dynamic perspective, it is necessary to consider the implications of recent flexible automation, which make it possible to view the production of less standardized products in a "quasi-continuous process" (Adler 1988). Hence, a new matrix's diagonal would be flattened out, as in Figure 2.3 (Boothroyd 1982; see Hayes and Wheelwright 1984). In fact, Hayes and Wheelwright (1984) discussed the impact of flexible technology as one of the limitations for the application of the matrix. They states that "such improvements in production flexibility, without movement along the diagonal, might be thought of as a third dimension to the matrix." Hence, if we separate this new dimension

from their product-process matrix, it will be possible to draw a new matrix as shown in Figure 2.4. In this new matrix, the vertical axis represents the degree of flexibility of the new process technology instead of the conventional category of process choice. Figure 2.4 depicts the wide range of variety and volume covered by flexible technology, whereas rigid technology covers only standardized and high volume products.

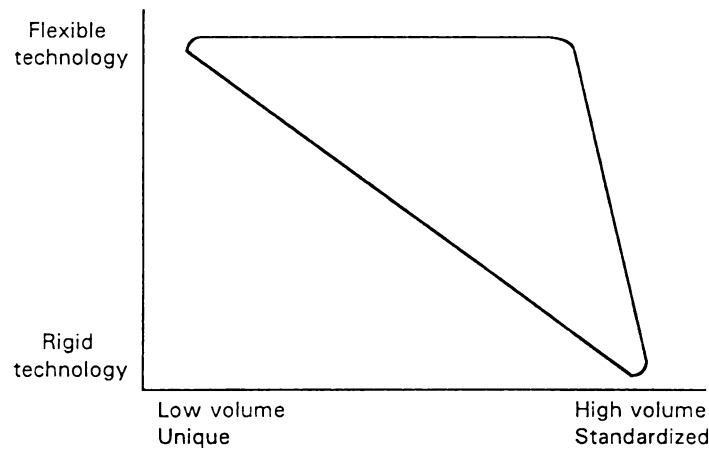


Figure 2.4. Integration of Technology and PLC

One of the major implications of such a revision is the undermining of a widely felt "intuition of a corollary between efficiency and rigidity" (Adler 1988). It can denounce the proposition, as suggested in an empirical study by Abernathy (1978b), that there is a fundamental dilemma between innovation and efficiency. The capability to produce a wide variety of products at low cost is a major advantage of flexible technology. Hence, as discussed in section 2.1.4, the most significant implication of the introduction of flexible technology like FMS, CIM, and CAM is the coexistence of differentiation and low cost as a firm's strategic focus.

2.2.4 Summary and Implications

According to the review of literature, the potential paths for the market/product

evolution may not be given as the main propositions of the PLC theory. As shown in Figure 2.5, there may be four possible states of the market/product requirements a firm at any stage of the PLC may encounter in the future. Each of these four possible states may be reflected by a firm's overall competitive strategy as a combination between differentiation and cost leadership (Porter 1980). Hence, in this dissertation, the four states given in Figure 2.5 will be distinguished by two exogenous variables -- volume and variety. Another finding by the literature review in this section is the possible coexistence of differentiation and low cost strategies, which means the simultaneous pursuit of both *economies of scope* and *economies of scale* by the adaptation of flexible process technology.

In this dissertation, flexibility and cost efficiency are chosen as competitive priorities representing differentiation strategy and cost leadership strategy, respectively. Through the scenario analysis with a dynamic control model, the study will attempt to find which strategy is suitable for each of the four possible states in Figure 2.5. The study will also explore whether the coexistence of differentiation strategy and cost leadership strategy is possible and under what condition it is possible.

	Volume Increasing	Volume Decreasing
Variety Increasing	A	B
Variety Decreasing	C	D

Figure 2.5. Four Stages of the Possible Evolution of the PLC

2.3 NEW PROCESS TECHNOLOGY AND MANUFACTURING FLEXIBILITY

2.3.1 New Process Technology

2.3.1.1 Automation of New Process Technology

Automation is defined as "the technology concerned with the application of complex mechanical, electronic, and computer-based systems in the operation and control of production (Groover 1980). A very similar definition of automation can be found in the *Encyclopedia Britannica*; " a significant substitution of mechanical, electrical, or computerized action for human effort and intelligence a technology concerned with carrying out a process by means of programmed commands ... capable of operating without human intervention." Groover (1980) states that automation includes: (1) automatic machine tools for processing work parts; (2) automatic materials handling systems; (3) automatic assembly machines; (4) continuous-flow processes; (5) feedback control systems; (6) computer process control systems; and (7) information systems to support manufacturing activities. Groover also lists the economic and social reasons for automating which include the following: (1) increased productivity; (2) high cost of labor; (3) labor shortages; (4) trend of labor toward the service sector; (5) safety; (6) high cost of raw materials; (7) improved product quality; (8) reduced manufacturing lead time; and (9) reduction of in-process inventory.

2.3.1.2 Rigid Automation and Flexible Automation

Traditionally, the manufacturing system has been represented by two kinds of equipment. The first one -- *dedicated* machinery, such as transfer lines -- is best suited for mass production of a single part. This process specialization permits low unit costs, but it inhibits flexibility. The second kind of equipment -- nonintegrated *general purpose*

machine tools -- is best suited for the very small batch production of different parts (Gupta and Goyal 1989). Due to the high degree of flexibility, costs per unit tend to be high, but the flexibility of the process can accommodate design changes, demand fluctuations, and shifts in product mix.

These definitions -- *dedicated* and *general purpose* -- are applicable to the concepts separating process choices used in Hayes and Wheelwright's product-process matrix. Today, advanced manufacturing systems such as flexible manufacturing systems (FMSs), computer aided design/manufacturing (CAD/CAM), and Just-in-Time (JIT), offer a new dimension for the definition of process technology -- flexibility (Groover 1980, Gupta and Goyal 1989). With the combination of the concept of automation and *flexible* system and *dedicated* system, automated process technology can be categorized into two groups -- *flexible automation* and *rigid automation* (Groover 1980).

Whereas the rigid automation is related to cost efficiency, the flexible automation is adopted to improve the firm's flexibility. Flexible automation like FMS and CIM has brought about significant advantages over traditional batch manufacturing by reducing the level of WIP inventory (Ranky 1983), manufacturing lead time, and improving utilization of resources (Jaikumar 1986). As compared to conventional systems, the greater flexibility provided by such automation also allows it to be used for successive generations of products and gives it a longer useful life than traditional process investments (Gupta and Goyal 1989).

Cox (1981) refer to an experience of the Ford Motor Company to illustrate the advantage of flexible automation over rigid automation; "to convert one plant to manufacture six-cylinder engines instead of eight-cylinder engines, it was necessary to remove and replace all the tooling in the plant It also suggests why, in an increasingly uncertain and volatile worldwide market, a more flexible manufacturing technology would offer economic advantages to mass producers." In addition, flexible technology also provides many additional benefits such as better product quality, reduced inventory and

floor space, lower throughput and lead times, and faster response to market shifts (Groover 1985; Hayes and Jaikumar 1988; Kaplan 1986). In their review paper for new manufacturing technology, Naik and Chakravarty (1992) summarizes the characteristics of the flexible systems with high fixed costs, low variable costs, dynamic reallocation and coordination of resources, small lot sizes, and shift from the economies of scale to the economies of scope.

2.3.1.3 Measurement for the Flexibility of New Process Technology

There are not many attempts to find the differences between rigid and flexible automation. Groover (1980) separates these two automation with the fixed sequence of the operations in the rigid automation versus the programmable sequence of the operations in the flexible automation. This difference in programmability separates two automation with the number of parts or products each automation can handle economically. Groover lists the examples of two types of automation; (1) transfer lines, automatic assembly, and so forth as rigid automation and (2) numerically controlled machine tool as flexible automation.

The most frequently used measure for the flexibility of the production system in past research (Burstein 1986; Groover 1980; Fine and Freund 1986) is the number of parts or products produced. It is also consistent with the definition of production flexibility by Browne (1984). In particular, Gaimon (1986) uses a flexibility index indicating a firm's combined capability for product-mix, volume, quality of output, and customer service acquired by the flexible technology. She considers the flexibility index as positively related to the acquisition rate of the flexible technology acquired and to the growth of the firm's market demand.

These examples of both automation suggested by Groover (1980) and the anecdotal evidence in the literature typify the measurement for the distinction between two automation. The variety of parts or products that each automation can handle

economically provides the conceptual foundation for the measurement. In addition, there is no clear border line between two automation. For example, we will call the automation that can handle two products more rigid than the automation that can handle four products. Hence, the relative distinction between two types of automation can be made according to the degree of flexibility, defined as the number of products or parts producible (see also Meredith and Suresh 1986).

Given the definition of a system's flexibility as being the number of producible product (part) types the most critical issue in the measurement of a system's flexibility is whether the system's flexibility is related to the system's capacity level in units of output. It may not be appropriate to conjecture that the system's flexibility will increase as more machines are installed, which has been a widely used assumption in the analytical studies for new process technology. A good illustration is presented in the study by Nakarur (1992). According to his measurement index for the system's flexibility, the system's flexibility is independent on the number of machines in a system. Rather, the system's flexibility is dependent on the flexibility of each machine, such as producibility of excess capacity of other machines. Hence, the overall system's flexibility may have to be considered independently of the capacity of process technology in the development of the model in this dissertation.

2.3.2 Effects of New Process Technology

Trade-offs against the costs of the capital investment and the human resources are a wide range of benefits attributed to new process technology. These benefits include lower direct manufacturing costs resulting from reductions in setup time, processing time, labor requirements, lead time, inventory, factory space, and so on (Jaikumar 1986). The effects of new process technology can be grouped into two categories - internal effects and external effects. Internal effects include mainly the effects on manufacturing lead time and the cost structure of production system. External effects include the effect on the



firm's sales, usually the result of the internal effect.

2.3.2.1 Effects on Manufacturing Lead Time

Manufacturing lead time is the combination of processing time, setup time, and waiting time. New process technology can reduce the significant portion of time a part or product spends in the shop (Jaikumar 1986) like throughput time, waiting time (Goldhar and Jelinek 1983; Groover 1980), and setup time (Groover 1980). For example, one major computer integrated facility at Messerschmitt-Bolkow-Blohm in Augsburg, West Germany, reduced production lead time for the Tornado fighter plane from 30 months to 18 months (Jelinek and Goldhar 1983). A survey result by Jaikumar (1986) also shows the drastic cut in processing time to one third on average after the installation of FMSs.

One significant advantage of the lead time reduction is the reduction of WIP inventory. Since the setup time becomes negligible in new process technology, the EOQ can approach one as in JIT system. More importantly, the range of EOQ the system can handle at reasonable costs may be much wider than the traditional system can handle. Another important advantage is faster market response. The results of faster market response include less safety stock, fast response to inaccurate forecast, and widened product line (Meredith 1987).

2.3.2.2 Effects on Cost Structure

Total manufacturing costs include fixed cost and variable costs. Fixed cost is related to capital investment in machinery and equipment in the factory. A survey result shows initial investment cost in FMS ranges between \$10 and \$25 millions (Smith et al. 1986; see also Jelinek and Goldhar 1984). The investment costs are higher from traditional job-shop, automated transfer line, to flexible manufacturing system, like FMS and CIM. Hence, each additional automated capacity increases the fixed cost of capital investment. The flexibility embedded in the acquired new process technology may

increase further the fixed cost of capital investment. This proposition might be inferred from the fact that the investment cost for the flexible production systems like FMS or CIM is enormous compared to the cost for the stand alone NC machines.

Variable costs can be measured in terms of the order quantity and the variety of products or parts processed. As discussed above, there are two types of variable costs -- the scale-related costs and the variety-related costs. Stalk (1988) suggests that, in a flexible manufacturing system, the variety-related costs start lower and increase more slowly as the product or part variety grows than in a conventional manufacturing system. Hence, a flexible system enjoys more variety with lower total costs than do traditional factories, which are still forced to make the trade-off between scale and variety.

Hough (1989) emphasizes the reduction in direct labor (see also Gaimon 1985; and Jaikumar 1986) and a probable flattening of the learning curve as the effects of automation. He also points out the reduction in indirect labor and other elements of overhead. Depending upon the degree of automation, he asserts, there should be a diminished opportunity for workers to learn better ways of accomplishing a task, primarily due to the reduction of direct labor. In addition, elements of learning due to improvements in tool coordination, shop organization, and inventory systems would be eliminated by the ability to simulate production processes and layouts prior to setting up a plant (see also Levy 1960 and Wild and Port 1987).

2.3.2.3 Effects on Sales Growth

The effect on sales growth of new process technology is an indirect result of faster market response and/or widened product line. As discussed above, new process technology allows the firm to update products continuously and thus tends to increase the range of product line, its complexity, and its rate of change. It also creates an entry barrier against competition due to increased technological content of products, closer market links, and improved responsiveness (Goldhar and Jelinek 1994). These overall

effects may increase a firm's market share. Roth et al. (1991) suggest that new process technology improves the firms' market share through the anticipated improvements in outputs and allows the firms to pursue a broader marketing strategy, thereby enabling them to capture a portion of their competitors' demand.

The result of an empirical study by Thietart and Vivas (1984) shows that market share increases as investment and assets increase for all kinds of industry involved in their study. This result implies that the possible investment in new process technology has a positive relationship with the sales growth of the firms. In summary, the acquisition of automation of new process technology seems to be viewed usually as the substitution of the new automated capacity for the manual output capacity to improve manufacturing performance. Furthermore, the flexibility of new process technology is found to provide the manufacturing firms with additional cost and benefits. Hence, there should be clear distinction between the effects of the acquisition of mere "automation" of new process technology and the effects of the acquisition of "flexibility" of new process technology. This distinction should be considered in the process of the model development in this study.

2.3.3 New Process Technology and Learning Effect

Learning effect is an widely discussed in many studies of developing or applying the production function. Productivity improvement due to the learning effect was first identified by Wright (1936). Yelle (1979) found this effect existing in a number of industries from early in this century. Levy (1965) develops a learning function based on actual examples in which the rate of learning is related to the experience of workers which are exogenous to the cumulative production volume. Levy claims that the productivity improvement is realized by two factors, "the initial efficiency of the process" and "the autonomous learning effect." He assumes that "the initial efficiency of the process" depends on the firm's preplanning efforts including testing prototype process, training or

education of workers, and so on. On the other hand, "the autonomous learning effect" is assumed to depend on the cumulative experience of workers as the production system runs. Hence, his learning function implicitly assumes that the automated production system with a low level of labor force may show a slow learning effect with high initial efficiency compared to the conventional production system with a high level of labor force. Hence, his learning function assumes "the flattening learning curve" as discussed in section 2.3.2.2 (see also Hough 1989; Wild and Port 1987).

Recognizing the shortfall of conventional studies of the learning effect that dealt only producing homogeneous products, Meredith and Camm (1989) introduce a new term -- *synergy* -- to include the learning effect in a situation of adapting several new advanced technologies to produce a variety of products. The authors present a unit production cost function incorporating this *synergy* effect. The function assumes that the high synergy effects among new advanced technologies adopted by the manufacturing firm result in low unit production cost. They contend this function can be used in determining the order of acquisition of several new advanced technologies. The significance of their study is that they provide an approach to finding the learning effect due to the synergy of new advanced technologies. This is a significant development in view of the fact that the conventional studies of the learning effect have focused only on the improvement in labor productivity or labor cost. However, a major drawback of this study is that the *synergy* effect can only be estimated after physical running of new advanced technologies which would be almost prohibitive due to the huge amount of costs and time involved.

Roth et al. (1991) applied this *synergy* concept in developing their analytic model to study the optimal acquisition of new flexible technology. They views the *synergy* effect as causing a structural shift in the level of "technological progress" of the production system, which they use as a new term for the learning effect reflecting gains in system utilization and productivity. This learning effect is assumed to result from improvements in layouts, machine loadings, machine speeds, yields, use and integration of system

components, and management methods. Like Levy's learning function, their model implicitly assumes high system synergy afforded by new flexible technology results in a flattening learning curve. This is the same as the view of others like Levy (1965), Hugh (1989), and Wild and Port (1987) who argue that more automation leads to less room for the learning effect.

2.3.4 Analytic Studies for New Technology Acquisition

Analytic studies in new technology acquisition have many different approaches in terms of methodology. Most studies have used either mathematical programming (Burstein 1986; Fine and Freund 1986; Li and Tirupati 1992) or optimal control theory (Amit and Ilan 1990; Gaimon 1985, 1986, 1989, 1992; Roth et al. 1991). Addressed in these studies are the issues such as trade-offs between scale and scope, the timing of acquisition, the size of acquisition, and the effect of learning on optimal acquisition. In this section, several key models are presented and discussed with issues related to this dissertation.

2.3.4.1 The Model of Fine and Freund

Fine and Freund (1990) presents a two-stage stochastic model for optimally choosing a portfolio of flexible and nonflexible manufacturing capacity. Their model is very similar to Burstein's (1986) except their model includes stochastic demand and multiple products. A similar study by Li and Tirupati (1992) presents a nonlinear model for the technology choice with concave cost functions. The focus of Li and Tirupati's study is the development of an efficient heuristic algorithm. Fine and Freund's model focuses on the economic tradeoffs between the acquisition costs of flexible capacity and a firm's ability to respond flexibly to future uncertain demand. They claim that the model captures a technology's flexibility characteristics with greater revenue resulting from broader product mix capabilities and lower operating costs due to economies of scope.

Fine and Freund formulate a single-period, multi-product, dual-technology problem to maximize the total profit by netting the technology acquisition costs and the manufacturing costs out of the total revenue. Below is the formulation of their model.

$$\begin{aligned}
 \max \quad & -r_F K_F - \sum_j r_j K_j + \sum_i p_i \sum_j \{R_{ij}(Y_{ij} + Z_{ij}) - C_j(Y_{ij} + Z_{ij})\}, \\
 & \{K_F, K_j; j = 1, \dots, n\} \\
 & \{Y_{ij}, Z_{ij}; i = 1, \dots, k, j = 1, \dots, n\} \\
 \text{subject to} \quad & Y_{ij} - K_j \leq 0, \quad i = 1, \dots, k, \quad j = 1, \dots, n, \\
 & \sum_j Z_{ij} - K_F \leq 0, \quad i = 1, \dots, k, \\
 & Y_{ij} \geq 0, \quad i = 1, \dots, k, \quad j = 1, \dots, n, \\
 & Z_{ij} \geq 0, \quad i = 1, \dots, k, \quad j = 1, \dots, n, \\
 & K_j \geq 0, \quad j = 1, \dots, n, \\
 & K_F \geq 0,
 \end{aligned}$$

The first two terms in the objective function are the technology acquisition costs for both flexible and dedicated technology. The term, p_i , represents the probability associated with the state i of the world for market demand. The term, $R_{ij}(Y_{ij}+Z_{ij})$, is the revenue function of product family j in state i . In their sensitivity analysis, the authors assume the revenue functions to be quadratic functions (i.e., linear demand functions). The term, $C_j(Y_{ij}+Z_{ij})$, represents the manufacturing variable cost. The terms, Y_{ij} and Z_{ij} , represent the amounts of product family j in state i produced by dedicated capacity j and flexible capacity, respectively.

In numerical examples, due to the enormous number of possible states of the world and the condition for uniqueness of the optimal solution, Fine and Freund carry out sensitivity analysis in a two-product case. Moreover, by assuming that the variable costs for either technology are very low, they exclude the variable costs from the objective function. In the first sensitivity analysis, they explore analytically the sensitivity of the optimal capacity levels to the acquisition costs. In the second sensitivity analysis, they explore the sensitivity of the optimal capacity levels to the changes in the distribution of demand. A major drawback of their model is that it separates two technologies only by their acquisition costs, and thus it misses many potential benefits of flexible technology in

the formulation. In fact, the elimination of the economies of scope from the model, i.e., the elimination of variable cost, may diminish the significance of their study.

2.3.4.2 The Model of Gaimon

Gaimon conducted many studies related to automation (June 1985, September 1985, 1986, 1989, 1992). Her studies have addressed many issues such as diminishing returns (1985a), productivity enhancement of labor (1985b), application of game theory (1989), and lagged learning effect (1992). In most of her work, she views the acquisition of automation as the substitution of automated capacity for manual output capacity.

Below is one of her models that is closely related to this dissertation.

$$\int_0^T \{[p(t) - B(t) - b(t)]d(t) - c(t)a(t) + s(t)r(t) - m(t)q(t)\}e^{-rt} dt \\ + gf(T)e^{-rT} + hq(T)e^{-rT}$$

subject to

$$d(t) = d_1(t) - d_2(t) + d_3f(t),$$

$$q'(t) = a(t) - r(t), \quad q(0) = q_0,$$

$$b'(t) = -\alpha(t)a(t)b(t), \quad b(0) = b_0,$$

$$f'(t) = \beta(t)a(t), \quad f(0) = f_0,$$

$$d(t) \geq 0, \quad t \in (0, T),$$

$$d(t) \leq q(t), \quad t \in (0, T),$$

$$q(t) - a(t) \geq r(t),$$

$$a(t) \in (0, A(t)), \quad r(t) \in (0, R(t)), \quad p(t) \geq 0.$$

In this model, the term, $f(t)$, represents the flexibility index summarizing a firm's capabilities with respect to product-mix, volume, quality of output, and customer service. Therefore, this model assumes, as described in the demand function, that a firm with a high index level of flexibility has the potential to increase its demand by manufacturing products whereas a firm with less flexible productive capacity may be unable to produce. One important aspect of this model is related to the state equation for the flexibility index.

The term, $\beta(t)$, is defined as a measure of the effectiveness that acquiring technology has on increasing the level of flexibility index at time t . Gaimon defined this term as a function of time to capture the possibility of anticipated technological advancement. According to the constraint for $f(t)$, the more flexible the system, the higher the value of $\beta(t)$, and vice versa. In addition, according to the third and fourth constraints, both the unit operating cost and the system's flexibility depend on the acquisition rate of automation. As discussed in Section 2.3.2.3, flexibility is the capability of the system which may be independent of the level of automation capacity. Therefore, it might be appropriate to have a control variable representing the rate of acquired flexibility independent from both the rate and the accumulated level of acquired automation capacity.

2.3.4.3 The Model of Roth et al.

The model of Roth et al. (1991) is an extension of Gaimon's model (1986). Roth et al. consider in their model the lagged learning effect, called as "technological progress," the market share increases due to the acquisition of new process technology, and the reduction of unit operating costs. In this model, the flexibility of the process system is proportionate to the rate of acquired flexible automation capacity. Thus the impact on market share and unit operating costs is proportionate to the rate of acquired flexible automation capacity. Below is the formulation of their problem.

$$\begin{aligned} \text{Max } [G_1 s(T) + G_2 k(T) + G_3 a(T)]E(T) - \int_0^T \{n[s - S]^2 + c_1 a^2 + c_2 r^2 \\ + [B + c_3]s + c_4[dk - s]^2 - c_5[dk - s]\} E dt \end{aligned}$$

subject to

$$s' = \gamma_1(a + \alpha k)(N - s) + \gamma_2 s.$$

$$x' = a.$$

$$k' = a + \alpha k - r.$$

$$\alpha' = -\psi\alpha(1 - \phi a/x).$$

$$c'_3 = -\beta a c_3.$$

$$a \in (0, A), r \in (0, R).$$

They assume that all demand is met through the available operating capacity or through the use of short-term measures that increase capacity. They also assume incremental timing strategy to upgrade a firm's capacity by asserting that radical diffusions of new technologies may cause disruptions and be more costly than are incremental diffusions. Hence, the cost functions for acquiring flexible automation and retiring conventional capacity are defined as quadratic. The presence of the capacity variable, k , makes the model capture the impact of technological progress due to the organizational learning in the total capacity and the market share. Hence, the change in total capacity and the market share over time is the function of both the change in flexible automation capacity and the change in the total capacity due to technological progress.

Interestingly, this technological progress factor, α , is considered as a state variable that is decreasing over time. Roth et al. also assume the rate of decrease in technological progress over time is decelerated by the system's synergy effect (Meredith and Camm 1989). This concept is the same as the flattening of the learning curve due to the acquisition of automation as discussed before. However, empirical evidence suggests that the learning effect is a function of cumulative experience, which is usually represented as a cumulative production level (see Yelle 1979). Hence, it may be appropriate to relate the value of reduction factor, ψ , to the cumulative demand level rather than to choose an arbitrary value for the factor. Overall, the contribution of this model is the extension of previous studies in this area including the detailed modeling aspects with the consideration of the interaction effects of both the organizational learning and the acquisition of flexible automation on both market share and unit operating costs.

2.3.5 Summary and Implications

In the review of the past analytic studies, there are three findings: (1) Lack of consideration for the flexibility aspect of new process technology; (2) Failure to link technology acquisition decisions with the corporate strategy; (3) Single dimensional definition of process technology as production capacity in units of output. In fact, these drawbacks are found mainly due to the single dimensional definition of new process technology as production capacity in units of volume. It is expected to enhance the richness of analytic models in the future studies with continuous efforts in developing conceptual works to distinguish two aspects of new process technology, automation capacity and flexibility. Hence, this dissertation attempts to propose an analytic model overcoming the drawbacks of the past studies by considering the two-dimensional aspect of new process technology.

2.4 RESEARCH STATEMENT

This dissertation addresses the linkage of the strategic orientation of SBUs regarding cost efficiency and flexibility with the acquisition decisions for new process technologies. Specifically, this study attempts to provide managers with a strategic framework for the acquisition decision process of new advanced technology as a practical tool for strategic decision making in technology acquisition. The focus of this study is on the development of an optimal control model for optimal decisions regarding the acquisition of new process technology to enhance the production volume and variety capability of the system and, using the scenario analysis, on the investigation of relationships between process technology choice and competitive priorities (cost efficiency vs. flexibility) of a firm's SBU.

The contribution of this study is also due to the fact that the acquisition of new process technology is considered to affect the production system along two important

dimensions, its production capacity in units of output and its ability to produce a variety of products or part-types. The choice of the mix of these two dimensions of process technology is also considered to affect its market potential regarding volume and variety in addition to unit production costs. The objective function considers the trade-off between the market potential and SBU goals regarding volume and variety. Through systematic scenario analysis, the evolution of process technology choice in relation to the strategic competitive priorities of the SBU along the stages of the product life cycle is thoroughly investigated.

CHAPTER III

STRUCTURAL FRAMEWORK FOR THE STRATEGIC ACQUISITION OF NEW PROCESS TECHNOLOGY: A CONCEPTUAL FRAMEWORK

As discussed in the previous chapter, the acquisition of new technology has significant strategic implications for a firm's long term market competitiveness. The understanding of relationships among various contingent variables surrounding a firm's internal and external operation environment is a prerequisite for the analysis of the strategic implications of technology acquisition (Madu and Georgantzas 1991). The structural framework proposed in the first section explains how technology decisions are related to the corporate strategy through the business strategy. This relationship will be a conceptual basis for developing the objective function of the model presented in Chapter 4. The following two sections explain how changes in a firm's market demand and manufacturing cost structure are affected by other variables. Hence, these two sections provide conceptual bases for the development of constraints of the model in Chapter 4.

The last section introduces a new concept called the "Product-Technology Box" by incorporating two dimensions of technology -- automation and flexibility -- into the normative concept of product-process matrix. This new concept has been supported by many researchers (Boothroyd 1982; Hayes and Wheelwright 1984; Adler 1988). With the results from the scenario analyses at the end, this research attempts to explore how the best fit between technology choice and market requirements within the new "Product-Technology Matrix" evolves due to the optimal acquisition of new process technology along the stages of a product life cycle.

3.1 DECISION PROCESS FOR NEW TECHNOLOGY ACQUISITION

The decision process for the acquisition of technology is comprised of three levels of decision as depicted in Figure 3.1. In this structural diagram decisions for the acquisition of new technology made at the functional level are linked to corporate strategy and business strategy. Decisions related to the corporate strategy are the relative importance weight given to a particular strategic priority, either *flexibility* focus or *cost efficiency* focus, depending upon whether the firm pursues a *differentiation strategy* or a *cost leadership strategy* (Porter 1980). Decisions related to business strategy include each *SBU's goals* for *the growth of market share in volume* and *the growth of market share in product (part) variety*.

The growth of market share in volume is related to the corporate strategy of pursuing cost efficiency whereas the growth of market share in product (part) variety is related to the corporate strategy of pursuing flexibility. Firms with the strategic priority of cost efficiency will try to achieve economies of scale by increasing sales in volume. On the contrary, firms with the strategic priority of flexibility will try to achieve economies of scope by increasing sales in variety. Hence, the goals of a firm's SBU are closely related to the strategic priority stipulated by the corporate strategy. In addition, the real values of SBU's goals are to be set according to the firm's projection for future market conditions along the market product life cycle.

When the SBU's goals are set at the business level, decisions regarding the acquisition of new technology will be made at the functional level. Decisions for the acquisition of technology include the *timing* and *size* of investment in *automation capacity of new process technology*, *flexibility of new process technology*, and the *reduction of conventional capacity*. Since new process technology is defined in two dimensions - automation capacity and flexibility - in this dissertation, the acquisition of new process technology entails two separate decisions, one for the acquisition of

automation capacity and another for the acquisition of flexibility.

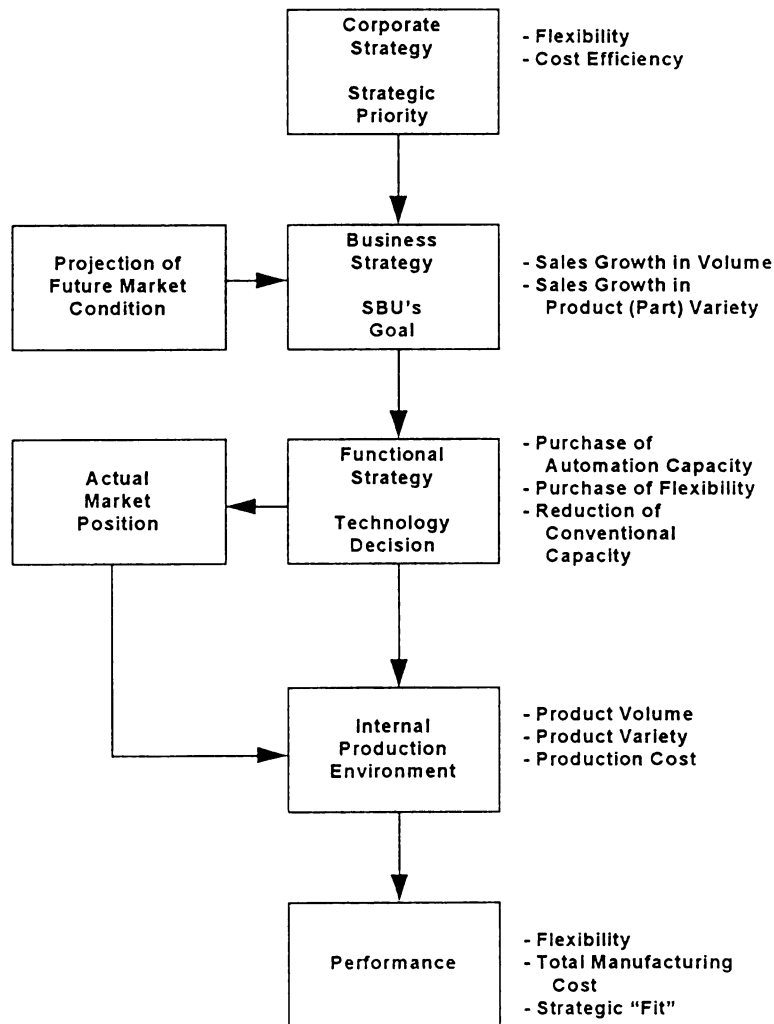


Figure 3.1 Structural Diagram of the Decision Process for the Acquisition of New Advanced Technology

As discussed in Chapter II, many have asserted that optimal decisions for the acquisition of technology should be contingent upon the *strategic priority* decided at the corporate level and the following *SBU's goals* decided at the business level (Porter 1980;

Skinner 1967; Simmonds 1981; see also Swamidass and Newell 1987⁸). Hence, the model in this dissertation includes variables related to the SBU's goals and the coefficients related to the strategic priority. In doing so, this dissertation explores how decisions for the acquisition of new technology are related to the desired business goals as well as the firm's strategic priority.

According to Figure 3.1, decisions for the acquisition of new technology affect internal production environment, which consists of production volume, production variety, and manufacturing cost structure. Technology decisions also affect the firm's actual market position in terms of both sales volume and product variety (refer to section 2.3.2.3). Hence, the model in this dissertation will measure both *product volume flexibility* and *product mix flexibility* of the firm by comparing the internal production environment with the actual market position. Detailed relationships among variables related to technology decisions will be discussed in the next section.

The overall performance to be measured in the model includes not only the total costs related to both technology investment and production as well as flexibility in terms of production volume and product variety, but also the costs related to the strategic "fit," which represents the consistency of decisions made at various levels in the hierarchy of strategy as emphasized explicitly or implicitly by many researchers (Frohman 1982, 1985; Garrett 1986; Hayes and Wheelwright 1984; Schroeder 1990; Skinner 1974; Wheelwright 1984). The relationship between conceptual linkage from corporate strategy to production environment and actual scheme for measuring the overall performance in the model is depicted in Figure 3.2, in which the corporate strategy dictates SBU's goal, the technology decisions affects SBU's actual demand, and the SBU's production environment dictates its production decisions. The model can measure the strategic "fit" by comparing

⁸ This empirical study reveals the positive relationship between the perceived environmental uncertainty and the manufacturing flexibility of a firm. In this study, the manufacturing flexibility is measured with respect to the product mix flexibility.

SBU's goals with its actual demand while it can measure flexibility by comparing actual demand with production decisions.

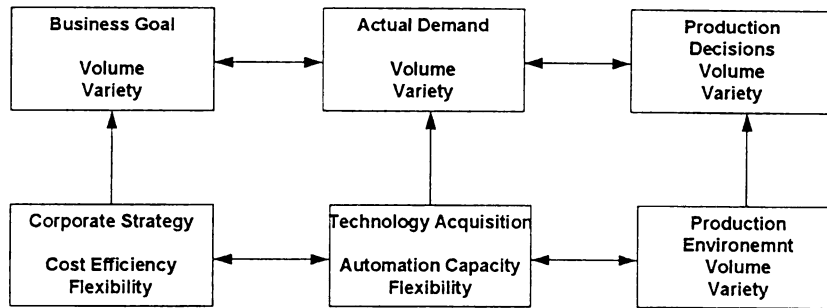


Figure 3.2 Linkage Among Various Decisions

Table 3.1

Objectives of The Acquisition of New Technology

Strategic Objective	Tactical and Operational Objectives
Consistency with the firm's competitive strategy Min [Desired Business Goals - Actual Market Position]	Flexibility maximization - volume - variety Total costs minimization - investment cost - production cost

As described in Table 3.1, the strategic objective for technology decision making, called strategic *fit*, is the minimization of the deviation between a firm's actual market position through the acquisition of new technology and the desired business goals to align the acquisition of new technology with the firm's overall competitive strategy. The tactical objective in this model is the minimization of costs related to the product volume flexibility

and product mix flexibility. Operationally, the acquisition of new technology should be decided to minimize the total costs combining fixed investment costs and the production variable costs through trade-offs with flexibility (Simmonds 1981). Particularly, by incorporating the strategic objective, the model can measure linkage between the strategic priority of corporate strategy and the acquisition decision for new advanced technology of functional strategy. Hence, the optimal control model presented in Chapter IV attempts to capture the linkage among strategies in the hierarchy of strategy and measure this linkage as the overall performance.

3.2 TECHNOLOGY AND EXTERNAL ENVIRONMENT

There are two possible causes for changes in a firm's aggregate demand. One of these causes is the change in internal competitive force, and the other is the change in external competitive force. This type of view can be found in the well-known Vidale-Wolfe sales response model (1957). Internal change may include change in delivery performance, service quality, product quality, or information systems for data communication. External change may include change in the position of the product in its own product life cycle, elasticity of demand due to competitive forces, general economic conditions, or other environmental forces (Roth et al. 1991).

As depicted in Figure 3.1, the actual market position of a manufacturing firm is assumed to be postulated in terms of both volume and variety. Anecdotal and empirical evidence provided in the literature suggest that the acquisition of new process technology improves a firm's market position (Goldhar and Jelinek 1984; Thietart and Vivas 1984). Unfortunately, these studies fail to address the distinction between improvement in market position in terms of volume and in terms of variety. Despite the lack of support from the literature, this study proposes that the improvement of market position in terms of volume is more closely related to the level of investment in the automation capacity of new

technology, whereas improvement of the market position in terms of variety is more closely related to the level of investment in the flexibility of new technology. The reasoning of this proposition is that volume change in market demand can be better met as more investment in new technology capacity improves the capacity utilization of a production system to meet the variation of sales in volume (Roth et al. 1991), whereas variety change in market demand can be better met as the acquisition of flexibility furnishes a production system with more flexibility since the customer's brand loyalty may be enhanced due to the benefits of better product quality, reduced lead time, and fast response to market shifts (Groover 1985; Hayes and Jaikumar 1988; Kaplan 1986).

As discussed in the previous section, minimization of the discrepancy between the SBU's goals and its actual market position plays a pivotal role in linking the strategic priority of the corporate strategy and decisions for the acquisition of new technology of the functional strategy. Since the technology decision affects a firm's actual market position, and the business goal is a replica of the corporate strategy with respect to sales growth and introduction of new products, by matching these two in close proximity, managers can make the technology decision that is sound and consistent with the objectives stipulated by corporate strategy.

3.3 TECHNOLOGY AND MANUFACTURING COST STRUCTURE

In this study it is assumed that a firm pays a fixed investment cost for new technology capacity and its flexibility separately. In fact, a stand-alone NC machine usually costs around \$300,000 to \$400,00 whereas an FMS, which combines these NC machines with other automated systems to increase the flexibility of a production system, can cost sometimes tens of millions of dollars (Bobrowski and Mabert 1988). Hence, the flexibility embedded in new process technology will require more investment in addition to the basic cost for mere automation capacity as shown in Figure 3.3.

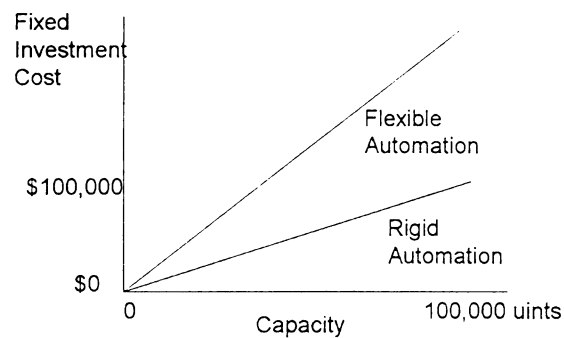


Figure 3.3 Technology and Investment Cost

As Stalk (1988) suggests, this study assumes there are two types of production **variable** costs - volume-related variable costs and variety-related variable costs. The **average** volume-related cost decreases as the degree of automation increases (see Roth et al. 1991). This type of cost decline results from the elimination of manual activities in **production** capacity due to the acquisition of new process technology. It is important to **note that** as the cumulative automation capacity increases, there will be less opportunity to **gain the** learning effect due to the low level of labor-intensive activities and the high level of **integration** among machinery and tools (Wild and Port 1987). Hence, the rate of decline of **volume-related** variable costs will decrease as the degree of automation increases (see **Figure 3.4**). In the model the initial value of volume-related variable costs of a production **system** will be determined by its initial degree of automation. In this dissertation, the **volume-related** learning effect is not considered.

The average variety-related costs reflect the costs of complexity in manufacturing, **including** setup, material handling, inventory, and many of the overhead costs attributed to the **degree** of product or part variety of a factory (Stalk 1988). The average variety-**related** costs increase as the production system processes more product (part) types. **Since** the system's flexibility in this dissertation is defined as the number of unique product

(part) types to be produced, the average variety-related costs increase as the system's flexibility increases as depicted in Figure 3.5. It is also assumed that the rate of increase in average variety-related costs becomes smaller as the cumulative system's flexibility increases.

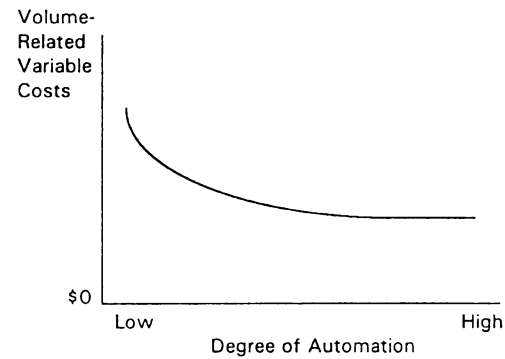


Figure 3.4. Automation and Average Volume-Related Variable Costs

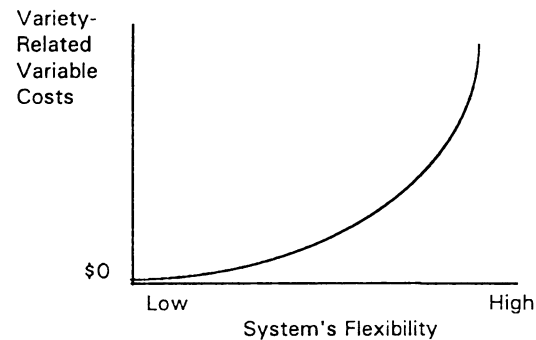


Figure 3.5. Flexibility and Average Variety-Related Variable Costs

3.2.1 PRODUCT-TECHNOLOGY BOX

In this dissertation new process technology is defined in two dimensions --

automation capacity and flexibility. Definitions for these two dimensions were already discussed in Chapter II (see section 2.3.1). Automation capacity of new technology is defined as production capacity substituted for the conventional production capacity. Flexibility is defined as the capability of the production system in terms of the number of product or part types the system can produce. Hence, any process technology can be defined by the combination of the degree of automation and the degree of flexibility. This definition of process technology is quite different from the definition of process technology found in the product-process matrix proposed by Hayes and Wheelwright (1979a).

In the product-process matrix the process technology is defined by the combination of a fixed degree of automation and a fixed degree of flexibility, such as high automation/low flexibility for transfer line and low automation/high flexibility for job shop. Unfortunately, as Hayes and Wheelwright (1979b) pointed out, their product-process matrix seems to be inappropriate as new process technology with a high degree of both automation and flexibility becomes available. New process technology allows firms to produce a wider range of product variety and volume at the same or lower cost than does conventional technology (high-automation/low-flexibility or low-automation/high-flexibility) defined along the vertical axis of the matrix. Hence, new process technology might allow firms to pursue both cost efficiency and flexibility at the same time (Porter 1980). Therefore, to be a viable paradigm of manufacturing strategy the product-process matrix may need to be revised to fill the gap between the existing normative concept behind the product-process matrix theory and the current trend of rapid diffusion of new process technology.

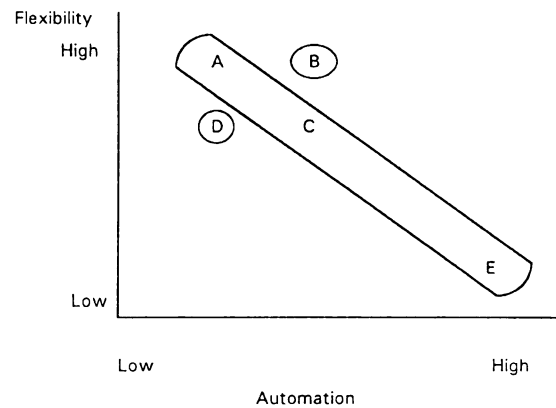


Figure 3.6 Technology Matrix

To fill such a gap, a new term, called a "Product-Technology Box," is proposed to **integrate** the PLC and a firm's technology choice as depicted in Figure 3.6. Unlike the **product**-process matrix suggested by Hayes and Wheelwright (1984), a new matrix, called a "**Technology Matrix**," combining automation in the horizontal axis and flexibility in the **vertical** axis is first devised to represent technology choices (see Figure 3.6). Technology choices on the diagonal in the new technology matrix have the same definitions as in the **product**-process matrix. The upper left corner (Job Shop), labeled as point A in Figure 3.6, **represents** a technology choice with high flexibility and low automation. The lower right corner (Transfer line), labeled as point E in Figure 3.6, **represents** a technology choice with low flexibility and high automation. The major difference of this new matrix is that **any** technology choice can be defined with the combination of the level of flexibility **given by** a point on the vertical axis and the level of automation given by a point on the **horizontal** axis.

Any off-diagonal points, such as B and D, have different definitions than in the **conventional** product-process matrix. In the conventional product-process matrix, the **firm at** point B has the same process technology as the firm at point A. In this new matrix the **firm at** point B (Firm B) has higher level of automation than the firm at point A (Firm A) **and** the higher level of flexibility than the firm at point C (Firm C). The firm at point D

(Firm D) has a lower level of flexibility than Firm A and a lower level of automation than Firm C. Hence, it is certain that Firm B (Firm D) needs more (less) fixed capital investment for its process technology than does Firm A or Firm C.

According to the normative concept of the product-process matrix, Firm A is suitable for the product structure of low volume and high variety whereas Firm C is suitable for the product structure of medium volume and medium variety. In this new matrix, Firm B has not only a high degree of flexibility, as does Firm A, to operate efficiently for up to high levels of product variety but also the medium degree of automation, as does Firm C, to operate economically for up to medium size of product volume. Therefore, Firm B might be able to achieve the economies of scale of Firm C as well as the economies of scope of Firm A, simultaneously. On the contrary, Firm D has a technology choice with the same level of flexibility as Firm C and the same level of automation as Firm A. According to the normative concept, Firm D would be suitable for the product structure of low volume and medium variety. Unfortunately, this kind of product structure cannot be found along the stages in the normal product life cycle. Consequently, the technology choice of Firm D is not considered in the conventional product-process matrix. However, since this choice has a lower level of fixed capital investment than others such as A, B, and C, and a firm's technology choice changes constantly over time due to the acquisition of new technology, this choice as initial process technology might have an advantage over the other positions in the dynamic environment. Therefore, this study does not exclude this position in the scenario analysis.

To this new technology matrix, a third dimension is attached to represent the stages of product life cycle. This third dimension is the same as the horizontal axis of the conventional product-process matrix. The product structures of the introductory stage through the declining stage of product life cycle, from low volume/high variety to high volume/low variety, are represented along this additional dimension. Hence, the "Product-Technology Box" combines all three dimensions in one diagram as depicted in Figure 3.7.

A point in the box has a corresponding product structure of a stage of the PLC and a corresponding technology choice. For example, at point X in Figure 3.7 Firm F is operating with a technology choice of a high degree of both automation and flexibility and facing with a product structure of the mature stage of the PLC.

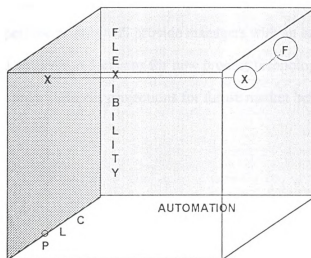


Figure 3.7 Product-Technology Box

One important feature of this box is that it is possible to identify the range of product structures suitable for any technology choice defined by the new technology matrix, which would be difficult with a two-dimensional matrix such as the product-process matrix. For example, Firm B might be suitable for the product structures ranging from the introductory stage to the growth stage of the product life cycle. A firm positioned at the upper right corner of the technology matrix may be suitable for the product structures ranging from the introductory stage to the mature stage of the product life cycle.

With the above new concept of Product-Technology Box, this dissertation attempts to explore analytically how a firm's technology choice evolves on the new

technology matrix according to the transition of PLC and the firm's choice of competitive priority for each stage of PLC. In particular, this study tries to identify how the evolution of technology choice on the technology matrix differs according to a firm's competitive priority -- either flexibility or cost minimization. This study also tries to explore how the technology choice evolves in two different market environments of the normal PLC and the reversal of PLC. Significantly, the analysis of the interaction effect between the types of PLC and the competitive priority will provide managers with an insightful guide for how to make optimal acquisition decisions for new process technology consistent with the competitive strategy under different projections for future market behavior.

CHAPTER IV

THE MODEL

In this chapter, a dynamic optimal control model for the acquisition of new technology is developed according to the conceptual frameworks proposed in Chapter III. This chapter is separated into three parts. In the first part, the general description of the model is provided along with the assumptions and the variable definitions. The second part presents the objective function of the model. The state constraints and the control variable boundaries are depicted in the third part. The model for this study follows the standard approaches taken by many analytic studies in the literature on process technology. The notation for time, (t) , is suppressed in the objective function and the subsequent constraints unless it is required.

4.1 INTRODUCTION

This section starts with a brief description of the proposed model. Then the assumptions for the model are presented, followed by the description of the notation used in the model.

4.1.1 General Description of The Model

As mentioned in chapter II, few past analytic studies regarding process technology investment have considered *flexibility* as one of the objectives in their models. Past analytic studies related to process technology generally view the acquisition of technology as the capacity expansion, frequently combined with the learning effect. The major

drawback of their models is that they consider the cost efficiency as the only objective. The model presented here includes not only cost efficiency but also costs related to flexibility as the performance measures in the objective function. Particularly, by incorporating implicitly relative importance weights placed on two strategic priorities, *cost efficiency* and *flexibility*, according to the corporate strategy, the model attempts to embed the linkage between the corporate strategy and the functional strategy. Hence, it allows decision makers to render the optimal policy not only for its best positioning of technology choice in the product-technology matrix but also for the technology investment strategically viable according to the relative emphasis given to each of two competitive priorities -- *cost efficiency* and *flexibility*.

The model in this dissertation considers both *product volume flexibility* and *product mix flexibility*. These two types of flexibility are included explicitly in the objective function as the difference between actual production in volume and market demand in volume and the difference between actual production in variety and market demand in variety. Hence, any deviations in terms of volume and variety incur costs deteriorating the overall performance of a firm's SBU. According to the perspective of this study, the types of flexibility considered in the model should adequately portray the strategic implications of new technology acquisition conditioned by the external strategic variables, actual market demand in volume and variety. In this regard, the above two types of flexibility are considered as the most suitable ones in reflecting strategic implications with respect to the positioning of technology choice in the product-technology matrix proposed in Chapter III (see Figure 3.6).

4.1.2 Assumptions

1. The firm is manufacturing products of a single type.
2. The market behaves in perfect competition. Hence, there is no dominant competitor in the market.

3. There is no change in the technology choices of the competitors in the market.
4. The prices are fixed over the planning horizon.
5. New advanced technologies are readily available and there is no barrier for individual firms to access new advanced technologies.
6. Changes in the aggregate market demand follow a smooth transition as in the PLC curve.
7. There is no volume related learning effect in the average volume-related costs with new process technology.
8. The average variety-related costs are decided by the flexibility of the system, not by actual product (part) variety produced by the system.
8. There is no change in managerial control policy, other than specified by the variables in this model, over the planning horizon.
9. The timing policy for the process technology acquisition is smooth, evolutionary changeover from old to new technology within an existing plant.

4.1.3 Variables

In this section, endogenous variables and exogenous variables are grouped separately. State and control variables are defined as endogenous variables. Cost coefficients and other parameters are defined as exogenous variables.

4.1.3.1 Endogenous Variables

- $x(t)$ = accumulated level of automation capacity of new technology as production capacity in units of output at time t , $x(0) = x_0$, (state variable),
- $k(t)$ = total production capacity in units of output at time t , $k(0) = k_0$, (state variable),
- $s(t)$ = overall system flexibility (manufacturing flexibility) defined as the number of products (parts) the production capacity handles at time t , $s(0) = s_0$, (state variable),
- $v(t)$ = aggregate market demand of the firm in units of output at time t , $v(0) = v_0$, (state

variable),

$m(t)$ = market demand of the firm in number of products (or parts) types at time t , $m(0) = m_0$, (state variable),

$b_1(t)$ = average volume-related variable cost at time t , $b_1(0) = b_{10}$, (state variable),

$b_2(t)$ = average variety-related variable cost at time t , $b_2(0) = b_{20}$, (state variable),

$a(t)$ = acquisition rate of automation capacity of new technology in units of output at unit time t , $a(t) \in (0, A(t))$, (control variable),

$f(t)$ = acquisition rate of flexibility of new technology measured in number of product (part) types newly acquired new technology can handle at unit time t , $f(t) \in (0, F(t))$, (control variable),

$r(t)$ = rate of scrapping/reducing the level of conventional (existing) capacity in units of output at unit time t , $r(t) \in (0, R(t))$, (control variable),

$p(t)$ = rate of actual production in units of output at unit time t , $p(t) \in (0, P(t))$, (control variable),

$q(t)$ = rate of actual production in number of product (part) types at unit time t , $q(t) \in (0, Q(t))$, $0 < Q(t) \leq k(t)/\psi$, (control variable).

4.1.3.2 Exogenous Variables

$Y_v(t)$ = total market size exogenously determined in terms of aggregate volume at time t ,

$Y_m(t)$ = total market size exogenously determined in terms of product (part) variety at time t ,

$V(t)$ = business unit (SBU) goal level of aggregate demand in units of output at time t

$M(t)$ = business unit (SBU) goal level of demand in number of product (part) types at time t ,

c_1 = acquisition cost per squared unit of automation, $a(t)$,

c_2 = acquisition cost per squared unit of flexibility, $f(t)$,

c_3 = scrapping/reducing cost per squared unit of conventional (existing) capacity, $r(t)$,

c_4 = cost per unit squared deviation between the actual production in volume and the

market demand in volume,

- c_5 = cost per unit squared deviation between the actual number of products (parts) types produced by the production capacity and the number of products (parts) types demanded by the market,
- e_1 = cost per unit squared deviation between actual aggregate market demand in volume and SBU's goal in volume,
- e_2 = cost per unit squared deviation between actual number of products (parts) types demanded by the market and SBU's goal in number of products (parts) types,
- π_1 = market response factor per unit of acquired new technology capacity for the change of SBU's aggregate demand in volume, $0 < \pi_1 < 1/A(t)$,
- π_2 = exogenously predetermined coefficient representing natural growth/decay of the product life cycle in volume, $-1 < \pi_2 < D_v$, where D_v is a predetermined upper bound (saturation level) on the growth factor in terms of volume,
- ϕ_1 = market response factor per unit of acquired flexibility for the change of SBU's demand in variety, $0 < \phi_1 < 1/F(t)$,
- ϕ_2 = exogenously predetermined coefficient representing natural growth/decay of the product life cycle in variety, $-1 < \phi_2 < D_m$, where D_m is a predetermined upper bound (saturation level) on the growth factor in terms of product (part) variety,
- α = effectiveness factor of acquired automation capacity on reducing average volume-related cost, $0 < \alpha < 1$,
- B_1 = the lower bound of b_1 , the volume-related cost,
- β = effectiveness factor of acquired flexibility on reducing average variety-related cost, $0 < \beta_2 < 1$,
- ρ_1 = effectiveness (synergy) factor of acquired flexibility of new technology on improving overall system flexibility due to the system synergy, $0 < \rho_1 < 1$,
- ρ_2 = effectiveness factor of reducing system's overall flexibility due to the attrition of conventional (existing) capacity, $0 < \rho_1 < 1$,
- H = a large number in the constraint for the relationship between a and f ,
- W = a large number in the constraint for the relationship between p and q ,

- ψ = a coefficient representing the proportionate loss of volume capacity due to the production of one product (part) type,
- r = a coefficient representing the proportionate loss of system's flexibility due to the scrapping/reducing of conventional (old) capacity.
- G_1 = value per unit market demand of the firm in volume at terminal time, T ,
- G_2 = value per unit market demand of the firm in variety at terminal time, T ,
- G_3 = value per unit capacity at terminal time, T ,
- G_4 = value per unit of overall system flexibility at terminal time, T ,
- $E(t)$ = e^{-it} , a discounting factor, where i is a discount rate,
- T = a terminal time of the planning horizon.

4.2 THE OBJECTIVE FUNCTION

The overall objective of the model is to maximize a SBU's strategic value, including discounted values of its market share and technological capabilities at the terminal time, while subtracting the total tangible and intangible costs over the planning horizon. The dual-criterion objective function depicted in equation (4.1) addresses the trade-offs between two competitive priorities -- cost efficiency and flexibility. This function includes both tangible costs and intangible costs related to a system's flexibility. Tangible costs include both the capital investment cost for the acquisition of automation capacity and flexibility of new technology and the production variable costs. Intangible costs include the costs of over-flexibility and under-flexibility represented by the difference between achieved flexibility and required flexibility in terms of both volume and product (part) variety. Also included in the objective function are the costs related to the discrepancies between actual demand level and business goal level in terms of both volume and product variety. Minimization of these costs guides the acquisition decision for new

advanced technology to maintain the consistency between the firm's strategic focus and its technology acquisition decision as a part of functional strategy.

$$\begin{aligned} \text{Max } [G_1 v(T) + G_2 m(T) + G_3 k(T) + G_4 s(T)]E(t) - \int_0^T \{c_1 a^2 + c_2 f^2 + c_3 r^2 + (b_1 + \\ b_2)p + c_4(p - v)^2 + c_5(q - m)^2 + e_1(v - V)^2 + e_2(m - M)^2\}Edt \end{aligned} \quad (4.1)$$

The salvage values, $G_1 v(T)$, $G_2 m(T)$, $G_3 k(T)$, and $G_4 s(T)$, correspond to the market valuation of the firm's market share in volume and variety and the valuation of the capability of the firm's production technology at the terminal time. These values also provide linkages for the continuation of the firm beyond the planning horizon (see also Roth et al. 1991).

The first term, $c_1 a^2$, represents the acquisition cost for automation capacity of new technology at time t . The term, $c_2 f^2$, is the acquisition cost for flexibility of new technology at time t . The term, $c_3 r^2$, is the cost for scrapping or reducing conventional (existing) capacity. The model represents the costs for acquiring automation capacity of new technology and its flexibility and scrapping/reducing conventional capacity as quadratic⁹ since it is assumed that large acquisition of new technology is more difficult to assimilate into the existing system than the smaller acquisitions (see also Gaimon 1990; Farley et al. 1987; Roth et al. 1991). With the same analogy, it is assumed that the larger the conventional capacity scrapped/reduced, the more destructive it is for the production system to reorganize. The total variable costs are denoted as the multiplication of $(b_1 + b_2)$, the sum of the average volume-related variable cost and the average variety-related variable cost, by p , the actual production level in units. These first four terms in the integration are the tangible costs, which are directly related to *cost efficiency as a strategic priority*.

⁹ For the purpose of simplicity, the quadratic cost functions for the technology acquisition and attrition are assumed as found in the literature (see studies of Gaimon and Roth et al). For the sensitivity analysis as the extension of this study, it may be possible to assume different cost functions.

The next two terms in the objective function are the costs related to the system's flexibility in terms of both lead time and product variety. The first term, $c_4(p - v)^2$, is the cost for over-flexibility and under-flexibility of product volume flexibility, represented by the squared difference between actual production volume and market demand in volume. The second term, $c_5(q - m)^2$, is the cost for over-flexibility and under-flexibility of product mix flexibility, described as the squared difference between the number of products (parts) types produced by the system as achieved product (part) mix flexibility and the number of products (parts) types demanded by the market as required product (part) mix flexibility.

The last two terms, $e_1(v-V)^2$ and $e_2(m-M)^2$, are the costs related to the firm's strategic consistency depicted as the discrepancy between the firm's actual market position and the desired market position of the strategic business unit (SBU). In this model, both desired level of volume and desired level of variety as business goals, V and M , are assumed to be determined exogenously according to the firm's competitive strategy and the projection of future market conditions as discussed in section 3.1. A similar quadratic representation like these two terms can be found in the model developed by Roth et al. (1991) (see also Holt et al. 1960; Bergstorm and Smith 1970; Chang and Jones 1970). Roth et al. (1991) explain the term in their model as the squared difference between actual market share and desired market share as the SBU's goal such that "when the actual market position exceeds the goal, the firm incurs a penalty cost because its organizational structure and resources are strained. On the other hand, an opportunity cost is incurred when the firm underachieves its goal level of demand." Any deviation from the desired business goal has a significant impact on the firm's competitiveness and long term survival (Roth et al. 1991). Unlike the model of Roth et al., this model considers not only the sales volume but also the product (part) variety as the elements of market position. The firm's ability to introduce more products to the market is directly related to the firm's innovativeness, which is another key element for the firm's competitiveness and long term

survival. Hence, the last two terms in the objective function measure the firm's strategic competitiveness in two dimensions of both product volume and product variety.

As described above, the objective function of this model consists of three parts, tangible costs combining fixed investment costs and production variable costs, costs related to the system's flexibility, and costs related to the firm's strategic competitiveness. The relative importance recognized by a firm can be accommodated by manipulating the values of cost coefficients for three parts. Particularly, the trade-offs between cost efficiency and flexibility can be explored by changing the values of cost coefficients for flexibility, c_4 and c_5 , in the objective function. Technically, the small values of cost coefficients for flexibility, c_4 and c_5 , relative to those for tangible costs, c_1 , c_2 , c_3 , b_1 , and b_2 , means the firm's strategic priority is focused on *cost efficiency*. On the contrary, the large values of cost coefficients for flexibility relative to those for tangible costs means the firm's strategic priority is focused on *flexibility*. Hence, depending upon the firm's strategic focuses according to the values of these coefficients the firm will make different optimal acquisition decisions for new advanced technology. To reflect the top priority of the strategic "fit" emphasized by most manufacturing firms (see Fine and Hax 1985), the values for cost coefficients of strategic competitiveness, e_1 and e_2 , might be given the highest values among the cost coefficients.

4.3 CONSTRAINTS

In this section, the constraints for state variables will be presented followed by the upper bound conditions for control variables. The factors not included in the constraints are assumed to be constant.

4.3.1 Change in Market Demand

A firm may increase total demand in two separate ways. First, a firm can increase

the total demand by capturing the portion of the market share of its competitors through the acquisition of new technology. Second, the total demand can be increased according to the natural growth or decay of the market. As discussed previously, in this study the market demand is viewed in two dimensions, volume and variety. Hence the state equations for the change in market demand are depicted by equation (4.2.1) and equation (4.2.2) in terms of volume and variety respectively. As discussed in section 3.2, both demand response functions are formulated like the well-known Vidale-Wolfe sales response model (Vidale and Wolfe 1957; see also Bass 1980). Y_v and Y_m are total market size in terms of volume and variety respectively, whereas v and m are the firm's actual market demand in terms of volume and variety respectively.

$$v' = \pi_1 a(Y_v - v) + \pi_2 v, \quad v(0) = v_0 \quad (4.2.1)$$

The acquisition of automation capacity in equation (4.2.1) serves as the market stimulus. Since π_1 represents the market responsiveness to the acquisition of automation capacity, the term, $\pi_1 a(Y_v - v)$, denotes the fraction of the competitors' market share in volume captured at any instant time due to the acquisition of automation capacity (see also Kotabe and Murray 1990). The market growth/decay parameter, π_2 , in equation (4.2.1) characterizes the shape of the curve of the exogenous total market demand in volume of *the* PLC. In this study, the firm's aggregate demand is assumed to follow the typical S-shaped curve according to the conventional PLC theory. Hence, the term, $\pi_2 v$, in *equation* (4.2.1) denotes the instantaneous effect on the firm's demand in volume due to *the* changes of the external market forces at a particular stage of PLC.

$$m' = \phi_1 f(Y_m - m) + \phi_2 m, \quad m(0) = m_0 \quad (4.2.2)$$

The state equation for demand variety as depicted by equation (4.2.2) is very

similar to equation (4.2.1) except for the market stimulus factor. As in equation (4.2.1), the parameter, ϕ_1 , in equation (4.2.2) denotes the market responsiveness to the acquisition of flexibility for increasing the firm's product (part) variety of the market demand. It may represent the customers' perception for the firm's innovativeness to introduce more new products (parts) in the market due to the improved flexibility (see Swamidass and Newell 1987). The term, $(Y_m - m)$, represents product (part) types that are available and unique in the market, but recognized by customers as product (part) types not produced by the firm. Accordingly, the first term, $\phi_1 f(Y_m - m)$, denotes the fraction of market product (part) variety captured by the firm at any instant time due to the acquisition of flexibility. The parameter for natural market growth/decay in variety, ϕ_2 , characterizes the changes in product (part) variety along the PLC curve (see also Butler 1988). Hence, the term, $\phi_2 m$, represents the total exogenous change in the firm's demand variety induced by other competitive factors than the acquisition of new technology. According to the formulas given in equation (4.2.1) and equation (4.2.2), both v and m are nonnegative for all $t \in [0, T]$.

4.3.2 Change in Variable Costs

As discussed in section 3.3, the production variable costs are comprised of both volume-related costs and variety-related costs. In equation (4.3.1), the parameter, α , denotes the effectiveness in structural downward shift of the average volume-related cost curve due to the acquisition of automation capacity. According to a study by Buzzell and Wiersema (1981), the reduction in the per unit production and inventory cost is found proportionate to the level of the per unit production and inventory cost at time t (see also Roth et al. 1991). The acquisition of automation capacity, a , causes this structural shift of the volume-related cost. Accordingly, the term, $-\alpha a$, represents the fraction of the volume-related cost, b_1 , to be reduced due to the acquisition of automation capacity at time t . As defined before, B_1 is the lower bound of b_1 . Hence, b_1 approaches

asymptotically B_1 as t goes to infinity. Since new process technology has low level of manual activities involved, the volume-related learning effect becomes insignificant (see section 3.3). Hence, the volume-related learning effect is not considered in this model.

$$b_1' = -\alpha a(b_1 - B_1), \quad b_1(0) = b_{10} \quad (4.3.1)$$

$$b_2' = \beta(s'/s)b_2, \quad b_2(0) = b_{20} \quad (4.3.2)$$

The next state equation (4.3.2) depicts the change in the average variety-related cost due to the acquisition of flexibility. The parameter, β , denotes the proportionate increase in the average variety-related cost due to the increase in product (part) variety that the system processes. The term, $\beta(s'/s)$, represents the fraction of the average variety-related cost that changes according to the change in the product (part) variety processed by the system, s , as illustrated in Figure 3.5. As discussed in section 3.3, the term, s'/s , shows that the increase in the average variety-related cost is decelerated as the cumulative level of overall system flexibility increases. According to the formulas given in equation (4.3.1) and equation (4.3.2), it follows that both b_1 and b_2 are nonnegative for all $t \in [0, T]$.

4.3.3 Change in Production Capacity

The change in the production capacity in units of output, k' , is depicted in equation (4.4) as the net difference between the acquisition of automation capacity and the scrapping/ reducing of conventional (existing) capacity.

$$k' = a - r, \quad k(0) = k_0 \quad (4.4)$$

4.3.4 Change in Cumulative Capacity of New Technology

The change in total accumulated capacity of new technology is represented by the

acquisition rate of new capacity as expressed in equation (4.5). In the scenario analysis, the initial value of x , $x(0)$, determines the initial values of v , the firm's market demand in volume, and b_1 , the average volume-related cost. According to equation (4.5), x is nonnegative for all $t \in [0, T]$. This variable is included to calculate the cumulative investment for automation capacity.

$$x' = a, \quad x(0) = x_0 \quad (4.5)$$

4.3.5 Change in Overall System Flexibility

The overall system flexibility at time t is defined as the number of products (parts) processed by the system at time t . The state equation (4.6) expresses the change in the overall system flexibility due to the acquisition of flexibility. The parameter, ρ_1 , is the effectiveness factor in assimilating the flexibility embedded in the acquired new technology into the total production system to improve the overall system flexibility. This effectiveness factor is quite similar to the synergy factor introduced by Meredith and Camm (1989), which represents the synergy effect among different technologies to reduce in the average production cost due to the acquisition of new technology (see also Roth et al. 1991). Hence, ρ_1 is a maximum system effectiveness representing the organization's ability to assimilate the flexibilities of different technologies. The high value of ρ_1 shows the high effectiveness between the existing technology and the newly acquired automation that realizes the full potential of newly acquired flexibility in improving the overall system flexibility (see also Ettlie and Reifeis 1987; Schroeder 1990). However, the system's flexibility can be reduced due to the scrapping/reduction of conventional or existing capacity. It is assumed here that the system's overall flexibility decreases proportionately by the scrapping/reduction of conventional or existing capacity. In this study, both ρ_1 and ρ_2 are assumed fixed.

$$s' = \rho_1 f - \rho_2 r, \quad s(0) = s_0 \quad (4.6)$$

4.3.6 Inequality Constraints

According to the definitions of automation and flexibility in this model, the acquisition of flexibility should be accompanied by the acquisition of automation. To ensure this, the inequality constraint (4.7.1) is required, where P is a large number. This constraint ensures the nonacquisition of flexibility required in the case of the nonacquisition of automation. It also permits the case of the positive acquisition of automation accompanied by the nonacquisition of flexibility, in which the acquired automation merely increase the capacity of existing automation without any change in the level of overall system flexibility. The constraint (4.7.2) depicts the relationship between p , actual production volume and q , actual production in variety. The explanation for constraint (4.7.2) is analogous to that for constraint (4.7.2)

$$Ha - f \geq 0 \quad (4.7.1)$$

$$Wp - q \geq 0 \quad (4.7.2)$$

$$p \leq k - \psi q \quad (4.7.3)$$

$$q \leq s \quad (4.7.4)$$

$$k \geq 0 \quad (4.7.5)$$

The constraints (4.7.3) and (4.7.4) depict that actual production in volume and variety, p and q , are bounded by actual production capacity in volume and variety, respectively. Note that actual production volume capacity will be reduced proportionately as the number of product (part) types increases as shown in the right hand side of the constraint (4.7.3). The last (4.7.5) is the non-negativity constraints for the production capacity at time t .

4.3.7 Variable Boundaries

The upper and lower bounds for control variables are presented in equation (4.8). The maximum rate of new technology capacity acquisition at time t may be constrained by factors, such as budget (Gaimon 1985), the ability of the organizational infrastructure to assimilate the new technology, and the availability of the technology (Roth et al. 1991). The factors affecting the maximum rate of flexibility acquisition may be similar to those for new technology capacity acquisition. The upper bound on reducing existing old capacity may depend on restrictions due to labor contracts, the ability of the organization to make production process changeovers, and the impact of such changes on the organization (Roth et al. 1991). The upper bounds for p and q , P and Q , are depicted by the constraints (4.7.3) and (4.7.4).

$$a \in (0, A), f \in (0, F), r \in (0, R), p \in (0, P), \text{ and } q \in (0, Q). \quad (4.8)$$

4.4 SUMMARY

In summary, the optimal control model presented in this chapter contains a multi-criterion objective function to maximize the total value of a firm over the planning horizon. The model has seven state constraints, six inequality constraints, and the boundary constraints for the control variables. The whole model is depicted below.

$$\begin{aligned} \text{Max } [G_1 v(T) + G_2 m(T) + G_3 k(T) + G_4 s(T)]E(t) - \int_0^T \{c_1 a^2 + c_2 f^2 + c_3 r^2 + (b_1 + \\ b_2)p + c_4(p - v)^2 + c_5(q - m)^2 + e_1(v - V)^2 + e_2(m - M)^2\}Edt \end{aligned}$$

subject to

$$v' = \pi_1 a(Y_v - v) + \pi_2 v,$$

$$m' = \phi_1 f(Y_m - m) + \phi_2 m,$$

$$b_1' = -\alpha a(b_1 - B),$$

$$b_2' = \beta(s'/s)b_2 ,$$

$$k' = a - r ,$$

$$x' = a ,$$

$$s' = \rho_1 f - \rho_2 r ,$$

$$Ha - f \geq 0 ,$$

$$Wp - q \geq 0 ,$$

$$p \leq k - \psi q ,$$

$$q \leq s ,$$

$$k \geq 0 ,$$

$$v(0) = v_0,$$

$$m(0) = m_0$$

$$b_1(0) = b_{10},$$

$$b_2(0) = b_{20},$$

$$k(0) = k_0,$$

$$x(0) = x_0,$$

$$s(0) = s_0, \text{ and}$$

$$a \in (0, A), f \in (0, F), r \in (0, R), p \in (0, P), \text{ and } q \in (0, Q)$$

CHAPTER V

SOLUTION APPROACH

This chapter presents both the analytical and the numerical solution approaches for the optimal control model presented in Chapter IV. Section 5.1 discusses the analytic optimal solutions for the acquisition of new technology and the scrapping/reducing of conventional capacity. Section 5.2 describes the discretized non-linear version of the model to solve with GRG2 in Microsoft Excel®.

5.1 OPTIMAL POLICIES

This section first displays the necessary optimality conditions from the Hamiltonian equation (5.1) and the Lagrangian equation (5.2). Then it presents the optimal policies for the acquisition rate of new technology and the scrapping/reducing rate of conventional capacity.

5.1.1 Necessary Conditions

The Hamiltonian equation corresponding to the model presented in Chapter IV is given in equation (5.1), where λ_1 , λ_2 , λ_3 , λ_4 , λ_5 , λ_6 , and λ_7 are the adjoint variables related to the state variables, v , m , b_1 , b_2 , k , x , and s , respectively, and E is the discounting factor as defined in section 4.1.3.2.¹⁰

¹⁰ The interpretation for each of the adjoint variables is the marginal value of its respective state variable.

$$\begin{aligned}
H = & \lambda_1 v' + \lambda_2 m' + \lambda_3 b_1' + \lambda_4 b_2' + \lambda_5 k' + \lambda_6 x' + \lambda_7 s' - \\
& \{c_1 a^2 + c_2 f^2 + c_3 r^2 + (b_1 + b_2)p + c_4((p - q)^2 + \\
& c_5(q - m)^2 + e_1(v - V)^2 + e_2(m - M)^2\}E,
\end{aligned} \tag{5.1}$$

Due to the inequality constraints in section 4.3.6, a Lagrangian equation is formed as

$$L = H + \eta_1(Ha - f) + \eta_2(Wp - q) + \eta_3(k - \psi q - p) + \eta_4(s - q), \tag{5.2}$$

where η_1 , η_2 , η_3 , and η_4 are Lagrange multipliers. The last nonnegativity constraint for the production capacity is not considered explicitly in the above equation. Later, during the numerical solution procedure if $r(t) - a(t) > k(t)$ occurs for any time $t \in [0, T]$, then the algorithm will modify the value of $r(t)$ in order to make $r(t) - a(t) = k(t)$ so that $k(t) \geq 0$ is not violated.

The optimality conditions for the model are presented below. Equations (5.3) through (5.9) are the same constraints as presented in Chapter IV with the initial values for the state variables. Equations (5.10) through (5.21) are derived from the Lagrangian equation (5.2) by taking the first derivatives with respect to the state and adjoint variables. Detailed expressions for the conditions from (5.10) through (5.16) are shown in Appendix I. The complimentary slackness conditions of (5.22)-(5.25) are needed for the inequality constraints (4.7.1)-(4.7.4) to be satisfied. The necessary conditions and the complementary slackness conditions for the optimality of the model are;

$$v' = \pi_1 a(Y_v - v) + \pi_2 v, \quad v(0) = v_0, \tag{5.3}$$

$$m' = \phi_1 f(Y_m - m) + \phi_2 m, \quad m(0) = m_0, \tag{5.4}$$

$$b_1' = -\alpha a(b_1 - B), \quad b_1(0) = b_{10}, \tag{5.5}$$

$$b_2' = \beta(s/s)b_2, \quad b_2(0) = b_{20}, \tag{5.6}$$

$$k' = a - r, \quad k(0) = k_0, \quad (5.7)$$

$$x' = a, \quad x(0) = x_0, \quad (5.8)$$

$$s' = \rho_1 f - \rho_2 r, \quad s(0) = s_0, \quad (5.9)$$

$$\lambda_1' = -\delta L/\delta v, \quad \lambda_1(T) = G_1 E(T), \quad (5.10)$$

$$\lambda_2' = -\delta L/\delta m, \quad \lambda_2(T) = G_2 E(T), \quad (5.11)$$

$$\lambda_3' = -\delta L/\delta b_1, \quad \lambda_3(T) = 0, \quad (5.12)$$

$$\lambda_4' = -\delta L/\delta b_2, \quad \lambda_4(T) = 0, \quad (5.13)$$

$$\lambda_5' = -\delta L/\delta k, \quad \lambda_5(T) = G_3 E(T), \quad (5.14)$$

$$\lambda_6' = -\delta L/\delta x, \quad \lambda_6(T) = 0, \quad (5.15)$$

$$\lambda_7' = -\delta L/\delta s, \quad \lambda_7(T) = G_4 E(T), \quad (5.16)$$

$$\delta L/\delta a = 0, \text{ for } a = (0, A), \quad (5.17)$$

$$\delta L/\delta f = 0, \text{ for } f = (0, F), \quad (5.18)$$

$$\delta L/\delta r = 0, \text{ for } r = (0, R), \quad (5.19)$$

$$\delta L/\delta p = 0, \text{ for } p = (0, P), \quad (5.20)$$

$$\delta L/\delta q = 0, \text{ for } q = (0, Q), \quad (5.21)$$

$$\eta_1 \geq 0, \quad Ha - f \geq 0, \quad \eta_1(Ha - f) = 0, \quad (5.22)$$

$$\eta_2 \geq 0, \quad Wp - q \geq 0, \quad \eta_2(Wp - q) = 0, \quad (5.23)$$

$$\eta_3 \geq 0, \quad k - \psi q - p \geq 0, \quad \eta_3(k - \psi q - p) = 0, \text{ and } \quad (5.24)$$

$$\eta_4 \geq 0, \quad s - q \geq 0, \quad \eta_4(s - q) = 0. \quad (5.25)$$

5.1.2 Optimal Policies for Acquiring New Technology

In Theorem 1, the optimal policies for the control variables, $a(t)$ and $f(t)$, satisfying both the necessary conditions and the complementary slackness condition in section 5.1.1, are stated.

Theorem 1: The optimal policies for the acquisition rates of automation capacity and flexibility are depicted below. According to the complementary slackness condition of

(5.22), there are two possible cases for the optimal policies for the acquisition rates of automation capacity and flexibility.

Case 1. If $Ha(t) - f(t) > 0$, then $\eta_1(t) = 0$ and $a(t) > 0$ and $f(t) \geq 0$.

Hence,

$$a(t) = \begin{cases} A(t), & \text{if } \theta_a(t) \geq A(t) \\ \theta_a(t), & \text{if } 0 < \theta_a(t) < A(t) \end{cases} \quad \text{and} \quad (5.26)$$

$$f(t) = \begin{cases} F(t), & \text{if } \theta_f(t) \geq F(t) \\ \theta_f(t), & \text{if } 0 < \theta_f(t) < F(t) \\ 0, & \text{if } \theta_f(t) \leq 0 \end{cases} \quad (5.27)$$

, where

$$\begin{aligned} \theta_a(t) = & \{ \lambda_1(t)\pi_1[Y_v - v(t)] - \lambda_3(t)\alpha[b_1(t) - B] \\ & + \lambda_5(t) + \lambda_6(t) + \eta_1(t)H \} / 2c_1E(t) \end{aligned} \quad (5.28)$$

and

$$\begin{aligned} \theta_f(t) = & \{ \lambda_2(t)\phi_1[Y_m - m(t)] + \lambda_4(t)\beta\rho_1s^{-1}(t)b_2(t) \\ & + \lambda_7(t)\rho_1 - \eta_1(t) \} / 2c_2E(t). \end{aligned} \quad (5.29)$$

Case 2. If $Ha(t) - f(t) = 0$, then $\eta_1(t) \geq 0$ and both $a(t)$ and $f(t) = 0$.

Hence,

if $\theta_a(t) \leq 0$ with $\eta_1(t)$ being ignored,

$a(t) = 0$ and $f(t) = 0$ regardless of the value of $\theta_f(t)$.

Theorem 1 assures that the acquisition of flexibility should be accompanied by the acquisition of automation capacity. Here, equations (5.28) and (5.29) are the solutions of necessary conditions (5.17) and (5.18) with respect to $a(t)$ and $f(t)$, respectively. When $\theta_a(t)$ is positive, Case 1 holds. In Case 1, although the firm purchases automation capacity, it may or may not purchase the flexibility depending on the value of the numerator in equation (5.29). When $\theta_a(t)$ is not positive, then Case 2 holds. In Case 2, $a(t)$ becomes 0 and $f(t)$ also becomes zero regardless of the value of $\theta_f(t)$ due to the

complementary slackness condition (5.22). Hence, when there is no acquisition of automation capacity there should be no acquisition of flexibility.

Ignoring the Lagrange multiplier $\eta_1(t)$, the interpretation of the optimal policies for the acquisition of new technology should be focused on the adjoint variables in equation (5.28) and equation (5.29). First, in equation (5.28), the acquisition of automation capacity depends on the combination of four marginal values associated with: (1) additional unit of demand in volume due to the acquisition of automation capacity, $\lambda_1(t)\pi_2(Y_v-v(t))$; (2) the reduction of average volume-related cost due to the acquisition of automation capacity, $-\lambda_3(t)\alpha[b_1(t)-B]$; (3) a unit increase in production capacity, λ_5 ; and (4) a unit increase in automation capacity, λ_6 . Hence, the acquisition rate of automation is the net marginal contribution to the objective function of a unit increase in automation capacity at time t divided by its discounted purchase cost, $2c_1E(t)$.

It is interesting to note that, even though the marginal value of increasing production capacity or automation capacity, λ_5 or λ_6 , is negative in equation (5.28), it is still possible to purchase automation capacity due to the other considerations, such as demand increase in volume and lowering production costs. In particular, as seen in the first term of the numerator, total market size, Y_v , as an exogenous variable, can have an impact on the acquisition of automation capacity. This means the firm's acquisition policy of the automation capacity depends on the external market conditions, as discussed in Chapter III.

As depicted in equation (5.29), the acquisition of flexibility depends on the combination of three marginal values associated with: (1) unit increase of demand in variety due to the acquisition of flexibility, $\lambda_2(t)\phi_1(Y_m-m(t))$; (2) increase in the average variety-related cost due to the acquisition of flexibility, $\lambda_4(t)\beta\rho_1s^{-1}(t)b_2(t)$; and (3) increase in the overall system's flexibility due to the acquisition of flexibility. Hence, equation (5.29) represents the acquisition rate of flexibility as the net contribution to the objective function of the additional unit purchase of flexibility at time t divided by its

discounted purchase cost, $2c_2E(t)$. As for the acquisition of automation capacity in equation (5.28), the total market sizes in volume and variety, Y_v and Y_m , in equation (5.29) also affect the acquisition of flexibility.

Hence, the existence of exogenous market variables in equation (5.28) and equation (5.29) suggests that the firms should determine the acquisition policy for the new technology with due consideration of potential market growth or decay in the future. In fact, it would be much easier to increase a firm's market share through the acquisition of new technology in a market with a growing phase than in a market with a declining phase. In the latter case, the investment in new technology at the early stage with a wrong market forecast might cause a serious financial strain to the firm with actual aggregate sales declining in the future and, consequently, result in the loss of the firm's competitive strength in the long run. This is why, as the model suggests, the decision making process for the acquisition of new technology should consider external market conditions along with the firm's strategic priority.

5.1.3 Optimal Policy for Reducing Conventional Capacity

In Theorem 2, the optimal policy for the scrapping/reducing rate of conventional capacity resulting from the optimality condition (5.19) is presented.

Theorem 2: The optimal scrapping/reducing rate of conventional capacity is

$$r(t) = \begin{cases} R(t), & \text{if } R(t) \leq \theta_r(t) \\ \theta_r(t), & \text{if } 0 < \theta_r(t) < R(t) \\ 0, & \text{if } \theta_r(t) \leq 0 \end{cases} \quad (5.30)$$

$$, \text{ where } \theta_r(t) = - [\lambda_4(t)\beta\rho_2s^{-1}(t)b_2(t) + \lambda_5(t) + \lambda_7(t)\rho_2]/2c_3E(t). \quad (5.31)$$

Theorem 2 states the scrapping/reducing rate of conventional capacity is determined as the policy shown in equation (5.30). Equation (5.31) is the result of solving

necessary condition (5.19) with respect to $r(t)$. According to equation (5.31), the rate of scrapping/reducing conventional capacity depends on three marginal values associated with: (1) decrease in average variety-related costs due to unit decrease in conventional capacity, $-\lambda_4(t)\beta\rho_2s^{-1}(t)b_2(t)$; (2) decrease in production capacity due to unit decrease in conventional capacity, $-\lambda_5(t)$; and (3) decrease in overall system flexibility due to unit decrease in conventional capacity, $-\lambda_7(t)\rho_2$. Hence, the scrapping/reducing rate of conventional capacity is determined as the ratio of the sum of three marginal values to the discounted cost of the reducing conventional capacity as shown in equation (5.31). Note that the firm would reduce the conventional capacity as the marginal value of additional production capacity, $\lambda_5(t)$, is negative and the others are nil in equation (5.31). Therefore, it is possible to see the acquisition of new technology and the scrapping/reducing of conventional capacity at the same time since the new technology can be purchased although $\lambda_5(t)$ is negative as discussed in section 5.1.2.

5.1.4 Optimal Policies for Production Rates

Theorem 3 provides two optimal policies for the rate of production, one for production volume and another for production variety.

Theorem 3: The optimal policies for the rate of production are depicted below.

According to the complementary slackness condition of (5.23), there are two possible cases for the optimal policies for the rate of production.

Case 1: If $Wp(t) - q(t) > 0$, then $\eta_2(t) = 0$, $p(t) > 0$, and $q(t) \geq 0$

Hence,

$$p(t) = \begin{cases} P(t), & \text{if } \theta_p(t) \geq P(t) \\ \theta_p(t), & \text{if } 0 < \theta_p(t) < P(t) \end{cases}, \text{ and} \quad (5.32)$$

$$q(t) = \begin{cases} Q(t), & \text{if } \theta_q(t) \geq Q(t) \\ \theta_q(t), & \text{if } 0 < \theta_q(t) < Q(t) \\ 0, & \text{if } \theta_q(t) \leq 0 \end{cases} \quad (5.33)$$

where

$$\theta_p(t) = [(2c_4v(t) - b_1(t) - b_2(t))E(t) + \eta_2(t)W - \eta_3(t)]/2c_4E(t) \quad (5.34)$$

and

$$\theta_q(t) = (2c_5m(t)E(t) - \eta_2(t) - \eta_3(t)\psi - \eta_4(t))/2c_5E(t). \quad (5.35)$$

Case 2: If $Wp(t) - q(t) = 0$, then $\eta_2(t) \geq 0$, $p(t) = 0$, and $q(t) = 0$.

Hence, if $\theta_p(t) \leq 0$, $p(t) = 0$ and $q(t) = 0$ regardless of the value of $\theta_q(t)$.

Theorem 3 states the optimal policies for production levels in terms of volume and variety are determined as shown in (5.32) and (5.33). Equation (5.34) and (5.35) are the solutions of necessary conditions (5.20) and (5.21) with respect to $p(t)$ and $q(t)$, respectively. Explanation for Case 1 and Case 2 of Theorem 3 is similar to that of Theorem 1. Case 1 explains that no production in variety is possible although there is positive production in volume. Case 2 explains the fact that no production in volume should accompany no production in variety.

Ignoring Lagrange multipliers, equations (5.34) and (5.35) state that production level in volume is determined by $v(t)$, the actual demand in volume, and production level in variety by $m(t)$, the actual demand in variety. Furthermore, according to the constraint (4.7.3), production level in volume is limited by $k-\psi q$, effective production capacity in volume. Production level in variety is also constrained by s , the level of system's flexibility according to the constraint (4.7.4). Therefore, $P(t)$ and $Q(t)$, the upper bounds of $p(t)$ and $q(t)$, might have different values at any time t depending upon whether the constraints (4.7.3) and (4.7.4) are satisfied or not.

If the values of $\theta_p(t)$ and $\theta_q(t)$ violates any of the constraints (4.7.3) and (4.7.4) when both $\eta_1(t)$ and $\eta_2(t)$ are ignored, the values of Lagrange multipliers for violated

constraints become positive and the optimal values for $p(t)$ and $q(t)$ have to be modified accordingly.

5.2 SOLUTION ALGORITHM

5.2.1 Discretized Non-Linear Version of the Model

Since the closed form solutions for the model can not be obtained due to the dynamic interactive behavior of the state, control, and adjoint variables, it is approximated through the conversion to a discrete-time non-linear problem. The converted problem is solved using GRG2 algorithm with the MicroSoft Excel®. The discrete-time non-linear problem is presented below.

$$\begin{aligned} \text{Max } [G_1v(T) + G_2m(T) + G_3k(T) + G_4s(T)]E(T) - \sum_{t=0}^{T-1} \{c_1a^2(t) + c_2f^2(t) + c_3r^2(t) \\ + [b_1 + b_2]p(t) + c_4[p(t) - v(t)]^2 + c_5[q(t) - m(t)]^2 + e_1[v(t) - V(t)]^2 \\ + e_2[m(t) - M(t)]^2\}E(t) \end{aligned} \quad (5.36)$$

subject to

$$v(t+1) = v(t) + \Delta t(\pi_1 a(t)[Y_v - v(t)] + \pi_2 v(t)), \quad \text{for } t = 0, \dots, T-1 \quad (5.37)$$

$$m(t+1) = m(t) + \Delta t(\phi_1 f(t)[Y_m - m(t)] + \phi_2 m(t)), \quad \text{for } t = 0, \dots, T-1 \quad (5.38)$$

$$b_1(t+1) = b_1(t) - \Delta t(\alpha a(t)b_1(t)), \quad \text{for } t = 0, \dots, T-1 \quad (5.39)$$

$$b_2(t+1) = b_2(t) + \Delta t(\beta[s'(t)/s(t)]b_2(t)), \quad \text{for } t = 0, \dots, T-1 \quad (5.40)$$

$$k(t+1) = k(t) + \Delta t(a(t) - r(t)), \quad \text{for } t = 0, \dots, T-1 \quad (5.41)$$

$$x(t+1) = x(t) + \Delta t a(t), \quad \text{for } t = 0, \dots, T-1 \quad (5.42)$$

$$s(t+1) = s(t) + \Delta t(\rho_1 f(t) - \rho_2 r(t)), \quad \text{for } t = 0, \dots, T-1 \quad (5.43)$$

$$Ha(t) - f(t) \geq 0, \quad \text{for } t = 0, \dots, T-1 \quad (5.44)$$

$$Wp(t) - q(t) \geq 0, \quad \text{for } t = 0, \dots, T-1 \quad (5.45)$$

$$p(t) \leq k(t) - \psi q(t), \quad \text{for } t = 0, \dots, T-1 \quad (5.46)$$

$$q(t) \leq s(t), \quad \text{for } t=0, \dots, T-1 \quad (5.47)$$

$$k(t) \geq 0, \quad \text{for } t=0, \dots, T \quad (5.48)$$

$$v(0) = v_0, \quad (5.49)$$

$$m(0) = m_0, \quad (5.50)$$

$$b_1(0) = b_{10}, \quad (5.51)$$

$$b_2(0) = b_{20}, \quad (5.52)$$

$$k(0) = k_0, \quad (5.53)$$

$$x(0) = x_0, \quad (5.54)$$

$$s(0) = s_0, \text{ and} \quad (5.55)$$

$$a(t) \in [0, A(t)], f(t) \in [0, F(t)], r(t) \in [0, R(t)], \\ p(t) \in [0, P(t)], \text{ and } q(t) \in [0, Q(t)] \quad (5.56)$$

In the preliminary study, the problem with base scenario is actually solved by taking the time step, Δt , in Equation (5.37) through (5.43) as both .5 and 1. It is found that the solutions with the time step of .5 give smoother results for the optimal values of control variables than with the time step of 1 as they are plotted in graphs, but the solutions in terms of the pattern of acquisition policy are quite insensitive to the values of time step.

5.2.2 Limitations

Since the solution of the non-linear problem by any commercial algorithm available right now usually depends on the initial values of decision variables, the solution process inevitably has to follow a trial and error procedure. To find whether the solution at a certain step is a local optimum, the values of control variables at that step are carefully checked to find whether there is some room for improvement in the objective function by the changes in the values of control variables without violating the constraints. If the solution is found to be a local optimum, the values of control variables are modified and,

then, the problem is re-run. With this kind of iterative procedure, most of the problems have been solved after several iterations.

The major limitation regarding this solution process is that the solutions are near optimal due to the conversion of the original continuous-time model to a discrete-time non-linear one. Since there is no closed form solution for this problem, this is the only option to find the optimal solution. The second limitation is a generic problem with most of solution algorithms for non-linear problems, which can not guarantee the global optimum. Since there is no theoretical background to find the global optimum, some of the solutions presented in this dissertation might be local optimum. However, since the objective function of the model here is convex, it can be expected that most of the solutions presented later in Chapter 6 would be global optimum.

The last limitation is the value of Δt which is considered as 1 in this study. Due to the capacity of the solution algorithm it was not allowed to have a small size of the time step. If a solution algorithm which can handle a large problem more experiments will be conducted with different sizes of the time step.

CHAPTER VI

SCENARIO ANALYSIS

In this chapter scenario analysis with hypothetical settings is conducted. The first section of this chapter presents a general description of the experimental design, and the second section presents the results of the scenario analysis and discusses the strategic and managerial implications of the effects of research factors on the optimal acquisition of automation capacity and flexibility.

6.1 OVERVIEW OF DESIGN FOR SCENARIO ANALYSIS

This section is an overview of experimental factors, the settings of factors, the level and value settings for their related variables for the scenario analysis. The strategic choice and the PLC as major experimental factors are explained in Section 6.1.1. In Section 6.1.2 initial process technology as a structural factor is explained. In Section 6.1.3 the level and value settings of research variables related to the experimental factors are presented. In Section 6.1.4 the value settings for other exogenous variables are explained. In Section 6.1.5 the hypothetical PLC curves used in the scenario analysis are discussed. In Section 6.1.6 the frameworks of the design for the scenario analysis are presented. Finally, in Section 6.1.7 the performance measures are explained.

6.1.1 Strategic Choices and The PLC

Major research factors identified in the literature review are the stage of the PLC and the choice of a firm's strategic priority (see Table 6.1 and Table 6.2). Table 6.1 depicts possible strategic choices of the combination of strategic priorities which a firm can pursue when the market behaves according to the evolution of conventional PLC theory from the introductory stage (I), to the growth stage (G), to the mature stage (M).

In Table 6.2 the possible strategic choices when the market behaves according to the theory of the reversal of the PLC are presented. In this scenario analysis the declining stage of the PLC is not included since this stage does not match with any point of the horizontal axis in the product-process matrix. Furthermore, each firm, as continuous business entities, may have different strategies for the existing production capacity at this stage according to the type of industry in which it is operating.

Table 6.1
Strategic Choices and The Normal PLC

Strategic Choice	Evolution of PLC*		
	I	G	M
1-1	Flexibility	Flexibility/ Cost Efficiency	Cost Efficiency
1-2	Cost Efficiency	→	
1-3	Flexibility	→	

* I stands for introductory stage, G stands for growth stage, and M stands for maturity stage.

In Table 6.1 the possible choices of the combination of strategic priorities during the evolution of the PLC are given: (1) choice 1-1, in which a firm's strategic priority is changing from flexibility for the introductory stage, and flexibility/cost efficiency for the growth stage, to cost efficiency for the mature stage; (2) choice 1-2, in which the strategic priority is always cost efficiency; and (3) choice 1-3, in which the strategic priority is always flexibility. Choice 1-1 is the one generally supported by the literature (Hayes and Wheelwright 1984; Hill 1980).

In Table 6.2 the PLC is assumed to evolve from the introductory stage (I), through the growth stage (G), and then back to the growth stage (RG) again. The possible

strategic choices are (1) choice 2-1, which is the same as choice 1-1 in Table 6.1; (2) choices 2-2 and 2-3, which are the same as choices 1-2 and 1-3, respectively; and (3) choice 2-4, which is similar to choice 1-1 except that it includes flexibility for the RG stage.

Table 6.2
Strategic Choices and the Reversed PLC

Strategic Choice	Reversal of PLC		
	I	G	RG*
2-1	Flexibility	Flexibility/ Cost Efficiency	Flexibility
2-2	Cost Efficiency	→	
2-3	Flexibility	→	
2-4	Flexibility	Flexibility/ Cost Efficiency	Flexibility

* RG stands for reversed growth stage.

6.1.2 Positioning of Initial Process Technology

There are two structural variables related to the positioning of initial process technology: (1) s_0 , the initial level of flexibility and (2) X_0 , the initial level of automation. As shown in Figure 6.1, there are four types of initial process technology with different combinations of s_0 and X_0 : (1) Firm A with high s_0 and low X_0 ; (2) Firm B with high s_0 and high X_0 ; (3) Firm C with low s_0 and low X_0 ; and (4) Firm D with low s_0 and high X_0 . In Figure 6.2 the combination of levels of these two variables determines a firm's initial process technology in the technology matrix.

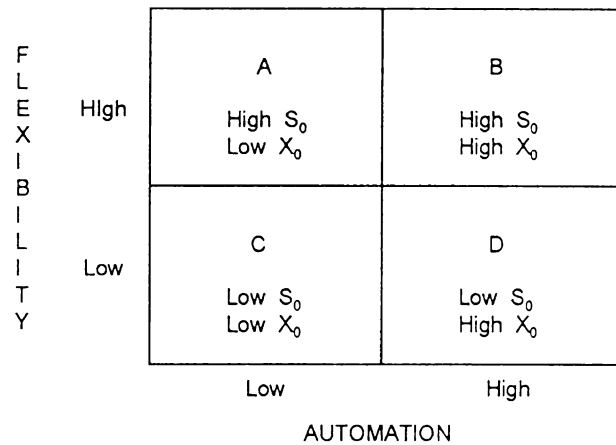


Figure 6.1 Four Types of Initial Technology Choice

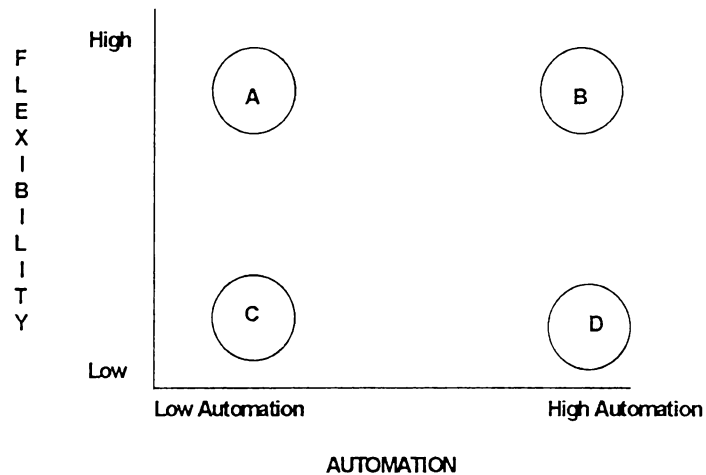


Figure 6.2 Positioning of Initial Technology Choice

According to the normative concept of the Product-Process Matrix, Firm A, with high flexibility and low economies of scale, is suitable for the production of products of high variety and low volume. On the contrary, Firm D, with low flexibility and high economies of scale, is suitable for the production of products of low variety and high volume. Firm B, with high flexibility and high economies of scale, can operate efficiently in a wide span of operating environments from the high variety/low volume stage to the low variety/high volume stage. Firm C is also included in the analysis, although this has

not been considered as a practical setting in a static environment. However, there is yet no conclusive theory for the best initial technology choice in a dynamic environment such as the one in this study.

6.1.3 Settings of Variables

The values of some exogenous variables as defined in section 4.1.3.2 change according to the different combination of levels of the factors discussed in section 6.3.1. In Table 6.3 the variables whose settings are changing according to the evolution of the PLC include (1) $Y_v(t)$, the total market size in volume; (2) $Y_m(t)$, the total market size in variety; (3) π_2 , the growth/decay factor of a firm's market share in volume; and (4) ϕ_2 , the growth/decay factor of a firm's market share in variety. The settings for $Y_v(t)$ and π_2 are the same for all stages of the PLC. The settings for $Y_m(t)$ and ϕ_2 are also the same for all the stages of PLC. This is due to the fact that both π_2 and ϕ_2 follow the behavior of the total market size according to the evolution of the PLC.

Table 6.3

Variable Settings for the Stages of the PLC

Variables	Stages of PLC			
	I	G	M	RG
$Y_v(t)$	MG	FG	SG	MG
$Y_m(t)$	FG	FD	SD	SG
π_2	MG	FG	SG	MG
ϕ_2	FG	FD	SD	SG

* F stands for fast, M for medium, S for slow, G for growth, and D for decline

The settings of $Y_v(t)$ -- the total market size in volume -- are (1) medium growth at the introductory stage; (2) fast growth at the growth stage; (3) slow growth at the mature stage; and (4) medium growth at the reversed growth stage. The settings for $Y_m(t)$ -- the total market size in variety -- are (1) fast growth at the introductory stage; (2) fast decline at the growth stage; (3) slow decline at the mature stage; and (4) slow growth at the reversed growth stage.

Table 6.4

Variable Settings for Strategic Priorities

Variables	Strategic Priority		
	Flexibility	Cost Efficiency	Flexibility /Cost Efficiency
C_4	H*	L	M
C_5	H	L	M
$V(t)$	L	H	M
$M(t)$	H	L	M

As depicted in Table 6.4, variables related to the strategic priority are (1) c_4 , costs for inflexibility of lead time; (2) c_5 , costs for inflexibility of variety; (3) $V(t)$, the business goal of the market share in terms of volume; and (4) $M(t)$, the business goal of the market share in terms of variety. The settings of c_4 and c_5 are (1) high values for c_4 and c_5 when a firm's strategic priority is flexibility; (2) low values for c_4 and c_5 when a firm's strategic priority is cost efficiency; and (3) medium values for c_4 and c_5 when a firm's strategic priority is flexibility/cost efficiency. The settings of $V(t)$ are (1) low for the priority of flexibility; (2) high for the priority of cost efficiency; and (3) medium for the priority of flexibility/cost efficiency. The settings of $M(t)$ are (1) high for the priority of flexibility;

(2) low for the priority of cost efficiency; and (3) medium for the priority of flexibility/cost efficiency.

Table 6.5

Value Settings of Research Variables
Related to the Strategic Choice

	High	Medium	Low
C_4	100	50	25
C_5	200	100	50
μ_v	.002	.001	.0005
μ_m	.01	.005	.0025

The values corresponding to the levels of research variables related to the strategic choice are depicted in Table 6.5. The values of C_5 are twice that of C_4 at each level to reflect the difference in the acquisition cost between automation capacity and flexibility. The value settings for $V(t)$ and $M(t)$, the SBU's goals of the market share in terms of volume and variety, are represented by the growth factors -- μ_v and μ_m -- in the functions defined below. It is assumed that

$$V(t) = Y_v(t) (c + \mu_v(t-i)) \text{ and}$$

$$M(t) = Y_m(t) (d + \mu_m(t-i)),$$

where both c and d are .1 at time 0 and represent the firm's market share at the starting time of each stage of the PLC, and i is the index of the initial period of each stage of the PLC.

As depicted in Table 6.6, the variables related to structural factors -- s_0 and x_0 -- are (1) b_{10} , the initial average volume-related cost and (2) b_{20} , the initial average variety-related cost. The settings of these two variables are (1) high b_{10} and low b_{20} for Firm A; (2) low b_{10} and low b_{20} for Firm B; (3) high b_{10} and high b_{20} for Firm C; and (4) low b_{10} and high b_{20} for Firm D.

Table 6.6

Variable Settings for the Positioning of Initial Technology Choice

Initial Technology Choice			Initial Production Cost	
Type	x_0	s_0	Volume-Related (b_{10})	Variety-Related (b_{20})
A	L	H	H	H
B	H	H	L	H
C	L	L	H	L
D	H	L	L	L

* H stands for high and L for low

Table 6.7

Value Settings of Research Variables
Related to Initial Process Technology

	High	Low
x_0 (b_{10})	150 (25)	50 (30)
s_0 (b_{20})	100 (15)	10 (10)

The value setting for these two variables are presented in Table 6.7. The values in parentheses are the initial values for average volume- and variety- related variable costs -- b_{10} and b_{20} -- corresponding to each level of x_0 and s_0 . These values are determined after the preliminary runs. The high value of b_{10} and b_{20} are set arbitrarily at 30 and 10 with x_0 at 50 and s_0 at 10. After running several problems with different settings of the other variables, the values of b_{10} and b_{20} corresponding to the values of x and s , 150 and 100 are interpolated from the solutions. As a result, the value for b_{10} is 25 when x_0 is 150 and the value of b_{20} is 15 when s_0 is 100.

6.1.4 Values of Exogenous Variables

The values of the base scenario is presented in Table 6.8. Most of the values in the base scenario are similar to those in the study by Roth and Gaimon (1991). However, there are some exogenous variables unique to this model. The values of these exogenous variables are set after some experimentation with various levels for each one.

The values of G_1 , G_2 , G_3 , and G_4 -- the marginal values at the terminal time of the firm's market share in volume, $v(T)$, the firm's market share in variety, $m(T)$, the capacity in volume, $k(T)$, and the system's flexibility, $s(T)$ -- are set at 300, 600, 50, and 100, respectively. The values of C_1 , C_2 , and C_3 -- the acquisition cost of automation and flexibility, and the scrapping cost of existing or conventional capacity -- are set at 50, 100, and 20, respectively. The cost of flexibility, C_2 , is set as twice the cost of automation, C_1 , in order to reflect the fact that the flexible system costs an enormous amount compared to a mere automated system such as the stand-alone NC machine.

The values of E_1 and E_2 -- the costs related to the strategic fit between business strategy and corporate strategy -- are set at 1000 and 2000, respectively. These values are larger than others because of the high priority given to the fit among strategies in different levels. During the preliminary runs, these two values have been found as major factors

influencing the effectiveness of initial process technology on the optimal policy for technology acquisition. This will be further discussed in detail later in Section 6.2.

Table 6.8
Value Settings for Exogenous Variables

Parameters	Value
G_1	300
G_2	600
G_3	50
G_4	100
C_1	50
C_2	100
C_3	20
E_1	1000
E_2	2000
π_1	.00002
ϕ_1	.0005
α	.002
β	.1
B	1
ρ_1	.8
ρ_2	.1
MA	200
MF	40
MR	20
ψ	.5
H	1.0E+10
W	1.0E+10

The values of the market responsiveness factor, π_1 and ϕ_1 , are set at .00002 and .0005, respectively. It has been found that these two values have a significant impact on the overall cost performance of each problem during preliminary runs (see also Roth and Gaimon 1991). Since the purpose of this dissertation is not to study the sensitivity analysis of research parameters with the model here, the values of these factors are

determined at reasonable levels after close scrutiny of the results of the preliminary runs. The values of effectiveness factors for the variables costs, α and β , are set at .002 and .1, respectively. It has been found that these two factors have a significant impact on the size of investment of both automation capacity and flexibility. However, they are not affecting the general pattern (policy) for the acquisition of automation capacity and flexibility.

The minimum value of the volume-related cost is assigned at 1. The effectiveness factors for the system's flexibility, ρ_1 and ρ_2 , are set at .8 and .1, respectively. Within the reasonable range of the values for these two factors, there has been no significant impact on the optimal solution with the base scenario. The upper bounds for the control variables -- $a(t)$, $f(t)$, and $r(t)$ -- are set at 200, 40, and 20, respectively. The value of ψ , the effectiveness factor of scrapping existing capacity($r(t)$) on the total capacity on volume($k(t)$), is set at .8. This factor is also found to be an insignificant factor affecting the optimal solutions. The values of H and W are set at both $1.0E+10$ as a large number.

6.1.5 Hypothetical PLC Curves

The difference between the normal PLC curve and the reversed PLC curve has already been discussed in Chapter II. Tables 6.9 and 6.10 depict the discretized values for π_2 and ϕ_2 for the normal PLC curve and the reversed PLC curve. π_2 defines the shape of the total market size of volume, and ϕ_2 the shape of the total market size of variety. The shapes of the PLC curves used for the scenario analysis are illustrated in Figures 6.3 through Figure 6.6. The curves in Figure 6.3 and Figure 6.5 depict the aggregate demand in units of output by combining the market demand of all products in a family. The total market demand of variety is also the aggregate demand of all products in the same family. It is assumed that

$$Y_v(t) = Y_v(0)^{(a+\pi_2(t-i))}, Y_v(0)=1000, \text{ and}$$

$$Y_m(t) = Y_m(0)^{(b+\phi_2(t-i))}, Y_m(0)=100,$$

where both a and b are the exponents for the values of Y_v and Y_m at the starting time of each stage of the PLC, both π_2 and ϕ_2 are the growth factor of Y_v and Y_m determined exogenously, and i is the index of the initial period of each stage of the PLC.

Table 6.9

The Values of Variables
of the Normal PLC

	t	π_2	ϕ_2	Y_v	Y_m
Introductory Stage	0	.02	.20	1000.0	100.0
	1	.04	.50	1020.0	120.0
	2	.10	.70	1060.8	180.0
	3	.20	.30	1166.9	306.0
Growth Stage	4	.30	.10	1400.3	397.8
	5	.30	.01	1820.3	437.6
	6	.30	-.01	2366.4	441.9
	7	.30	-.10	3076.4	437.5
	8	.30	-.40	3999.3	393.8
	9	.20	-.30	5199.1	236.3
	10	.10	-.20	6238.9	165.4
	11	.05	-.10	6862.7	132.3
Mature Stage	12	.03	-.05	7205.9	119.1
	13	.02	-.01	7422.1	113.1
	14	.01	-.01	7570.5	112.0
	15	.01	-.01	7646.2	110.9
	16	.01	-.01	7722.7	109.8
	17	.01	-.01	7799.9	108.7
	18	.01	-.01	7877.9	107.6
	19	.01	-.01	7956.7	106.5
	20	.01	-.01	8036.2	105.4

The shape of the normal PLC curves can be found ubiquitously in the literature. The shape of the reversed PLC curves as in Figure 6.4 and Figure 6.6 are yet unpopular.

Generally it is argued that the demand of volume after the growth stage of the reversed PLC continue to grow without entering into the maturity stage, and also the demand of variety continues to rise after the growth stage (Albernathy et al. 1983; Ayres and Steger 1983).

Table 6.10

The Values of Variables
of the Reversed PLC

	t	π_2	ϕ_2	Y_v	Y_m
Introductory Stage	0	.02	.20	1000.0	100.0
	1	.04	.50	1020.0	120.0
	2	.10	.70	1060.8	180.0
	3	.20	.30	1166.9	306.0
Growth Stage	4	.30	.10	1400.3	397.8
	5	.30	.01	1820.3	437.6
	6	.30	-.01	2366.4	442.0
	7	.30	-.10	3076.4	437.5
	8	.30	-.20	3999.3	393.8
	9	.20	-.10	5199.1	315.0
	10	.10	-.05	6238.9	283.5
	11	.05	-.01	6862.7	269.3
Reversed Growth Stage	12	.01	.01	7205.9	266.7
	13	.05	.05	7277.9	269.3
	14	.05	.10	7641.8	282.8
	15	.05	.10	8023.9	311.1
	16	.05	.10	8425.1	342.2
	17	.03	.05	8846.4	376.4
	18	.02	.03	9111.8	395.2
	19	.01	.01	9294.0	407.1
	20	.01	.01	9387.0	411.1

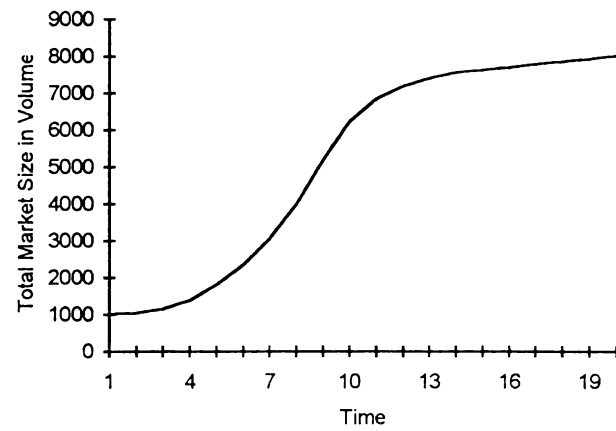


Figure 6.3 Changes in Total Market Volume of the Normal PLC

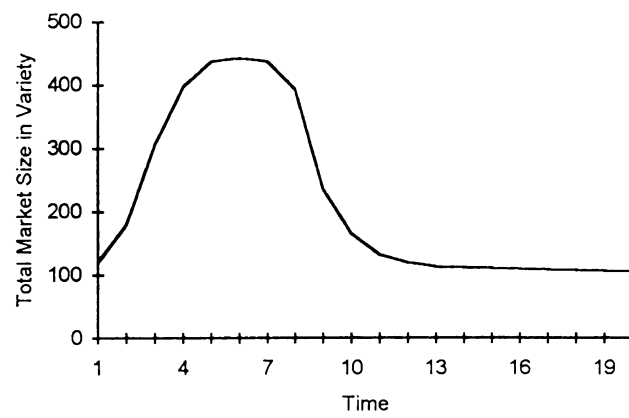


Figure 6.4 Changes in Total Market Variety of the Normal PLC

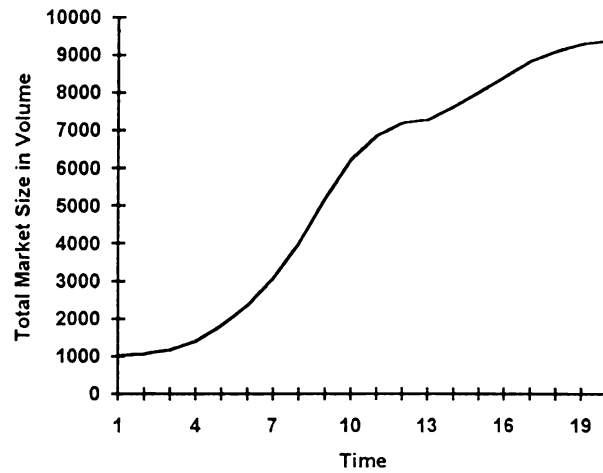


Figure 6.5 Changes in Total Market Volume of the Reversed PLC

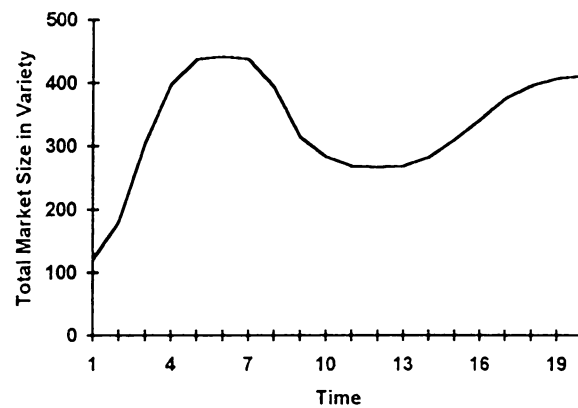


Figure 6.6 Changes in Total Market Variety of the Reversed PLC

6.1.6 Frameworks of Design

There are two frameworks of design for the scenario analysis according to the type of PLC. Table 6.11 presents a design framework with the normal (conventional) PLC, whereas Table 6.12 presents a design framework with the reversed PLC. There are two factors for the design (1) strategic choice and (2) initial technology choice. In Table 6.11 there are three levels of the first factor: (1) choice 1-1; (2) choice 1-2; and (3) choice 1-3.

In Table 6.12 there are four levels of the first factor: (1) choice 2-1; (2) choice 2-2; (3) choice 2-3; and (4) choice 2-4. There are the same four levels of the second factor in both Table 6.11 and Table 6.12: (1) Firm A; (2) Firm B; (3) Firm C; and (4) Firm D. The number of replications of the first design, as depicted in Table 6.11, is twelve, whereas for the second design there are sixteen replications. Therefore, the total number of replications for the scenario analysis is twenty-eight. This number will increase exponentially as more variables are included for other sensitivity analyses. The actual settings for the research variables for all cases are depicted in Table 6.13 and 6.14.

Table 6.11

Design Framework with the Normal PLC

Factors	Levels			
Strategic Choice	1-1	1-2	1-3	
Initial Technology Choice	A	B	C	D

Table 6.12

Design Framework with the Reversed PLC

Factors	Levels			
Strategic Choice	2-1	2-2	2-3	2-4
Initial Technology Choice	A	B	C	D

Table 6.6
Settings of the Research Variables

Strategic Choice	1-1 & 2-1				1-2 & 2-2				1-3 & 2-3				2-4			
Initial Process Technology	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
C_4	I	H	H	H	L	L	L	L	H	H	H	H	H	H	H	H
	G	M	M	M	L	L	L	L	H	H	H	H	M	M	M	M
	M or RG	L	L	L	L	L	L	L	H	H	H	H	H	H	H	H
C_5	I	H	H	H	L	L	L	L	H	H	H	H	H	H	H	H
	G	M	M	M	L	L	L	L	H	H	H	H	M	M	M	M
	M or RG	L	L	L	L	L	L	L	H	H	H	H	H	H	H	H
μ_v	I	L	L	L	H	H	H	H	L	L	L	L	L	L	L	L
	G	M	M	M	H	H	H	H	L	L	L	L	M	M	M	M
	M or RG	H	H	H	H	H	H	H	L	L	L	L	L	L	L	L
μ_m	I	H	H	H	L	L	L	L	H	H	H	H	H	H	H	H
	G	M	M	M	L	L	L	L	H	H	H	H	M	M	M	M
	M or RG	L	L	L	L	L	L	L	H	H	H	H	H	H	H	H
x0 s0 b10 b20	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H
	H	H	L	L	H	L	L	L	H	H	L	L	H	H	L	L
	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L
	H	H	L	L	H	H	L	L	H	H	L	L	H	H	L	L

Table 6.7
Value Settings of the Research Variables

Strategic Choice	1-1 & 2-1				1-2 & 2-2				1-3 & 2-3				2-4			
Initial Process Technology	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
C_4	I	100	100	100	25	25	25	25	100	100	100	100	100	100	100	100
	G	50	50	50	25	25	25	25	100	100	100	100	50	50	50	50
	M or RG	25	25	25	25	25	25	25	100	100	100	100	100	100	100	100
C_5	I	200	200	200	50	50	50	50	200	200	200	200	200	200	200	200
	G	100	100	100	50	50	50	50	200	200	200	200	100	100	100	100
	M or RG	50	50	50	50	50	50	50	200	200	200	200	200	200	200	200
μ_v	I	.0005	.0005	.0005	.002	.002	.002	.002	.0005	.0005	.0005	.0005	.0005	.0005	.0005	.0005
	G	.001	.001	.001	.002	.002	.002	.002	.0005	.0005	.0005	.0005	.001	.001	.001	.001
	M or RG	.002	.002	.002	.002	.002	.002	.002	.0005	.0005	.0005	.0005	.0005	.0005	.0005	.0005
μ_m	I	.01	.01	.01	.0025	.0025	.0025	.0025	.01	.01	.01	.01	.01	.01	.01	.01
	G	.005	.005	.005	.0025	.0025	.0025	.0025	.01	.01	.01	.01	.005	.005	.005	.005
	M or RG	.0025	.0025	.0025	.0025	.0025	.0025	.0025	.01	.01	.01	.01	.01	.01	.01	.01
x_0 s_0 b_{10} b_{20}		50	150	50	150	150	50	150	50	150	50	150	50	150	50	150
		100	100	10	10	10	10	10	100	100	10	10	100	100	10	10
		30	25	30	25	25	30	25	30	25	30	25	30	25	30	25
		15	15	10	10	10	10	10	15	15	10	10	15	15	10	10

6.1.7 Performance Measures

The optimal solution in the spreadsheet of Microsoft Excel[®] generates the total objective function value, the dichotomized values of the terms in the objective function, and the values of control variables and state variables. The possible performance measures comparing different scenarios include (1) optimal policy for the acquisition of automation and flexibility, (2) optimal policy for the scrapping/reducing of conventional capacity, (3) total automation capacity and the system's flexibility at time T, (4) total cost performance, and (5) total flexibility performance.

The first and second performance measures might provide managers with insight for the optimal investment policy in the presence of a specific corporate strategy. The fourth and fifth performance measures might help corporate executives to understand how they should plan their corporate strategies by bearing market demand behavior in their minds. The third performance measure indicates how a firm's process technology evolves in the product-technology box differently according to the choice of initial process technology and corporate strategy.

6.2 RESULTS OF ANALYSIS

One interesting observation from the results of all the cases is that there is no scrapping of existing or conventional capacity. Hence, the scrapping of conventional or existing capacity will not be discussed.

6.2.1 Analysis with the Normal PLC

As described in Chapter V, there are two research factors: strategic choice and initial process technology. For analysis with the Normal PLC, there are three levels of strategic choice -- 1-1 (mixed I), 1-2 (cost efficiency), and 1-3 (flexibility) -- and four levels of initial process technology -- A (high automation/low flexibility), B (high automation/high flexibility), C (low automation/low flexibility), and D (low automation/high flexibility). Hence, there are twelve cases in analysis with the Normal PLC.

6.2.1.1 Effect of Initial Process Technology

In this study a firm is assumed to choose one of four different initial process technologies, such as A (low automation/high flexibility), B (high automation/high flexibility), C (low automation/low flexibility), and D (high automation/low flexibility). Table 6.15 depicts the optimal acquisition of automation capacity for twelve cases with the Normal PLC, categorized according to the type of initial process technology. Figure 6.7 illustrates the results in Table 6.15 with graphs. Each graph depicts optimal policies (patterns) for automation capacity acquisition corresponding to three different strategic priorities for a given initial process technology. Since all four graphs look almost exactly the same, it can be readily concluded that there is no effect of initial process technology on the optimal acquisition policy for automation capacity.

Table 6.16 and Figure 6.8 illustrate the optimal acquisition of flexibility, categorized according to the type of initial process technology. Again, there is no effect of initial process technology on the optimal acquisition policy for flexibility. This is because the objective of the strategic fit in the objective function of the model has a greater weight than the others. Table 6.17 and 6.18 display the cumulative automation capacity and the cumulative system's flexibility. Figures 6.9 and 6.10 present the results in Tables 6.17 and 6.18 with graphs. Since optimal acquisition policies for both automation capacity and for flexibility with four different initial process technologies are the same under a given strategic choice as depicted by Figures 6.7 and 6.8, the cumulative levels of production capacity as depicted by four graphs in each figure are also identical. The upper half of Table 6.31 displays the cost performance of cases with the Normal PLC. It is also found that there is no effect of initial process technology on the overall cost performance.

No effect of initial process technology is caused by the highest weight being placed on e_1 and e_2 , the penalty cost for the strategic fit between an SBU's actual market position and its goal for the market position in terms of volume and variety. For example, suppose an SBU starts its operation with an initial process technology that has a high level of automation capacity, and its corporate strategy is cost efficiency. The SBU's goal for the volume demand growth, therefore, will be set at a high level and, in addition, the initial market share is the same for all cases by the assumption. Hence, there should be the acquisition of automation capacity to boost the market demand in volume in order to minimize the excessive penalty of the strategic fit between actual market share and the business goal in volume, even though there are other penalty costs incurred by the acquisition of automation capacity.

Additional experiments with low values of e_1 and e_2 (10 and 20) show an effect of initial process technology on the acquisition of flexibility (refer to Tables 6.32 - 6.35 and Figures 6.25 - 6.29). According to Figure 6.31, Firm C and Firm D, which have a low level of initial flexibility, invest in flexibility more than Firm A and Firm B, which have a

high level of initial flexibility. However, there is no difference in the acquisition of automation. This is because the same initial production capacity, $k(0)$, for all cases.

6.2.1.2 Effect of Strategic Choice

To analyze the effect of strategic choice, the results of cases with the Normal PLC are categorized in terms of strategic choice as depicted by Tables 19 through 22. The results of these tables are graphically illustrated by Figures 6.11 through 6.14. Each graph depicts optimal policies for flexibility acquisition according to the four different initial process technologies within a strategic choice. Since there is no effect of initial process technology on the optimal acquisition policy, each graph in Figure 6.11 and 6.12 shows almost a single line. The acquisition policy of automation capacity with strategic choice 1-1 in Figure 6.11 depicts a skewed investment during the mature stage because of the strategic priority of cost efficiency pursued during that stage. The acquisition of automation capacity with strategic choice 1-2 is substantial over the three stages, tailing down toward the end of the mature stage. Since strategic choice 1-2 has the strategic priority of cost efficiency throughout all three stages, a firm would try to purchase automation capacity. This is partly because of the savings made from the economies of scale, and partly because of the need to boost its SBU's market share in volume to meet the SBU's goal for high growth in volume demand despite the relatively expensive acquisition cost of automation capacity. This is why the acquisition of automation capacity in the cases with strategic choice 1-2 is greater than the cases with the other two strategic choices. The last graph illustrates the acquisition of automation capacity for the cases with strategic choice 1-3. Since the strategic priority for these cases is flexibility all the time, there is no significant investment in automation capacity partly due to the low growth goal for the market share in volume and partly due to a relatively high value for the unit acquisition cost of automation capacity compared to the other cost coefficients in the objective function.

In Figure 6.12 the investment in flexibility is low for those cases with strategic choice 1-2 as compared to the other cases. Since the strategic priority is cost efficiency for all periods with strategic choice 1-2, a firm would not invest in flexibility due to the relatively expensive unit acquisition cost of flexibility and a low priority given to the objective of flexibility. The comparison between strategic choice 1-1 and strategic choice 1-3 in Figure 6.12 indicates that the optimal acquisition policy for the flexibility of the two cases is almost identical during the introductory stage where the total market demand in variety increases sharply. Then, the acquisition of flexibility for the cases with strategic choice 1-3 becomes greater than those with strategic choice 1-1 until the end of the time horizon. The initial high investment in flexibility with these two strategic choices is caused by the high priority given to flexibility during the introductory stage and, consequently, the relatively inexpensive unit acquisition cost of flexibility. The second reason is related to the objective of minimizing the penalty cost of strategic fit by boosting the actual market demand in variety, which meets the goal of high market share growth in variety pursued during the introductory stage with both strategic choices. The greater investment in flexibility that strategic choice 1-3 shows compared to 1-1 after the introductory stage is due to the difference in strategic priorities.

Figure 6.13 and Figure 6.14 depict the cumulative levels of automation capacity and the system's flexibility, respectively. In Figure 6.13 cumulative levels of automation capacity for cases with strategic choice 1-2 increase at a faster rate than the cases with the other two strategic choices reflecting the high investment with the choice 1-2 as depicted by Figure 6.11. The cases with strategic choice 1-3 show the slowest growth of the cumulative levels of automation capacity. However, in Figure 6.14 the cases with strategic choice 1-3 show a faster growth of the cumulative levels of the system's flexibility than the cases with the other two strategic choices. Here, the cases with strategic choice 1-2 show the slowest growth of the cumulative level of the system's flexibility. Figure 6.13 and 6.14 show that the cases with strategic choice 1-1 have a

medium level of both automation capacity and system flexibility at the end of the mature stage, compared to those cases with the other two choices. The cases with strategic choice 1-2 have the highest level of automation capacity, but the lowest level of system's flexibility at the end. The cases with strategic choice 1-3 have the lowest level of automation capacity, but the highest level of system's flexibility at the end.

As depicted by Table 6.31 there is again no effect of initial process technology on the total cost performance. Among the four cases within each strategic choice, there is no significant difference in the total cost performance. Among the three strategic choices, strategic choice 1-3 show the lowest total cost performance. Strategic choice 1-2 is the worst in terms of total cost performance.

6.2.1.3 Conclusion

The results of the cases with the Normal PLC suggest that when the market demand follows the pattern of the Normal PLC, the manufacturing firm pursuing a strategy of cost efficiency should focus on investment in a rigid process technology with high automation and low flexibility, whereas a firm pursuing a strategy of flexibility or differentiation should focus on the investment for flexibility rather than the investment for automation capacity. These results are managerially intuitive since a firm with the strategic priority of cost efficiency wants to operate in the market with high volume and low variety, and a firm with the strategic priority of flexibility wants to operate in the market with low volume and high variety. The first firm should have a process technology which allows it to achieve the economies of scale for price competition, and the latter one should have a process technology which allows it to achieve the economies of scope for a product-variety competition.

The low total cost performance for the cases with strategic choice 1-3 may be due to their low investment in automation capacity. However, these cases have greater total penalty costs for flexibility and strategic fit compared to the other cases with the Normal

PLC. The most cost effective performances for flexibility and strategic fit are given by the cases with strategic choice 1-1, although they do have the highest total investment cost for technology acquisition compared to the cases with the Normal PLC. Considering the importance of the objectives of flexibility and strategic fit, the strategic choice with the Normal PLC should be 1-1 in which the strategic priority of a firm changes according to external market conditions.

6.2.2 Analysis with the Reversed PLC

In the analysis with the Reversed PLC, the first three levels of strategic choice -- 2-1 (mixed one), 2-2 (cost efficiency), and 2-3 (flexibility) -- are the same as the three strategic choices with the Normal PLC. The last choice, 2-4, is another mixed strategy in which the strategic priority is changing from flexibility for the introductory stage, through cost efficiency/flexibility for the growth stage, to flexibility for the mature stage. The levels of initial process technology are A, B, C, and D, the same as for the analysis with the Normal PLC. Therefore, the total number of cases with the Reversed PLC is sixteen.

6.2.2.1 Effect of Initial Process Technology

The results of the analysis with the Reversed PLC also indicate no effect of initial process technology. Tables 6.23 and 6.24 present the acquisition of automation capacity and flexibility with the Reversed PLC. The results are categorized according to the type of initial process technology. These results are illustrated graphically in Figures 6.15 and 6.16. Tables 6.25 and 6.26 display the cumulative automation capacity and the system's flexibility with the Reversed PLC. Figures 6.17 and 6.18 illustrate the results in the two tables graphically. Again, all the graphs in each figure are almost identical. This is again due to the high weight on the penalty cost (e_1 and e_2) for the strategic fit.

6.2.2.2 Effect of Strategic Choice

Tables 6.27 and 6.28 display the results for the optimal acquisition of automation capacity and flexibility with the Reversed PLC, categorized in terms of strategic choice. Figures 6.19 and 6.20 illustrate graphically the results in Tables 6.27 and 6.28, respectively. In Figure 6.19 each of the results with strategic choice 2-1 (Mixed Strategy) and 2-2 (Cost Efficiency) shows almost the same pattern of optimal acquisition policy for automation capacity as does the counterpart with the Normal PLC. With strategic choice 2-3 (Flexibility), there is some investment in automation capacity and significant investment in flexibility during the reversed growth stage which is quite different from the result for strategic choice 1-3 with the Normal PLC as depicted by Figures 6.12 and 6.13. This is mainly because of the continuing increase in market demand in terms of both volume and variety during the reversed growth stage. The optimal acquisition policy for automation capacity with strategic choice 2-4 in Figure 6.19 shows a steady investment over the three stages. However, the optimal acquisition for flexibility with strategic choice 2-4 in Figure 6.20 shows a significant amount of investment during the reversed growth stage compared to the cases with strategic choices 2-1 and 2-2.

One interesting observation from both Figure 6.19 and Table 6.31 is that the cases with strategic choice 2-4 have the lower total investment amount in automation capacity, and yet they allow firms to achieve a slightly higher market share in volume compared to those with strategic choice 2-3. In addition, with the strategic choice 2-4 firms can even have a higher level of cumulative automation capacity at the end of the mature stage than do those firms with strategic choice 2-3. This is due to the difference in optimal acquisition policies for automation capacity between the two strategic choices, depicted in Figure 6.19. In Figure 6.19 strategic choice 2-3 shows bulky investment during the growth stage and the reversed growth stage, but strategic choice 2-4 shows a steady and incremental pattern of investment over the three stages. Because of the quadratic cost

function for the acquisition of automation capacity in the objective function, a bulky investment costs more than a steady and incremental investment.

Tables 6.29 and 6.30 display cumulative automation capacity and flexibility, respectively, and are categorized in terms of strategic choice. Figures 6.21 and 6.22 depict the results of the two tables. These graphs show that the cases with strategic choice 2-1 generate process technology with medium levels of cumulative automation capacity, and flexibility at the end. The cases with strategic choice 2-2 generate process technology with the highest level of automation capacity and the lowest level of flexibility at the end. The cases with strategic choice 2-3 have the process technology with the lowest level of automation capacity and the highest level of flexibility at the end. The cases with strategic choice 2-4 have the process technology with a low but slightly higher level of automation capacity than strategic choice 2-3, and a high but slightly lower level of flexibility than strategic choice 2-3. This reflects the presence of cost efficiency/flexibility priority with strategic choice 2-4 during the growth stage as compared to flexibility priority with strategic choice 2-3 during that stage. During the growth stage the cost efficiency/flexibility priority of strategic choice 2-4 encourages investment in automation capacity, but deters the investment in flexibility a little more than the flexibility priority of strategic choice 2-3. In Table 6.29 the cumulative automation capacities for the cases of 2-3 are 888.5 and 988.5; those for the cases of 2-4 are a little higher, 946.0 and 1045.9. In Table 6.20 the cumulative system's flexibility for the cases of 2-3 are 470.0 and 381.0, and those for the cases of 2-4 are a little lower, 395.0 and 305.0

The bottom half of Table 6.31 depicts the cost performance of all sixteen cases with the Reversed PLC. For total cost performance, the best strategic choice is 2-4, which has a changing strategic priority congruent to the external market conditions. The worst strategic choice is 2-2 in which the strategic priority is cost efficiency for all three stages.

6.2.2.3 Conclusion

Optimal investment policy for process technology for a firm operating in the market with the Reversed PLC seems to be the same as when operating in the market with the Normal PLC. Again, the results of analysis with Reversed PLC indicate that the investment policy is high on the acquisition of automation capacity and low on the acquisition of flexibility when the firm's strategic priority is cost efficiency. The results also indicate that when the firm's strategic priority is flexibility a firm should invest more in flexibility and less in automation capacity.

The best strategy with the Reversed PLC is 2-4. The reason why the choice 2-3, flexibility, is inferior to 2-4 is that an SBU's goal of a relatively low growth in volume demand discourages the investment in automation capacity during the growth stage, which incurs an enormous penalty cost of the strategic fit later during the reversed growth stage. Compared to strategic choice 2-1, strategic choice 2-4 has relatively low total penalty costs of strategic fit. This indicates that the firm's strategic priority has to be congruous with the conditions of the external market environment. However, the cases with strategic choice 2-4 have a higher total flexibility cost than those with strategic choice 2-1. Considering the high unit penalty cost of flexibility for the cases with strategic choice 2-4, one can see the difference is insignificant between the two choices.

The structure of process technology at the terminal time has the most important strategic implication. Since the market following the pattern of the Reversed PLC will have the continued growth of volume and variety in the future, the process technology with high flexibility is key for survival in competition. Considering the importance of the system's flexibility in the future, the best choice would be 2-3. However, strategic choice 2-3 is considerably inferior in terms of total cost performance to strategic choices 2-4.

In conclusion, the best strategic choice with the Reversed PLC is strategic choice 2-4, which is a combination of strategic priorities: flexibility during the introductory stage, cost efficiency/flexibility during the growth stage, and flexibility during the reversed

growth stage. Again, with the Reversed PLC the structure of initial process technology has no effect on the overall performance and the optimal acquisition policy for process technology when the strategic fit in the hierarchy of strategies is considered the most important objective.

6.2.3 Comparison Between the Normal PLC and the Reversed PLC

This section is devoted to the discussion of the interaction effects of three research factors -- the PLC, strategic choice, and initial process technology -- on the optimal acquisition of new process technology, on the evolution of process technology, and on overall cost performance.

6.2.3.1 Optimal Acquisition of New Process Technology

In Table 6.31 the investment for new process technology for each case with the Reversed PLC is generally greater than the counterpart with the Normal PLC. This is due to the continuing growth of both volume and variety demand in the Reversed PLC. For example, the total investment cost with strategic choice 2-3 is almost fifteen percent higher than that with strategic choice 1-3. However, there is no significant difference in the investment amount in both automation capacity and flexibility between strategic choices 1-1 and 2-1, and between strategic choices 1-2 and 2-2.

There are no substitutions of new capacity for conventional capacity in any the cases of with both the Normal PLC and the Reversed PLC. This is because the scrapping cost outweighs the savings from the substitution with new process technology, which are mainly the decrease in volume- or variety- related costs. Finally, strategic choice 2-4 with the Reversed PLC has a slightly higher investment in automation capacity, but somewhat lower investment in flexibility than strategic choice 1-3 with the Normal PLC.

6.2.3.2 Evolution of Process Technology

Figures 6.23 and 6.24 illustrate the evolution of process technology for the Normal PLC and the Reversed PLC, respectively. The first point of each line is the initial position of process technology. Each of the other points in each line represents the position of process technology at the end of each stage of the PLC. There is no difference in the pattern of evolution of process technology between the Normal PLC and the Reversed PLC for each case. For cases with the first (1-1 and 2-1) and the second (1-2 and 2-2) strategic choices, there is little difference in the position between the Normal PLC and the Reversed PLC. However, with the strategic choice of flexibility, such as 1-3 or 2-3, the structure of process technology at the terminal time has higher levels of both automation capacity and flexibility with the Reversed PLC than with the Normal PLC. With strategic choice 2-4 the pattern of evolution of process technology shows a slightly higher level of automation capacity, but a slightly lower level of flexibility for all three stages than with strategic choice 2-3.

Table 6.31 provides detailed information regarding the level of automation and flexibility at the end of the mature stage for each case. In Table 6.31 the general salvage value of process technology for each case with the Reversed PLC is higher than the corresponding case with the Normal PLC. This reflects the higher amount of investment in process technology for the cases with the Reversed PLC than for those with the Normal PLC. One interesting observation is the higher level of the system's flexibility with strategic choice 2-4 compared to that with strategic choice 1-3, although the total investment amount in flexibility with strategic choice 2-4 is lower than is with strategic choice 1-3. This is again caused by the bulky investment in flexibility during the introductory stage with strategic choice 1-3 shown in Figure 6.12, compared to the steady investment with strategic choice 2-4 shown in Figure 6.20.

Table 6.31 shows that there is little difference in the cumulative automation capacity and a system's flexibility at the end between strategic choices 1-1 and 2-1, and

between strategic choices 1-2 and 2-2. However, strategic choice 2-3 has a terminal level of cumulative automation capacity and system flexibility that is almost fifteen percent higher and more than twenty percent higher, respectively, than strategic choice 1-3. Strategic choice 2-4 has almost the same level of cumulative system flexibility as strategic choice 1-3, but an almost twenty percent higher level of cumulative automation capacity than strategic choice 1-3 at the end. This high level of cumulative automation capacity at the end is due to the combined effect of continuing growth of market demand in both volume and variety with the Reversed PLC and the strategic priority of cost efficiency/flexibility during the growth stage with strategic choice 2-4.

6.2.3.3 Cost Performance

Generally, the total cost performance of each of the first three strategic choices with the Reversed PLC is inferior to the counterpart with the Normal PLC. The first two strategic choices, mixed I and cost efficiency, do not vary much in terms of the total cost performance between the two types of PLC. However, the third strategic choice of flexibility with the Reversed PLC has a total cost much higher than does the one with the Normal PLC. This higher cost is due to the considerable difference in the last four penalty costs between the two types of PLC as depicted in Table 6.31.

6.3 SUMMARY OF FINDINGS

In this section the findings from the scenario analysis are summarized. The findings related to the acquisition of new process technology are summarized in Section 6.3.1, followed by those related to the evolution of process technology in Section 6.3.2, and finally those related to the best strategic choice are summarized in Section 6.3.3

6.3.1 Acquisition of New Process Technology

1. According to the results of this study, a firm pursuing the strategic priority of cost efficiency invests in new process technology more than does a firm pursuing flexibility does.

This may be due to the relatively small value for the unit acquisition cost for flexibility compared to that for automation capacity. The results would be different if the value for the unit acquisition of flexibility were significantly higher than the value in this study. The cost of automation capacity is generally for hardware, such as tools, control devices, and other automated equipment whereas the cost of flexibility is mostly for software, such as control programs for a CNC machine or an FMS. Since the cost for hardware is much higher than the cost for software, the values for the acquisition costs of both automation capacity and flexibility used in this study seem to be fairly practical. Therefore, it may be safe to conclude that the cost efficiency priority generally leads a firm to a greater capital investment in new process technology than does the flexibility priority.

2. It is found that a firm whose strategic priority is flexibility invests more in the system's flexibility than in automation capacity, as compared to low investment in automation capacity and high investment in flexibility for a firm whose strategic priority is cost efficiency.

6.3.2 Evolution of Process Technology

1. According to the results of this study, the size of investment in process technology is larger with the Reversed PLC than with the Normal PLC.

2. There is little difference between the Normal PLC and the Reversed PLC in the pattern of evolution of process technology when a firm's strategic choice is changing priorities (flexibility-cost efficiency/flexibility-cost efficiency) or cost efficiency.

3. With its strategic priority of flexibility a firm should invest more in both automation capacity and flexibility when it operates in a market with the Reversed PLC than when operating with the Normal PLC.

6.3.3 Best Strategic Choice

1. According to the results of this study, for overall cost performance a firm with cost efficiency priority is greatly inferior to the one with the flexibility priority in both types of the PLC.

This is mainly due to the huge investment cost for automation capacity for the case with the strategic priority of cost efficiency, although the total production cost with the strategic priority of cost efficiency is lower than that with the priority of flexibility.

2. Based on the results of total cost performance, it can be concluded that a firm operating in a market with the Normal PLC should choose a strategic priority of flexibility, and that a firm operating in a market with the Reversed PLC should select its strategic priority congruent to the conditions of the external market environment.

3. A firm can achieve the best performance for both volume and variety flexibilities when it selects its strategic priority congruent to the external market environment. The firm can achieve both high volume and high variety flexibilities with the strategic choice of 1-1 when operating with the Normal PLC and with the strategic choice of 2-4 when operating with the Reversed PLC.

4. It is found that the acquisition policy of new process technology is really a strategic decision. A decision making process for technology acquisition should consider the strategic fit in the hierarchy of strategies.

6.3.4 Conclusion

Due to the enormous computational time for each case, the parameters and variables other than the experimental factors have fixed values for the scenario analysis in

this study. It may be difficult to generalize the results of scenario analysis unless there is sufficient number of experiments with different settings of those parameters and variables. However, based on the findings from the scenario analysis in this study, it is found that a firm's corporate and/or business strategy is a key factor affecting an optimal acquisition policy for process technology. The initial positioning of process technology by a firm is found to affect the optimal acquisition policy only when a firm considers the strategic priority as an insignificant factor for the technology acquisition decision. The external market environment also affects the optimal acquisition policy. Particularly when a firm's strategic priority is flexibility, the effect of external market conditions on both total cost performance and on an optimal acquisition policy for new process technology becomes significant.

In conclusion, the results of this scenario analysis demonstrate the importance of the technology acquisition decision in fitting the corporate or business strategy to external market conditions. For the optimal acquisition of new process technology, a firm has to select its strategic priority congruent to external market conditions. Finally, the findings from the scenario analysis in this dissertation support the argument by Wickham Skinner that the technology decision has to be made strategically.

Table 6.15
Acquisition of Automation Capacity with the Normal PLC

Initial Process Strategic Choice	A			B			C			D		
	1-1	1-2	1-3	1-1	1-2	1-3	1-1	1-2	1-3	1-1	1-2	1-3
0	46.9	119.5	0.0	0	46.9	119.5	0	46.9	119.5	0	46.9	119.5
1	48.5	123.5	12.1	1	48.5	123.5	1	48.5	123.5	1	48.5	123.5
2	48.6	123.0	23.6	2	48.6	123.0	2	48.6	123.0	2	48.6	123.0
3	47.6	118.9	41.7	3	47.6	118.9	3	47.6	118.9	3	47.6	118.9
4	47.1	115.6	58.7	4	47.1	115.6	4	47.1	115.6	4	47.1	115.6
5	50.2	121.2	61.2	5	50.2	121.2	5	50.2	121.2	5	50.2	121.2
6	53.5	126.3	64.0	6	53.5	126.3	6	53.5	126.3	6	53.5	126.3
7	56.9	130.1	67.9	7	56.9	130.1	7	56.9	130.1	7	56.9	130.1
8	59.8	131.4	74.3	8	59.8	131.4	8	59.8	131.4	8	59.8	131.4
9	66.4	137.7	68.3	9	66.5	137.7	9	66.4	137.7	9	66.5	137.7
10	73.7	139.7	53.9	10	73.7	139.7	10	73.7	139.7	10	73.7	139.7
11	81.5	135.0	36.4	11	81.5	135.0	11	81.5	135.0	11	81.5	135.0
12	94.8	128.3	26.2	12	94.8	128.3	12	94.8	128.3	12	94.8	128.3
13	101.7	122.2	20.0	13	101.7	122.2	13	101.7	122.2	13	101.7	122.2
14	104.4	117.0	14.8	14	104.4	117.0	14	104.4	117.0	14	104.4	117.0
15	102.8	110.5	13.9	15	102.8	110.5	15	102.8	110.5	15	102.8	110.5
16	96.8	101.5	13.6	16	96.8	101.5	16	96.8	101.5	16	96.8	101.5
17	83.8	86.5	13.4	17	83.8	86.5	17	83.8	86.5	17	83.8	86.5
18	58.1	59.3	12.5	18	58.1	59.3	18	58.1	59.3	18	58.1	59.3
19	8.8	8.8	8.9	19	8.8	8.8	19	8.8	8.8	19	8.8	8.8

Table 6.16
Acquisition of Flexibility with the Normal PLC

Initial Process Strategic Choice	A			B			C			D		
	1-1	1-2	1-3	0	1-1	1-2	1-3	0	1-1	1-2	1-3	0
0	28.1	7.3	29.6		28.1	7.3	29.4		27.3	7.3	29.1	
1	23.9	6.4	25.5	1	23.9	6.4	25.6	1	24.0	8.3	25.6	1
2	21.8	6.0	23.6	2	21.8	6.0	23.6	2	22.0	9.0	23.7	2
3	25.5	7.1	28.9	3	25.5	7.1	28.9	3	25.7	8.2	29.0	3
4	21.2	7.0	28.8	4	21.2	7.0	28.8	4	21.3	6.5	28.9	4
5	16.3	6.3	26.0	5	16.3	6.3	26.0	5	16.4	5.3	26.0	5
6	12.6	5.5	22.4	6	12.6	5.5	22.4	6	12.6	4.5	22.4	6
7	10.1	4.7	19.2	7	10.1	4.7	19.2	7	10.1	4.1	19.2	7
8	9.3	4.5	19.2	8	9.3	4.5	19.2	8	9.3	4.3	19.2	8
9	7.8	4.3	16.5	9	7.8	4.3	16.5	9	7.8	4.1	16.5	9
10	7.0	4.2	15.2	10	7.0	4.2	15.2	10	7.0	4.1	15.2	10
11	6.3	4.1	14.5	11	6.3	4.1	14.5	11	6.3	4.0	14.5	11
12	5.8	4.1	14.3	12	5.8	4.1	14.3	12	5.8	4.1	14.3	12
13	5.5	4.1	13.9	13	5.5	4.1	13.9	13	5.4	4.1	13.9	13
14	5.2	4.2	13.5	14	5.2	4.2	13.5	14	5.2	4.1	13.5	14
15	5.0	4.1	12.7	15	5.0	4.1	12.7	15	4.9	4.1	12.7	15
16	4.6	4.1	11.3	16	4.6	4.1	11.3	16	4.6	4.0	11.3	16
17	4.3	3.9	9.3	17	4.3	3.9	9.3	17	4.3	3.9	9.3	17
18	3.8	3.6	6.6	18	3.8	3.6	6.6	18	3.8	3.6	6.6	18
19	3.3	3.3	3.3	19	3.3	3.3	3.3	19	3.3	3.3	3.3	19

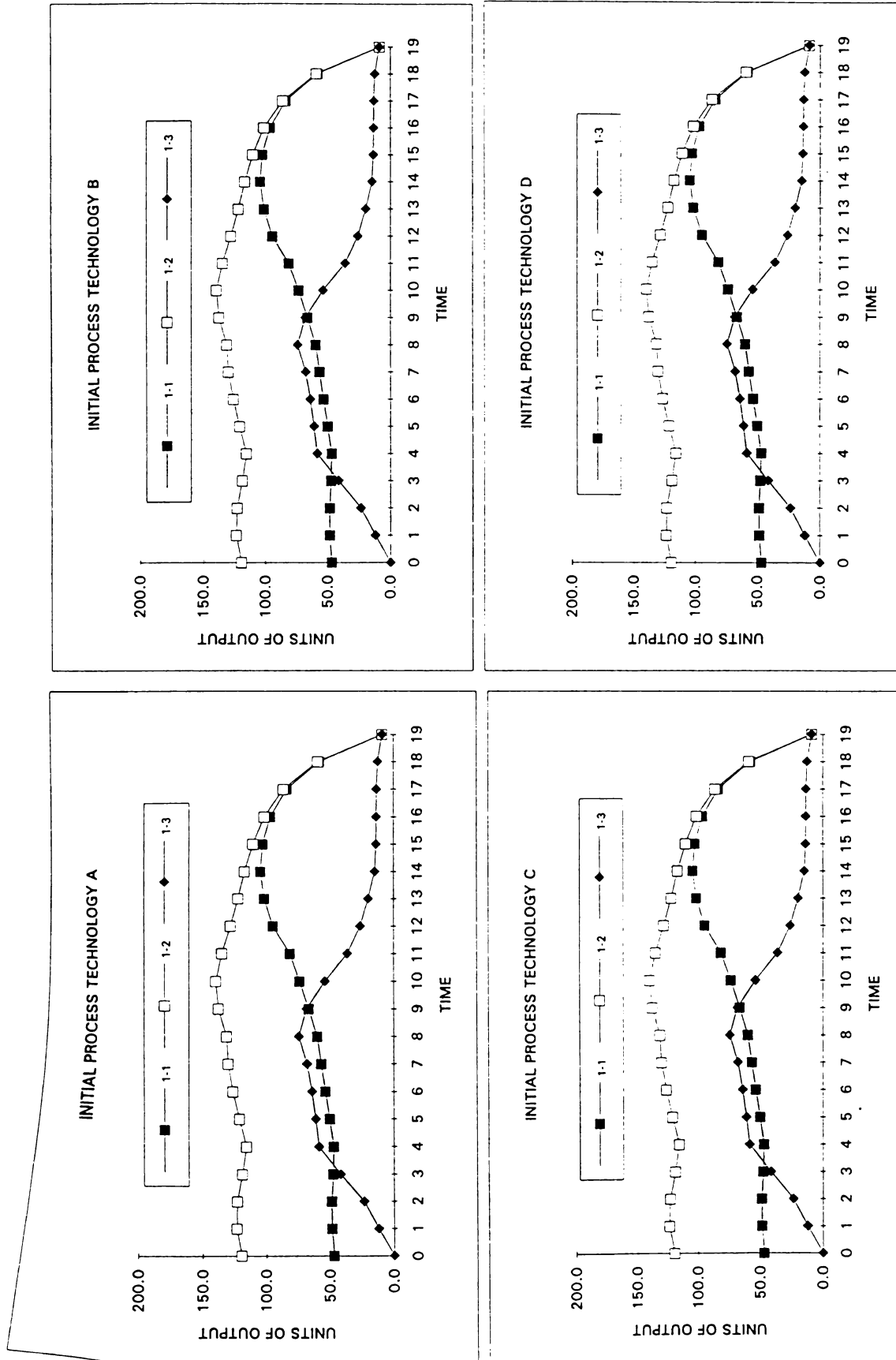


Figure 6.7 Acquisition of Automation Capacity with the Normal PLC

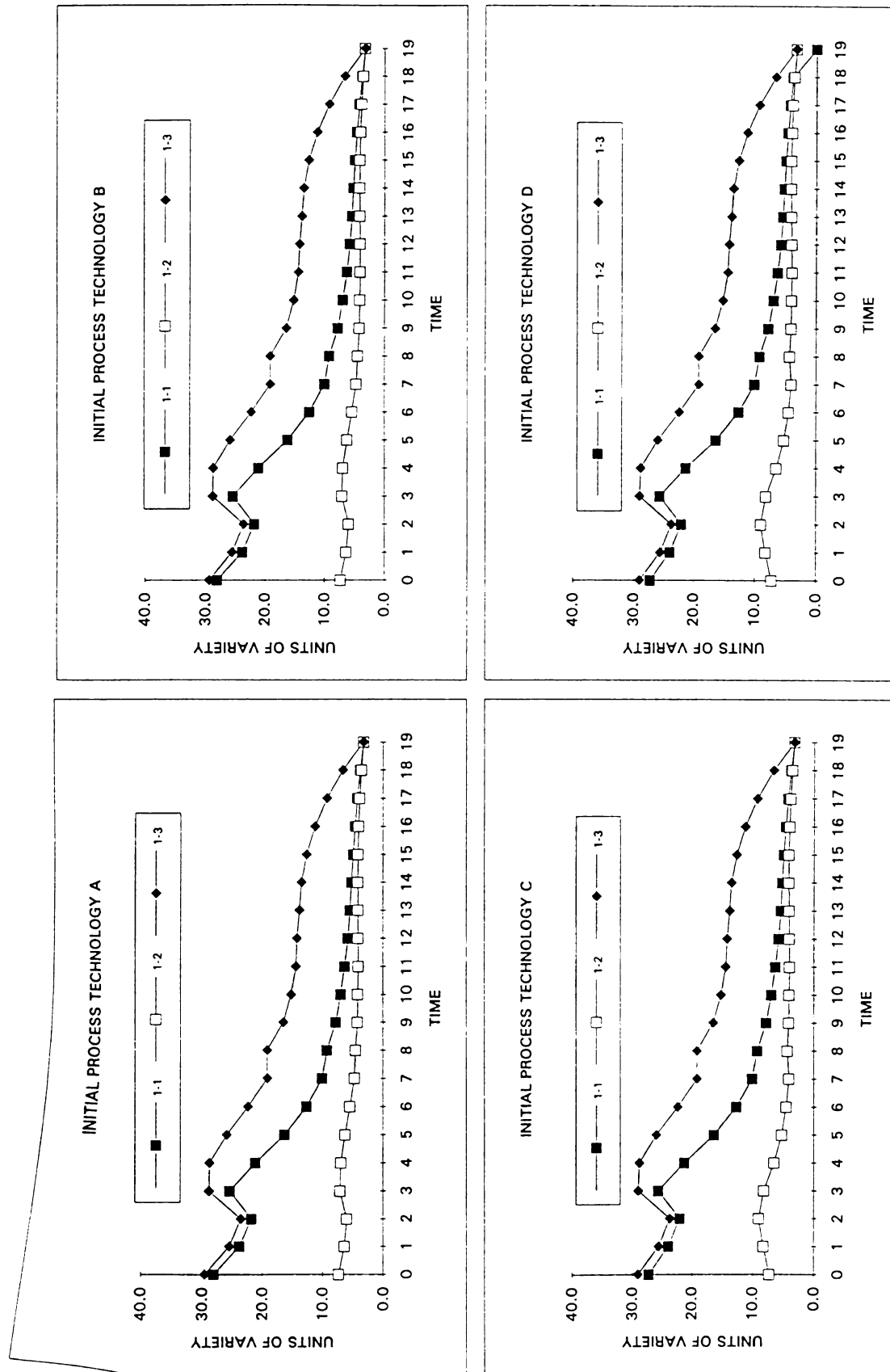


Figure 6.8 Acquisition of Flexibility with the Normal PLC

Table 6.17
Cumulative Automation Capacity with the Normal PLC

Initial Process Strategic Choice	A			B			C			D		
	1-1	1-2	1-3	1-1	1-2	1-3	1-1	1-2	1-3	1-1	1-2	1-3
0	50.0	50.0	50.0	0	150.0	150.0	0	50.00	50.00	0	150.0	150.0
1	96.9	169.5	50.0	1	196.9	269.5	1	96.9	169.5	1	196.9	269.5
2	145.4	293.0	62.1	2	245.4	393.0	2	145.4	293.0	2	245.4	393.0
3	194.1	416.0	85.7	3	294.0	516.0	3	194.1	416.0	3	294.0	516.0
4	241.6	534.9	127.4	4	341.5	634.9	4	241.6	534.9	4	341.6	634.9
5	288.8	650.5	186.1	5	388.6	750.5	5	288.8	650.5	5	388.6	750.5
6	339.0	771.7	247.2	6	438.8	871.7	6	339.0	771.7	6	438.9	871.7
7	392.5	897.9	311.3	7	492.4	997.9	7	392.5	898.0	7	492.4	998.0
8	449.4	1028.1	379.2	8	549.2	1128.1	8	449.4	1028.1	8	549.2	1128.1
9	509.2	1159.4	453.5	9	609.1	1259.4	9	509.2	1159.4	9	609.1	1259.4
10	575.7	1297.1	521.8	10	675.5	1397.1	10	575.7	1297.1	10	675.5	1397.1
11	649.3	1436.9	575.7	11	749.2	1536.9	11	649.3	1436.9	11	749.2	1536.9
12	730.8	1571.9	612.1	12	830.7	1671.9	12	730.8	1571.9	12	830.7	1671.9
13	825.5	1700.1	638.3	13	925.5	1800.1	13	825.5	1700.2	13	925.5	1800.2
14	927.2	1822.3	658.3	14	1027.1	1922.3	14	927.2	1822.3	14	1027.1	1922.3
15	1031.6	1939.3	673.1	15	1131.5	2039.3	15	1031.6	1939.3	15	1131.5	2039.3
16	1134.4	2049.8	687.0	16	1234.3	2149.8	16	1134.4	2049.8	16	1234.4	2149.8
17	1231.2	2151.3	700.6	17	1331.2	2251.3	17	1231.2	2151.3	17	1331.2	2251.3
18	1315.0	2237.8	714.0	18	1415.0	2337.8	18	1315.0	2237.8	18	1415.0	2337.8
19	1373.2	2297.1	726.5	19	1473.1	2397.1	19	1373.2	2297.1	19	1473.1	2397.1
20	1382.0	2305.9	735.4	20	1482.0	2405.9	20	1382.0	2305.9	20	1482.0	2405.9

Table 6.18
Cumulative System's Flexibility with the Normal PLC

Initial Process Strategic Choice	A			B			C			D		
	1-1	1-2	1-3	1-1	1-2	1-3	1-1	1-2	1-3	1-1	1-2	1-3
0	100.0	100.0	100.0	0	100.0	100.0	0	10.0	10.0	0	10.0	10.0
1	122.5	105.9	123.7	1	122.5	105.9	1	31.8	15.8	1	31.8	33.3
2	141.6	111.0	144.1	2	141.6	111.0	2	51.0	22.4	2	51.0	53.7
3	159.1	115.8	163.0	3	159.1	115.8	3	68.6	29.6	3	68.6	72.7
4	179.4	121.5	186.1	4	179.4	121.5	4	89.2	36.2	4	89.2	95.9
5	196.4	127.1	209.1	5	196.4	127.1	5	106.3	41.4	5	106.3	119.0
6	209.4	132.1	229.9	6	209.4	132.1	6	119.4	45.6	6	119.4	139.8
7	219.5	136.5	247.8	7	219.5	136.5	7	129.5	49.2	7	129.5	157.8
8	227.5	140.2	263.1	8	227.5	140.2	8	137.6	52.4	8	137.5	173.1
9	235.0	143.9	278.5	9	235.0	143.9	9	145.0	55.9	9	145.0	188.5
10	241.2	147.3	291.7	10	241.2	147.3	10	151.2	59.2	10	151.2	201.7
11	246.8	150.6	303.9	11	246.8	150.6	11	156.8	62.4	11	156.8	213.9
12	251.9	153.9	315.5	12	251.9	153.9	12	161.9	65.7	12	161.9	225.5
13	256.5	157.2	326.9	13	256.5	157.2	13	166.5	68.9	13	166.5	236.9
14	260.9	160.5	338.0	14	260.9	160.5	14	170.9	72.2	14	170.9	248.0
15	265.1	163.9	348.8	15	265.1	163.9	15	175.0	75.5	15	175.0	258.8
16	269.0	167.2	359.0	16	269.0	167.2	16	179.0	78.8	16	179.0	268.9
17	272.8	170.4	368.0	17	272.8	170.4	17	182.7	82.0	17	182.7	278.0
18	276.2	173.5	375.4	18	276.2	173.5	18	186.1	85.1	18	186.1	285.4
19	279.2	176.4	380.7	19	279.2	176.4	19	189.2	88.0	19	189.2	290.7
20	281.8	179.1	383.3	20	281.8	179.1	20	191.8	90.6	20	189.2	293.3

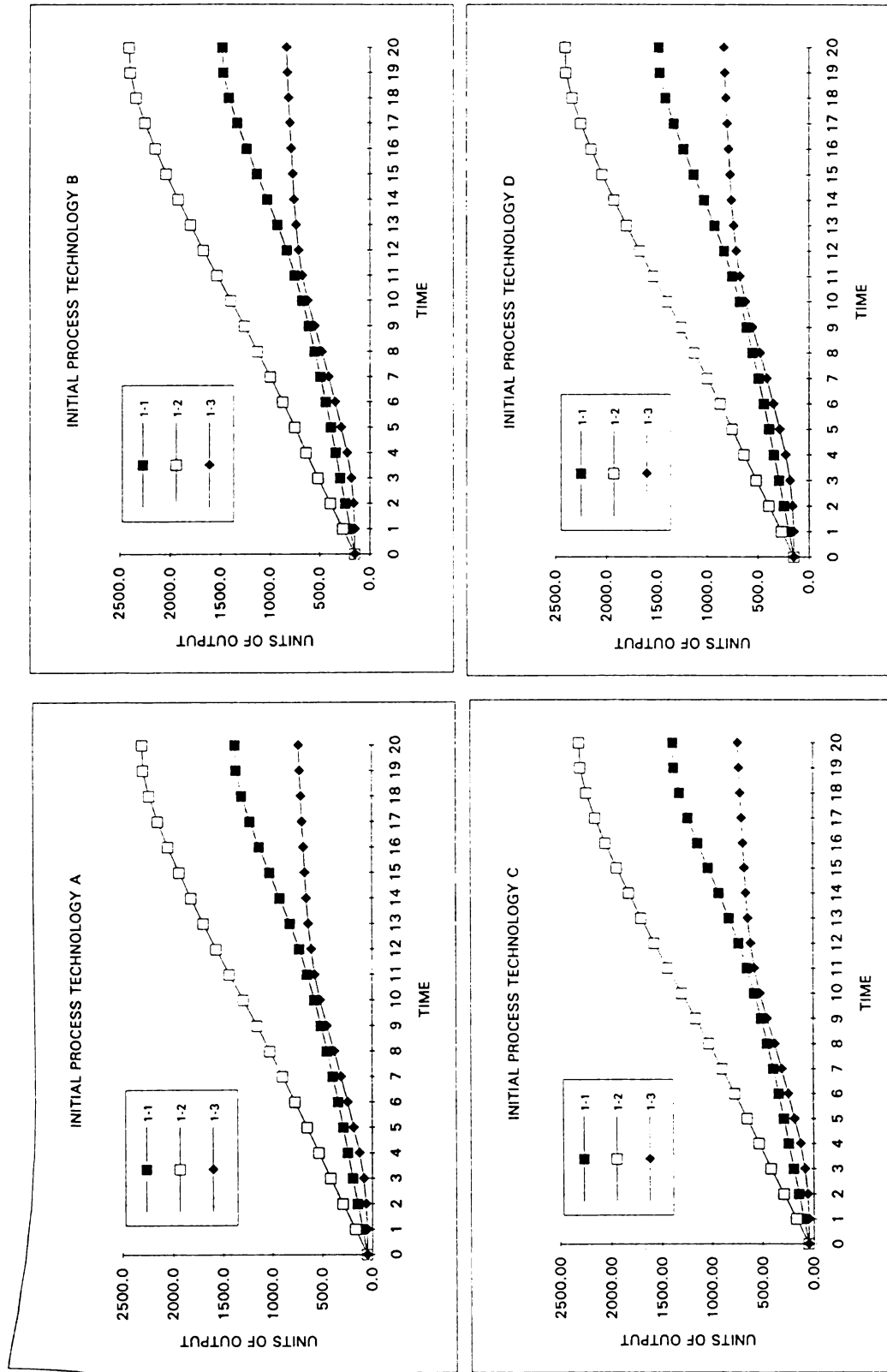


Figure 6.9 Cumulative Automation Capacity with the Normal PLC

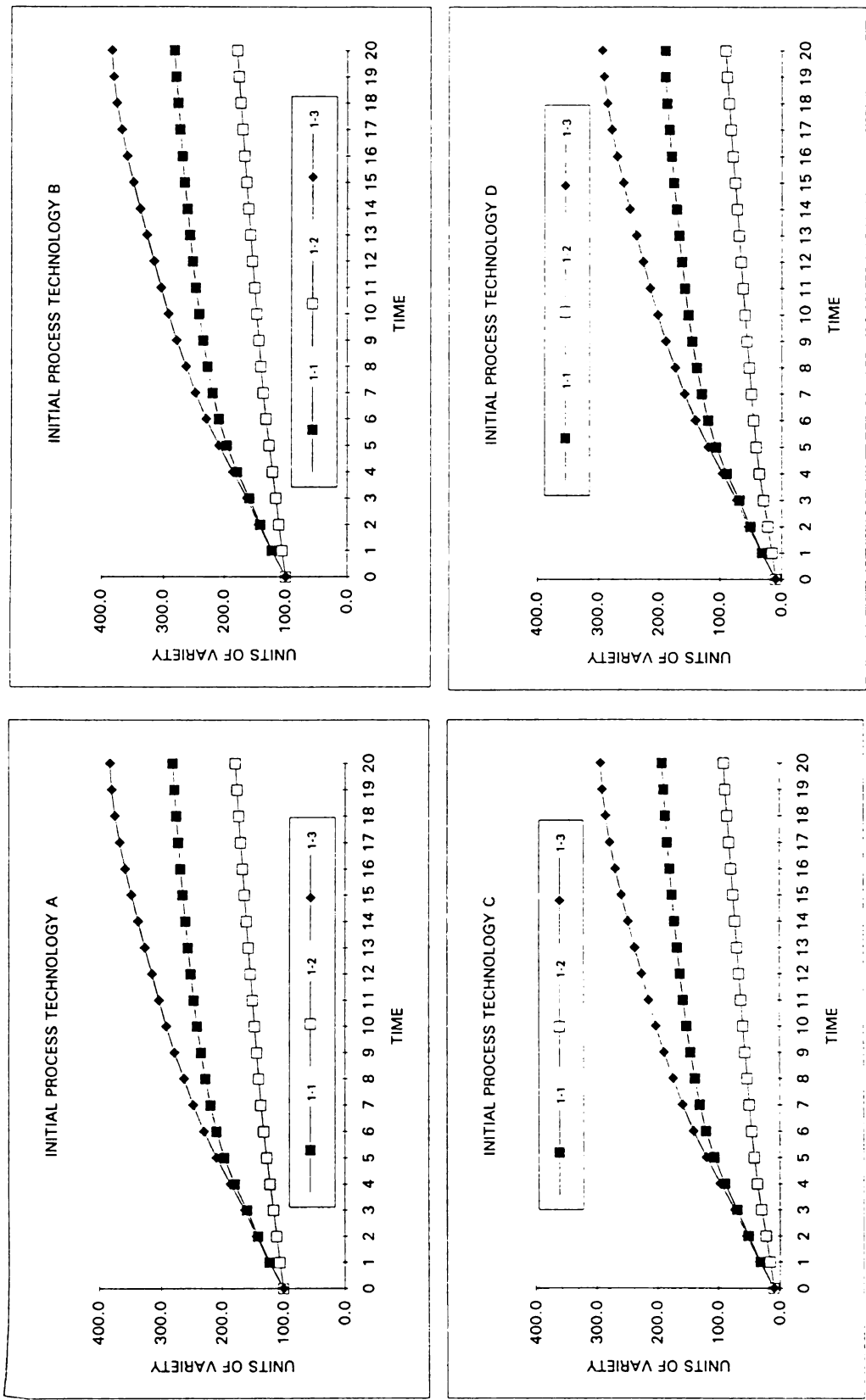


Figure 6.10 Cumulative System's Flexibility with the Normal PLC

Table 6.19

Strategic Choice Initial Process Technology	1-1				1-2				1-3			
	A	B	C	D	A	B	C	D	A	B	C	D
0	46.9	46.9	46.9	46.9	0	119.5	119.5	119.5	0	0.0	0.0	0.0
1	48.5	48.5	48.5	48.5	1	123.5	123.5	123.5	1	12.1	12.0	12.0
2	48.6	48.6	48.6	48.6	2	123.0	123.0	123.0	2	23.6	23.6	23.6
3	47.6	47.6	47.6	47.6	3	118.9	118.9	118.9	3	41.7	41.6	41.6
4	47.1	47.1	47.1	47.1	4	115.6	115.6	115.6	4	58.7	58.7	58.7
5	50.2	50.2	50.2	50.2	5	121.2	121.2	121.2	5	61.2	61.2	61.2
6	53.5	53.5	53.5	53.5	6	126.3	126.3	126.3	6	64.0	64.0	64.0
7	56.9	56.9	56.9	56.9	7	130.1	130.1	130.1	7	67.9	67.9	67.9
8	59.8	59.8	59.8	59.8	8	131.4	131.4	131.4	8	74.3	74.3	74.3
9	66.4	66.5	66.4	66.5	9	137.7	137.7	137.7	9	68.3	68.4	68.4
10	73.7	73.7	73.7	73.7	10	139.7	139.7	139.7	10	53.9	53.9	53.9
11	81.5	81.5	81.5	81.5	11	135.0	135.0	135.0	11	36.4	36.4	36.4
12	94.8	94.8	94.8	94.8	12	128.3	128.3	128.3	12	26.2	26.2	26.2
13	101.7	101.7	101.7	101.7	13	122.2	122.2	122.2	13	20.0	20.0	20.0
14	104.4	104.4	104.4	104.4	14	117.0	117.0	117.0	14	14.8	14.8	14.8
15	102.8	102.8	102.8	102.8	15	110.5	110.5	110.5	15	13.9	13.9	13.9
16	96.8	96.8	96.8	96.8	16	101.5	101.5	101.5	16	13.6	13.6	13.6
17	83.8	83.8	83.8	83.8	17	86.5	86.5	86.5	17	13.4	13.4	13.4
18	58.1	58.1	58.1	58.1	18	59.3	59.3	59.3	18	12.5	12.5	12.5
19	8.8	8.8	8.8	8.8	19	8.8	8.8	8.8	19	8.9	8.9	8.9

Table 6.20

Strategic Choice Initial Process Technology		1-1				1-2				1-3				
		A	B	C	D	A	B	C	D	A	B	C	D	
0	28.1	28.1	27.3	27.3	0	7.3	7.3	7.3	7.3	0	29.6	29.4	29.1	29.1
1	23.9	23.9	24.0	24.0	1	6.4	6.4	8.3	8.3	1	25.5	25.6	25.6	25.6
2	21.8	21.8	22.0	22.0	2	6.0	6.0	9.0	9.0	2	23.6	23.6	23.7	23.7
3	25.5	25.5	25.7	25.7	3	7.1	7.1	8.2	8.2	3	28.9	28.9	29.0	29.0
4	21.2	21.2	21.3	21.3	4	7.0	7.0	6.5	6.5	4	28.8	28.8	28.9	28.9
5	16.3	16.3	16.4	16.4	5	6.3	6.3	5.3	5.3	5	26.0	26.0	26.0	26.0
6	12.6	12.6	12.6	12.6	6	5.5	5.5	4.5	4.5	6	22.4	22.4	22.4	22.4
7	10.1	10.1	10.1	10.1	7	4.7	4.7	4.1	4.1	7	19.2	19.2	19.2	19.2
8	9.3	9.3	9.3	9.3	8	4.5	4.5	4.3	4.3	8	19.2	19.2	19.2	19.2
9	7.8	7.8	7.8	7.8	9	4.3	4.3	4.1	4.1	9	16.5	16.5	16.5	16.5
10	7.0	7.0	7.0	7.0	10	4.2	4.2	4.1	4.1	10	15.2	15.2	15.2	15.2
11	6.3	6.3	6.3	6.3	11	4.1	4.1	4.0	4.0	11	14.5	14.5	14.5	14.5
12	5.8	5.8	5.8	5.8	12	4.1	4.1	4.1	4.1	12	14.3	14.3	14.3	14.3
13	5.5	5.5	5.4	5.4	13	4.1	4.1	4.1	4.1	13	13.9	13.9	13.9	13.9
14	5.2	5.2	5.2	5.2	14	4.2	4.2	4.1	4.1	14	13.5	13.5	13.5	13.5
15	5.0	5.0	4.9	4.9	15	4.1	4.1	4.1	4.1	15	12.7	12.7	12.7	12.7
16	4.6	4.6	4.6	4.6	16	4.1	4.1	4.0	4.0	16	11.3	11.3	11.3	11.3
17	4.3	4.3	4.3	4.3	17	3.9	3.9	3.9	3.9	17	9.3	9.3	9.3	9.3
18	3.8	3.8	3.8	3.8	18	3.6	3.6	3.6	3.6	18	6.6	6.6	6.6	6.6
19	3.3	3.3	3.3	3.3	19	3.3	3.3	3.3	3.3	19	3.3	3.3	3.3	3.3

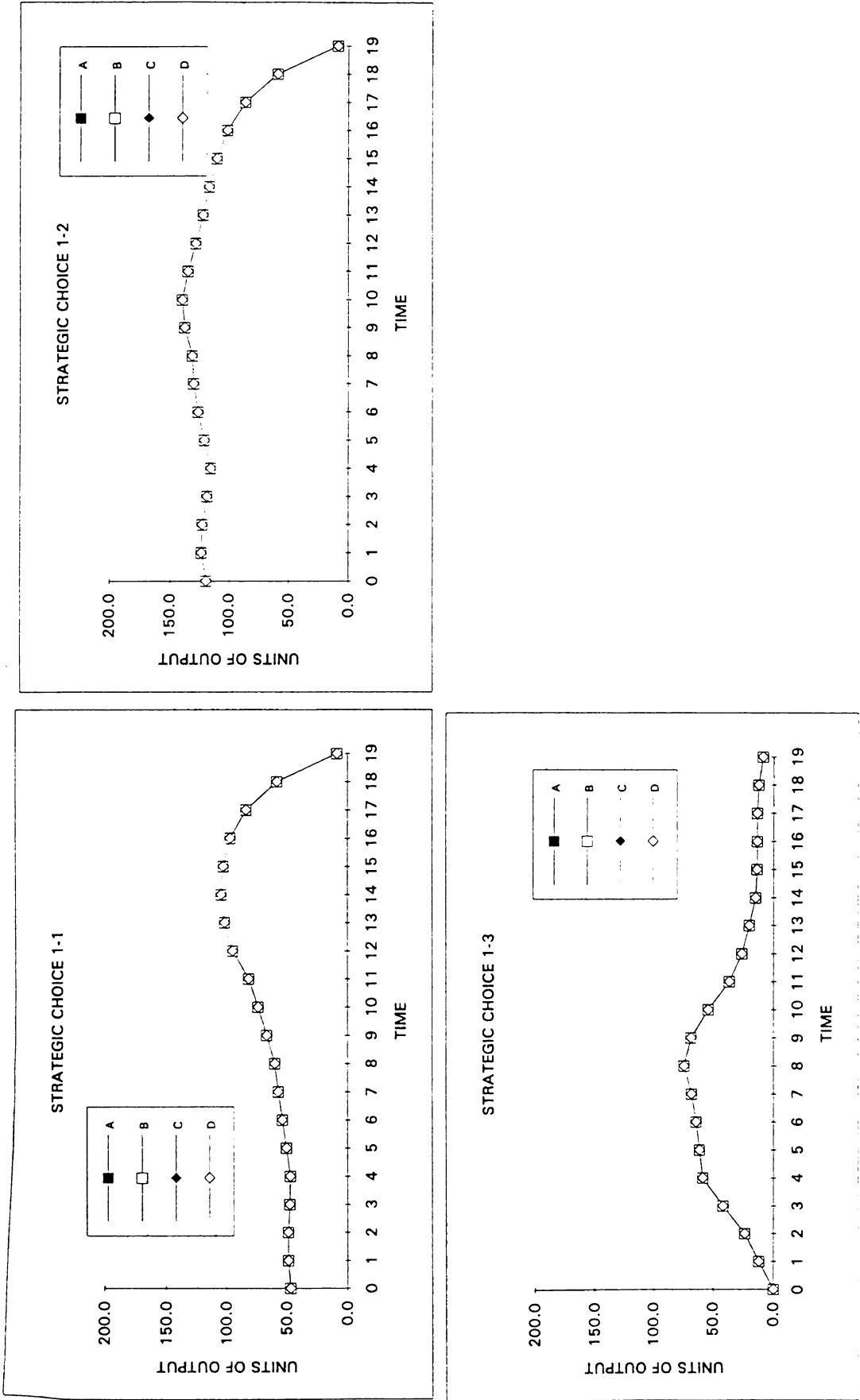


Figure 6.11 Acquisition of Automation Capacity with the Normal PLC

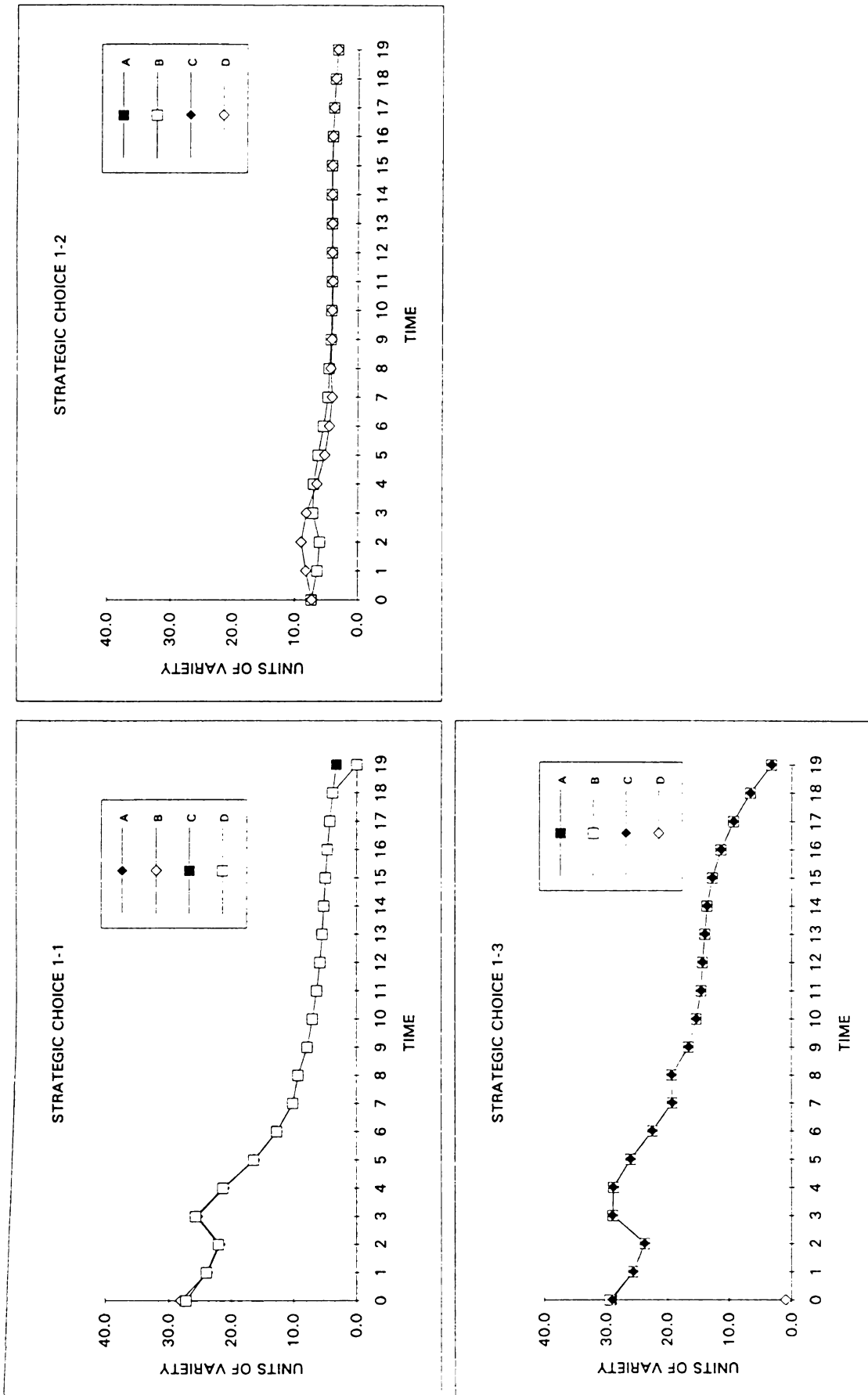


Figure 6.12 Acquisition of Flexibility with the Normal PLC

Table 6.21
Cumulative Automation Capacity with the Normal PLC

Strategic Choice Initial Process Technology	1-1				1-2				1-3			
	A	B	C	D	A	B	C	D	A	B	C	D
0	50.0	150.0	50.0	150.0	0	50.0	150.0	50.0	0	50.0	150.0	50.0
1	96.9	196.9	96.9	196.9	1	169.5	269.5	169.5	1	50.0	150.0	50.0
2	145.4	245.4	145.4	245.4	2	293.0	393.0	293.0	2	62.1	162.0	62.1
3	194.1	294.0	194.1	294.0	3	416.0	516.0	416.0	3	85.7	185.7	85.7
4	241.6	341.5	241.6	341.6	4	534.9	634.9	534.9	4	127.4	227.3	127.4
5	288.8	388.6	288.8	388.6	5	650.5	750.5	650.5	5	186.1	286.0	186.1
6	339.0	438.8	339.0	438.9	6	771.7	871.7	771.7	6	247.2	347.1	247.2
7	392.5	492.4	392.5	492.4	7	897.9	997.9	898.0	7	311.3	411.2	311.3
8	449.4	549.2	449.4	549.2	8	1028.1	1128.1	1028.1	8	379.2	479.1	379.2
9	509.2	609.1	509.2	609.1	9	1159.4	1259.4	1159.4	9	453.5	553.4	453.5
10	575.7	675.5	575.7	675.5	10	1297.1	1397.1	1297.1	10	521.8	621.8	521.8
11	649.3	749.2	649.3	749.2	11	1436.9	1536.9	1436.9	11	575.7	675.7	575.7
12	730.8	830.7	730.8	830.7	12	1571.9	1671.9	1571.9	12	612.1	712.1	612.1
13	825.5	925.5	825.5	925.5	13	1700.1	1800.1	1700.2	13	638.3	738.3	638.3
14	927.2	1027.1	927.2	1027.1	14	1822.3	1922.3	1822.3	14	658.3	758.3	658.3
15	1031.6	1131.5	1031.6	1131.5	15	1939.3	2039.3	1939.3	15	673.1	773.1	673.1
16	1134.4	1234.3	1134.4	1234.4	16	2049.8	2149.8	2049.8	16	687.0	787.0	687.0
17	1231.2	1331.2	1231.2	1331.2	17	2151.3	2251.3	2151.3	17	700.6	800.6	700.6
18	1315.0	1415.0	1315.0	1415.0	18	2237.8	2337.8	2237.8	18	714.0	814.0	714.0
19	1373.2	1473.1	1373.2	1473.1	19	2297.1	2397.1	2297.1	19	726.5	826.5	726.5
20	1382.0	1482.0	1382.0	1482.0	20	2305.9	2405.9	2305.9	20	735.4	835.3	735.4

Table 6.22
Cumulative System's Flexibility with the Normal PLC

Strategic Choice Initial Process Technology	1-1				1-2				1-3			
	A	B	C	D	A	B	C	D	A	B	C	D
0	100.0	100.0	10.0	10.0	0	100.0	100.0	10.0	0	100.0	100.0	10.0
1	122.5	122.5	31.8	31.8	1	105.9	105.9	15.8	1	123.7	123.5	33.3
2	141.6	141.6	51.0	51.0	2	111.0	111.0	22.4	2	144.1	144.0	53.7
3	159.1	159.1	68.6	68.6	3	115.8	115.8	29.6	3	163.0	162.9	72.7
4	179.4	179.4	89.2	89.2	4	121.5	121.5	36.2	4	186.1	186.1	95.9
5	196.4	196.4	106.3	106.3	5	127.1	127.1	41.4	5	209.1	209.1	119.0
6	209.4	209.4	119.4	119.4	6	132.1	132.1	45.6	6	229.9	229.9	139.8
7	219.5	219.5	129.5	129.5	7	136.5	136.5	49.2	7	247.8	247.8	157.8
8	227.5	227.5	137.6	137.5	8	140.2	140.2	52.4	8	263.1	263.2	173.1
9	235.0	235.0	145.0	145.0	9	143.9	143.9	55.9	9	278.5	278.5	188.5
10	241.2	241.2	151.2	151.2	10	147.3	147.3	59.2	10	291.7	291.8	201.7
11	246.8	246.8	156.8	156.8	11	150.6	150.6	62.4	11	303.9	303.9	213.9
12	251.9	251.9	161.9	161.9	12	153.9	153.9	65.7	12	315.5	315.5	225.5
13	256.5	256.5	166.5	166.5	13	157.2	157.2	68.9	13	326.9	326.9	236.9
14	260.9	260.9	170.9	170.9	14	160.5	160.5	72.2	14	338.0	338.0	248.0
15	265.1	265.1	175.0	175.0	15	163.9	163.9	75.5	15	348.8	348.8	258.8
16	269.0	269.0	179.0	179.0	16	167.2	167.2	78.8	16	359.0	359.0	268.9
17	272.8	272.8	182.7	182.7	17	170.4	170.4	82.0	17	368.0	368.0	278.0
18	276.2	276.2	186.1	186.1	18	173.5	173.5	85.1	18	375.4	375.4	285.4
19	279.2	279.2	189.2	189.2	19	176.4	176.4	88.0	19	380.7	380.7	290.7
20	281.8	281.8	191.8	189.2	20	179.1	179.1	90.6	20	383.3	383.4	293.3

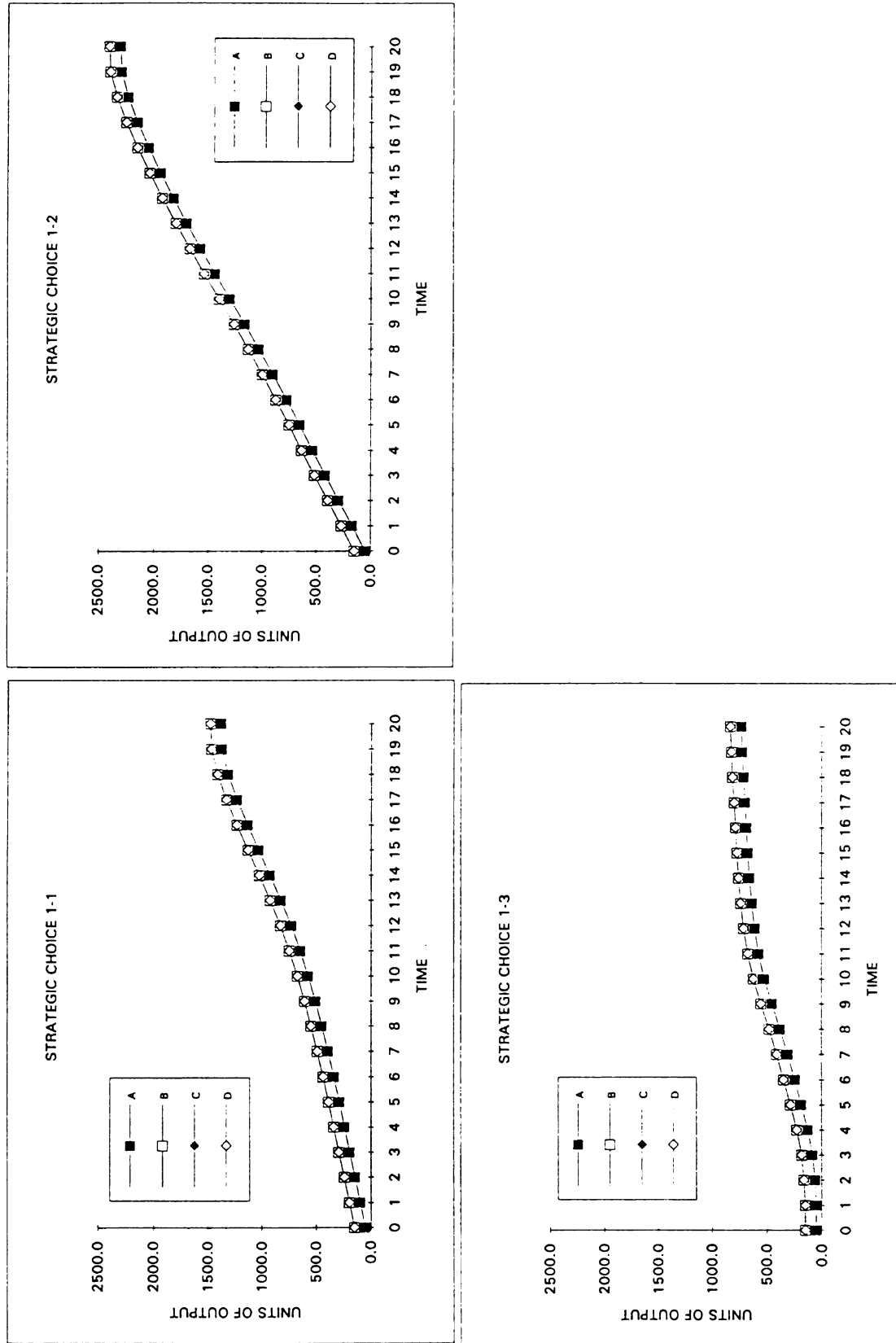


Figure 6.13 Cumulative Automation Capacity with the Normal PLC

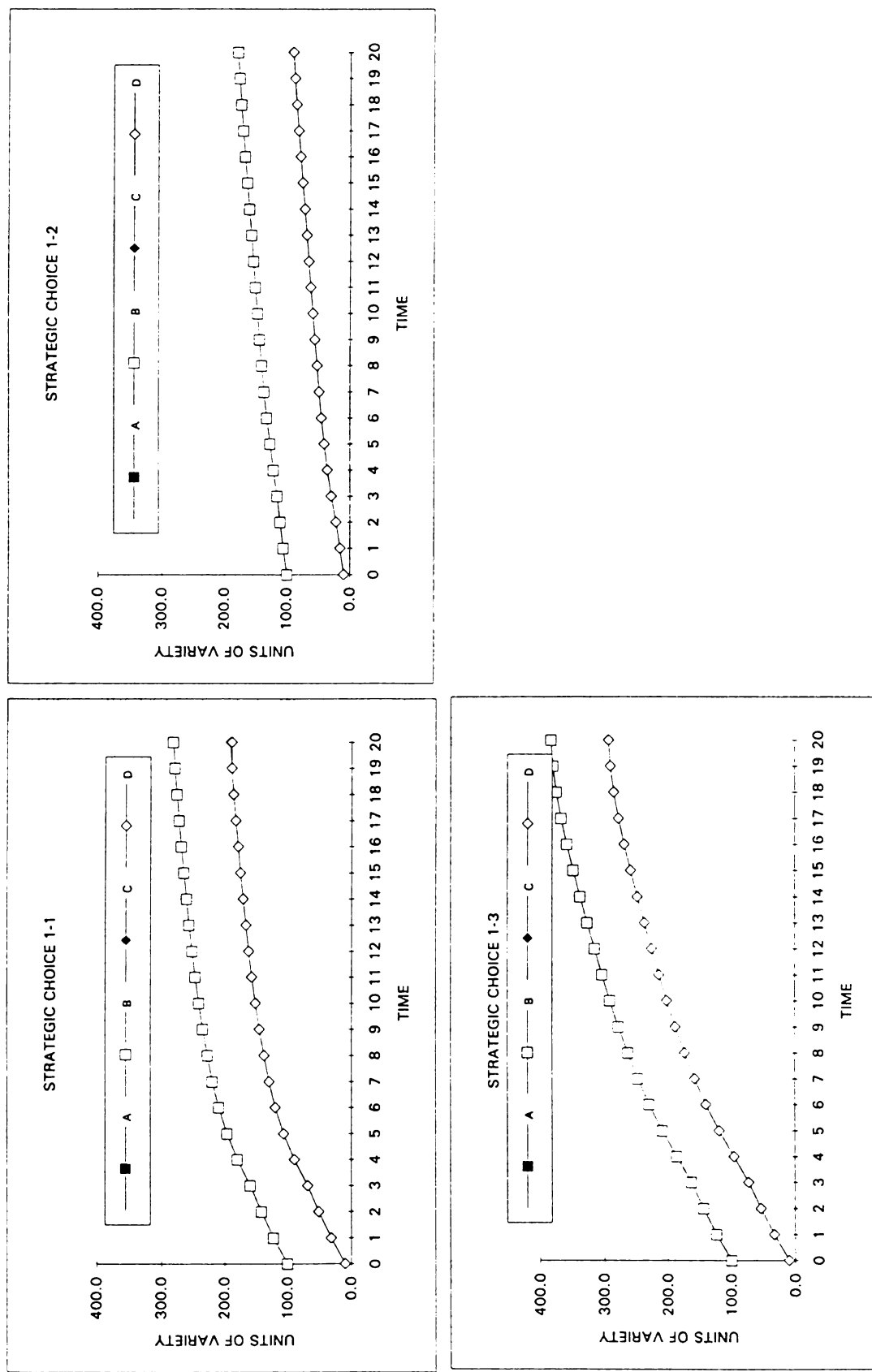


Figure 6.14 Cumulative System's Flexibility with the Normal PLC

Table 6.23
Acquisition of Automation Capacity with the Reversed PLC

Initial Process Technology Strategic Choice	A				B				C				D			
	2-1	2-2	2-3	2-4	2-1	2-2	2-3	2-4	2-1	2-2	2-3	2-4	2-1	2-2	2-3	2-4
0	47	120	0	40	0	47	120	0	40	0	47	120	0	47	120	0
1	49	124	0	42	1	49	124	0	42	1	49	124	0	49	124	0
2	48	123	10	44	2	48	123	10	44	2	48	123	10	48	123	10
3	47	119	40	47	3	47	119	40	47	3	47	119	40	47	119	40
4	45	116	68	50	4	45	116	68	49	4	45	116	68	45	116	68
5	48	121	71	52	5	48	121	71	52	5	48	121	71	48	121	71
6	51	126	74	55	6	51	126	74	55	6	51	126	74	51	126	74
7	54	130	78	58	7	54	130	78	58	7	54	130	78	54	130	78
8	57	132	86	60	8	57	132	86	60	8	57	132	86	57	132	86
9	63	138	67	60	9	63	138	67	60	9	63	138	67	63	138	67
10	80	140	52	57	10	80	140	52	57	10	80	140	52	80	140	52
11	86	136	35	50	11	86	136	35	50	11	86	136	35	86	136	35
12	101	133	17	45	12	101	133	17	45	12	101	133	17	101	133	17
13	105	124	41	41	13	105	124	41	41	13	105	124	41	105	124	41
14	108	121	44	39	14	108	121	44	39	14	108	121	44	108	121	44
15	108	116	46	41	15	108	116	46	41	15	108	116	46	108	116	46
16	103	108	45	45	16	103	108	45	45	16	103	108	45	103	108	45
17	92	95	33	36	17	92	95	33	36	17	92	95	33	92	95	33
18	65	66	23	25	18	65	66	23	25	18	65	66	23	65	66	23
19	9	9	9	9	19	9	9	9	9	19	9	9	9	9	9	9

Table 6.24
Acquisition of Flexibility with the Reversed PLC

Initial Process Technology	A				B				C				D			
	2-1	2-2	2-3	2-4	2-1	2-2	2-3	2-4	2-1	2-2	2-3	2-4	2-1	2-2	2-3	2-4
Strategic Choice	0	28.2	7.4	30.1	28.2	0	28.2	7.4	30.1	28.2	0	27.2	7.3	29.1	27.3	27.3
	1	23.9	6.4	25.7	23.9	1	23.9	6.4	25.7	23.9	1	24.0	8.2	25.7	24.1	24.1
	2	21.9	6.0	23.5	21.9	2	21.9	6.0	23.5	21.9	2	22.1	9.0	23.8	22.1	22.1
	3	25.5	7.1	28.8	25.5	3	25.5	7.1	28.8	25.5	3	25.8	8.2	29.1	25.8	25.8
	4	21.3	7.0	28.9	21.3	4	21.3	7.0	28.9	21.3	4	21.5	6.5	29.1	21.5	21.5
	5	16.6	6.4	26.5	16.7	5	16.6	6.4	26.5	16.7	5	16.7	5.3	26.6	16.7	16.7
	6	13.3	5.7	23.8	13.5	6	13.3	5.7	23.8	13.5	6	13.3	4.7	23.9	13.5	13.5
	7	11.7	5.4	22.8	12.3	7	11.7	5.4	22.8	12.3	7	11.8	4.7	22.8	12.3	12.3
	8	11.4	5.4	23.5	12.8	8	11.4	5.4	23.5	12.8	8	11.4	5.1	23.5	12.9	12.9
	9	10.5	5.2	22.1	13.0	9	10.5	5.2	22.1	13.0	9	10.5	5.1	22.1	12.9	12.9
	10	9.8	5.4	22.2	14.3	10	9.8	5.4	22.2	14.3	10	9.8	5.3	22.2	14.3	14.3
	11	9.3	5.5	23.1	16.4	11	9.3	5.5	23.1	16.4	11	9.3	5.5	23.1	16.4	16.4
	12	8.2	5.7	24.4	19.7	12	8.2	5.7	24.4	19.7	12	8.2	5.7	24.4	19.7	19.7
	13	7.6	5.9	24.7	21.6	13	7.6	5.9	24.7	21.6	13	7.6	5.9	24.7	21.6	21.6
	14	7.1	5.9	24.5	22.5	14	7.1	5.9	24.5	22.5	14	7.1	5.9	24.5	22.5	22.5
	15	6.9	6.0	24.6	23.1	15	6.9	6.0	24.6	23.1	15	6.9	6.0	24.6	23.2	23.2
	16	6.6	5.9	23.6	22.3	16	6.6	5.9	23.6	22.3	16	6.6	6.0	23.6	22.3	22.3
	17	6.2	5.7	21.5	20.7	17	6.2	5.7	21.5	20.7	17	6.2	5.7	21.5	20.7	20.7
	18	5.3	5.1	15.7	15.3	18	5.3	5.1	15.7	15.3	18	5.3	5.1	15.7	15.3	15.3
	19	3.7	3.8	3.7	3.7	19	3.7	3.8	3.7	3.7	19	3.7	3.8	3.7	3.7	3.7

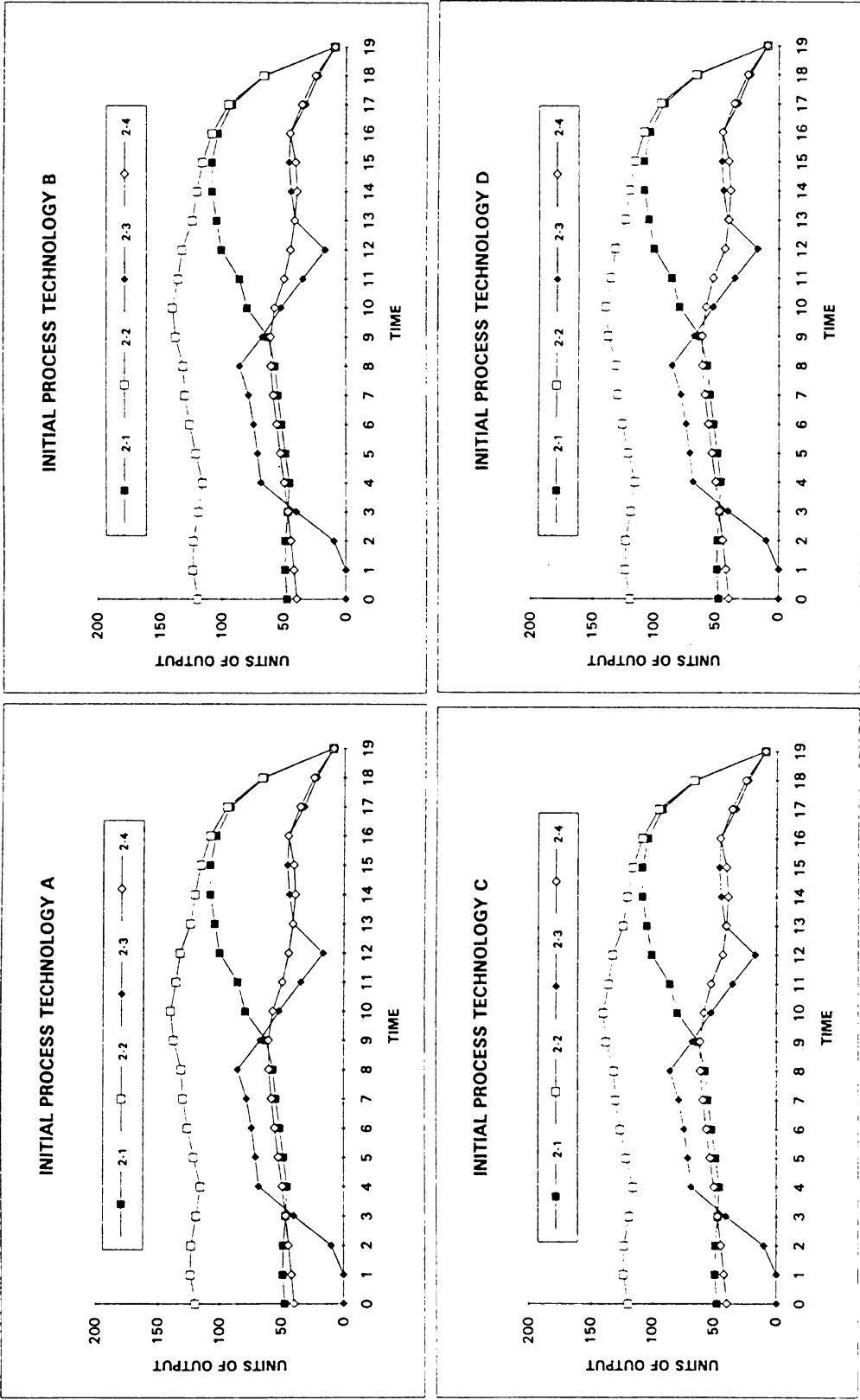


Figure 6.15 Acquisition of Automation Capacity with the Reversed PLC

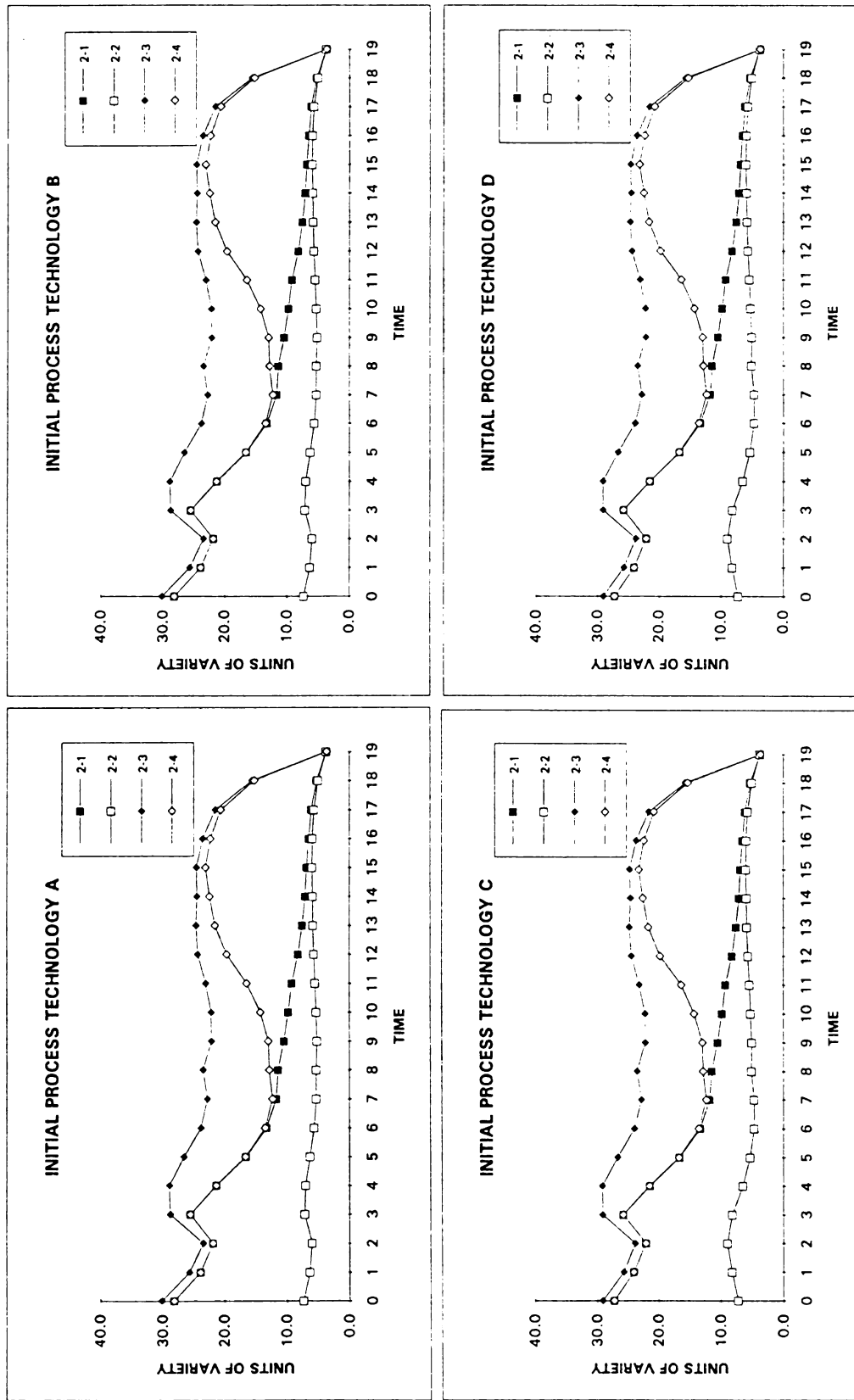


Figure 6.16 Acquisition of Flexibility with the Reversed PLC

Table 6.25
Cumulative Automation Capacity with the Reversed PLC

Initial Process Technology Strategic Choice	A				B				C				D			
	2-1	2-2	2-3	2-4	2-1	2-2	2-3	2-4	2-1	2-2	2-3	2-4	2-1	2-2	2-3	2-4
0	50	50	50	50	0	150	150	150	0	50	50	50	0	150	150	150
1	97	170	50	90	1	197	270	150	1	97	170	50	1	197	270	150
2	146	293	50	131	2	246	393	150	2	146	293	50	2	246	393	150
3	194	416	60	176	3	294	516	160	3	194	416	60	3	294	516	160
4	241	535	100	222	4	341	635	200	4	241	535	100	4	341	635	200
5	286	651	168	272	5	386	751	268	5	286	651	168	5	386	751	268
6	335	772	239	324	6	434	872	339	6	335	772	239	6	435	872	339
7	386	899	313	380	7	486	999	413	7	386	899	313	7	486	999	413
8	441	1029	392	438	8	540	1129	492	8	441	1029	392	8	540	1129	492
9	497	1160	477	498	9	597	1260	577	9	497	1160	477	9	597	1260	577
10	560	1298	545	559	10	660	1398	645	10	560	1298	545	10	660	1398	645
11	640	1439	597	616	11	739	1539	697	11	640	1439	597	11	739	1539	697
12	726	1575	632	666	12	825	1675	732	12	726	1575	632	12	825	1675	732
13	826	1707	649	710	13	926	1807	749	13	826	1707	649	13	926	1807	749
14	931	1831	690	752	14	1031	1931	790	14	931	1831	690	14	1031	1931	790
15	1039	1952	734	791	15	1139	2052	834	15	1039	1952	734	15	1139	2052	834
16	1147	2068	780	831	16	1247	2168	880	16	1147	2068	780	16	1247	2168	880
17	1250	2176	824	877	17	1350	2276	924	17	1250	2176	824	17	1350	2276	924
18	1342	2270	857	912	18	1442	2370	957	18	1342	2270	857	18	1442	2370	957
19	1408	2337	879	937	19	1508	2437	979	19	1408	2337	879	19	1508	2437	979
20	1417	2346	888	946	20	1517	2446	988	20	1417	2346	888	20	1517	2446	988

Table 6.26
Cumulative System's Flexibility with the Reversed PLC

Initial Process Technology Strategic Choice	A				B				C				D			
	2-1	2-2	2-3	2-4	2-1	2-2	2-3	2-4	2-1	2-2	2-3	2-4	2-1	2-2	2-3	2-4
0	100	100	100	100	0	100	100	100	0	10	10	10	0	10	10	10
1	123	106	124	123	1	123	106	124	1	32	16	33	1	32	16	32
2	142	111	145	142	2	142	111	145	2	51	22	54	2	51	22	51
3	159	116	163	159	3	159	116	163	3	69	30	73	3	69	30	69
4	180	122	186	180	4	180	122	186	4	89	36	96	4	89	36	89
5	197	127	210	197	5	197	127	210	5	106	41	119	5	106	41	107
6	210	132	231	210	6	210	132	231	6	120	46	141	6	120	46	120
7	220	137	250	221	7	220	137	250	7	130	49	160	7	130	49	131
8	230	141	268	231	8	230	141	268	8	140	53	178	8	140	53	141
9	239	145	287	241	9	239	145	287	9	149	57	197	9	149	57	151
10	247	150	305	251	10	247	150	305	10	157	61	215	10	157	61	161
11	255	154	322	263	11	255	154	322	11	165	66	232	11	165	66	173
12	263	158	341	276	12	263	158	341	12	173	70	251	12	173	70	186
13	269	163	360	292	13	269	163	360	13	179	75	270	13	179	75	202
14	275	168	380	309	14	275	168	380	14	185	79	290	14	185	79	219
15	281	172	400	327	15	281	172	400	15	191	84	310	15	191	84	237
16	287	177	419	345	16	287	177	419	16	197	89	329	16	197	89	255
17	292	182	438	363	17	292	182	438	17	202	94	348	17	202	94	273
18	297	186	455	380	18	297	186	455	18	207	98	366	18	207	98	290
19	301	191	468	392	19	301	191	468	19	211	102	378	19	211	102	302
20	304	194	471	395	20	304	194	471	20	214	105	381	20	214	105	305

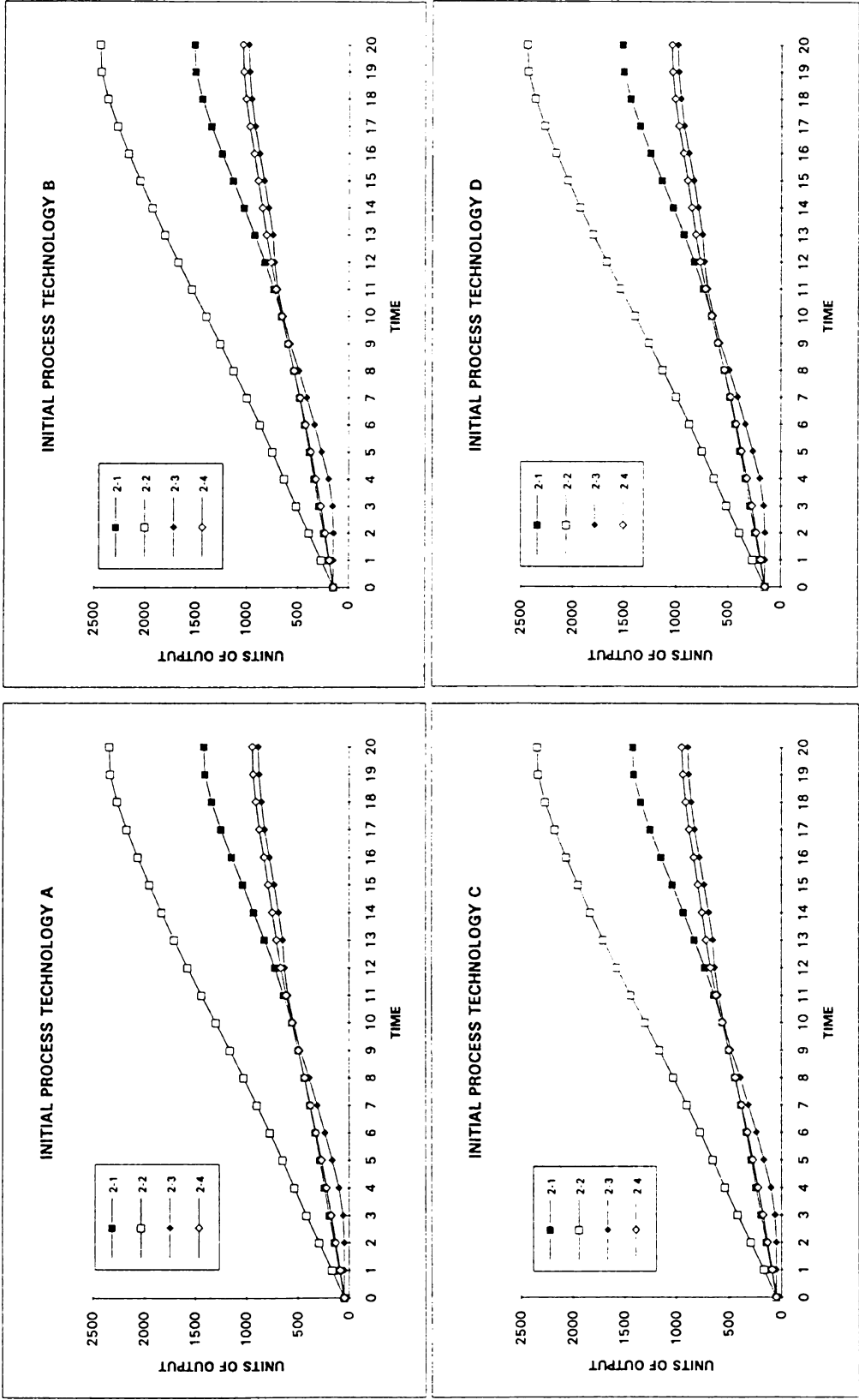


Figure 6.17 Cumulative Automation Capacity with the Reversed PLC

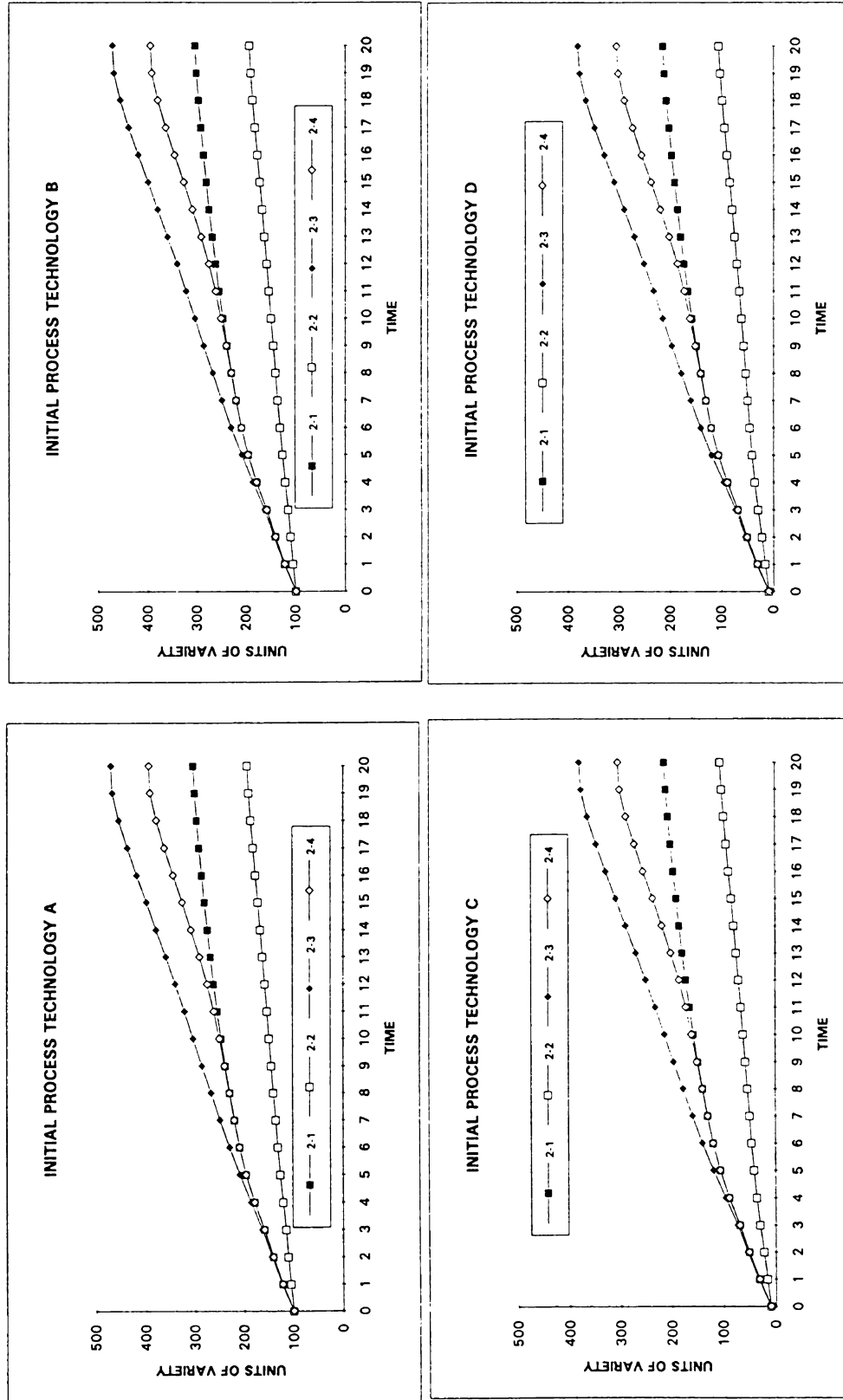


Figure 6.18 Cumulative System's Flexibility with the Reversed PLC

Table 6.27
Acquisition of Automation Capacity with the Reversed PLC

Strategic Choice Initial Process Technology	2-1				2-2				2-3				2-4			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
0	47	47	47	47	0	120	120	120	0	0	0	0	0	40	39	39
1	49	49	49	49	1	124	124	124	1	0	0	0	1	42	42	42
2	48	48	48	48	2	123	123	123	2	10	10	10	2	44	44	44
3	47	47	47	47	3	119	119	119	3	40	40	40	3	47	47	47
4	45	45	45	45	4	116	116	116	4	68	68	68	4	50	49	50
5	48	48	48	48	5	121	121	121	5	71	71	71	5	52	52	53
6	51	51	51	51	6	126	126	126	6	74	74	74	6	55	55	56
7	54	54	54	54	7	130	130	130	7	78	78	78	7	58	58	59
8	57	57	57	57	8	132	132	132	8	86	86	86	8	60	60	61
9	63	63	63	63	9	138	138	138	9	67	67	67	9	60	60	61
10	80	80	80	80	10	140	140	140	10	52	52	52	10	57	57	58
11	86	86	86	86	11	136	136	136	11	35	35	35	11	50	50	52
12	101	101	101	101	12	133	133	133	12	17	17	17	12	45	45	43
13	105	105	105	105	13	124	124	124	13	41	41	41	13	41	41	40
14	108	108	108	108	14	121	121	121	14	44	44	44	14	39	39	38
15	108	108	108	108	15	116	116	116	15	46	46	46	15	41	41	40
16	103	103	103	103	16	108	108	108	16	45	45	45	16	45	45	45
17	92	92	92	92	17	95	95	95	17	33	33	33	17	36	36	36
18	65	65	65	65	18	66	66	66	18	23	23	23	18	25	25	25
19	9	9	9	9	19	9	9	9	19	9	9	9	19	9	9	9

Table 6.28

Strategic Choice Initial Process Technology		2-1				2-2				2-3				2-4				
		A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	
0	28	28	27	24	27	0	7	7	7	0	30	30	29	29	0	28	28	27
1	24	24	24	24	24	1	6	6	8	1	26	26	26	26	1	24	24	24
2	22	22	22	22	22	2	6	6	9	2	23	23	24	24	2	22	22	22
3	26	26	26	26	26	3	7	7	8	3	29	29	29	29	3	26	26	26
4	21	21	21	21	21	4	7	7	7	4	29	29	29	29	4	21	21	22
5	17	17	17	17	17	5	6	6	5	5	27	27	27	27	5	17	17	17
6	13	13	13	13	13	6	6	6	5	6	24	24	24	24	6	14	14	14
7	12	12	12	12	12	7	5	5	5	7	23	23	23	23	7	12	12	12
8	11	11	11	11	11	8	5	5	5	8	23	23	24	23	8	13	13	13
9	11	11	11	11	11	9	5	5	5	9	22	22	22	22	9	13	13	13
10	10	10	10	10	10	10	5	5	5	10	22	22	22	22	10	14	14	14
11	9	9	9	9	9	11	6	6	5	11	23	23	23	23	11	16	16	16
12	8	8	8	8	8	12	6	6	6	12	24	24	24	24	12	20	20	20
13	8	8	8	8	8	13	6	6	6	13	25	25	25	25	13	22	22	22
14	7	7	7	7	7	14	6	6	6	14	25	25	25	25	14	22	22	22
15	7	7	7	7	7	15	6	6	6	15	25	25	25	25	15	23	23	23
16	7	7	7	7	7	16	6	6	6	16	24	24	24	24	16	22	22	22
17	6	6	6	6	6	17	6	6	6	17	22	22	22	22	17	21	21	21
18	5	5	5	5	5	18	5	5	5	18	16	16	16	16	18	15	15	15
19	4	4	4	4	4	19	4	4	4	19	4	4	4	4	19	4	4	4

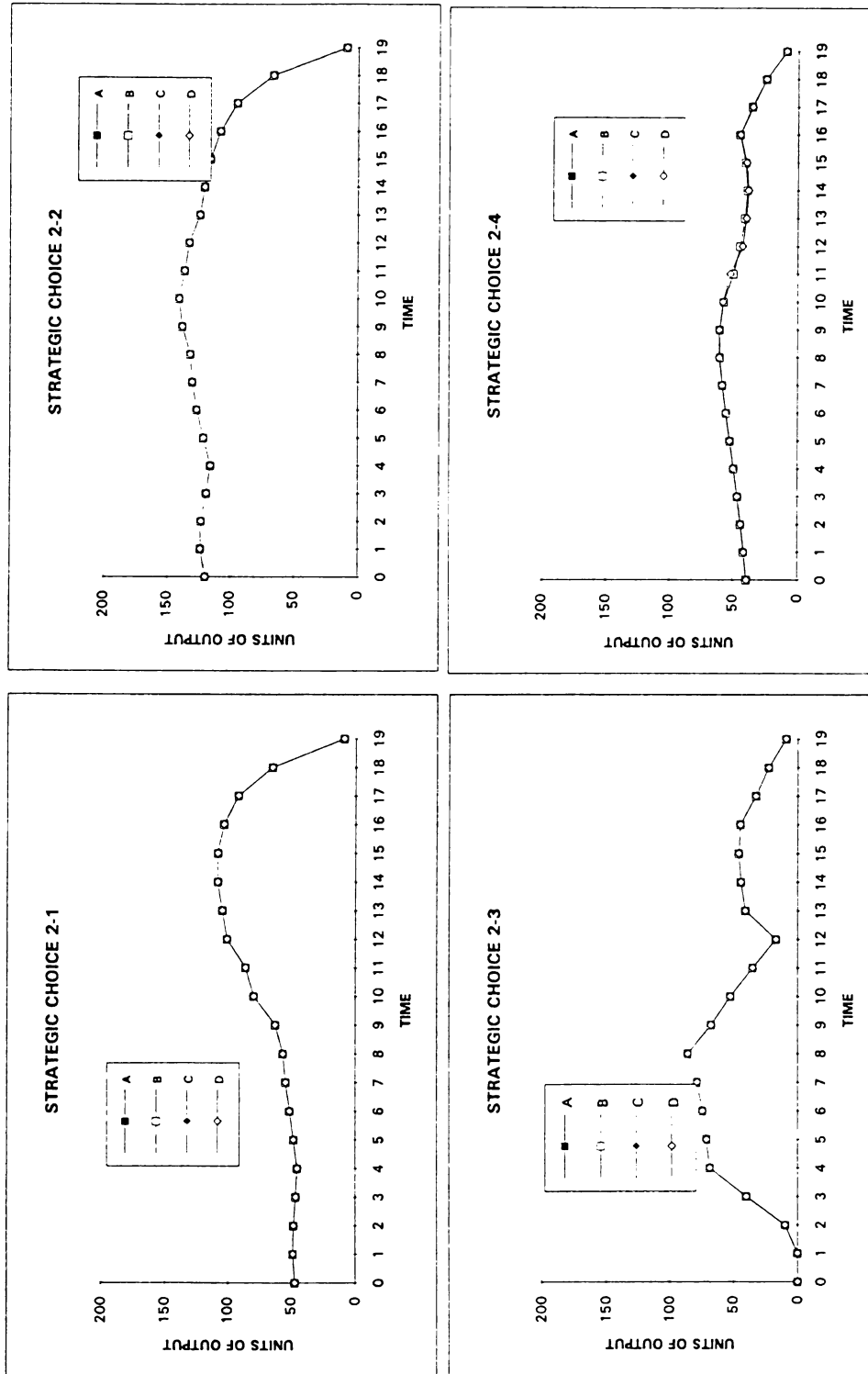


Figure 6.19 Acquisition of Automation with the Reversed PLC

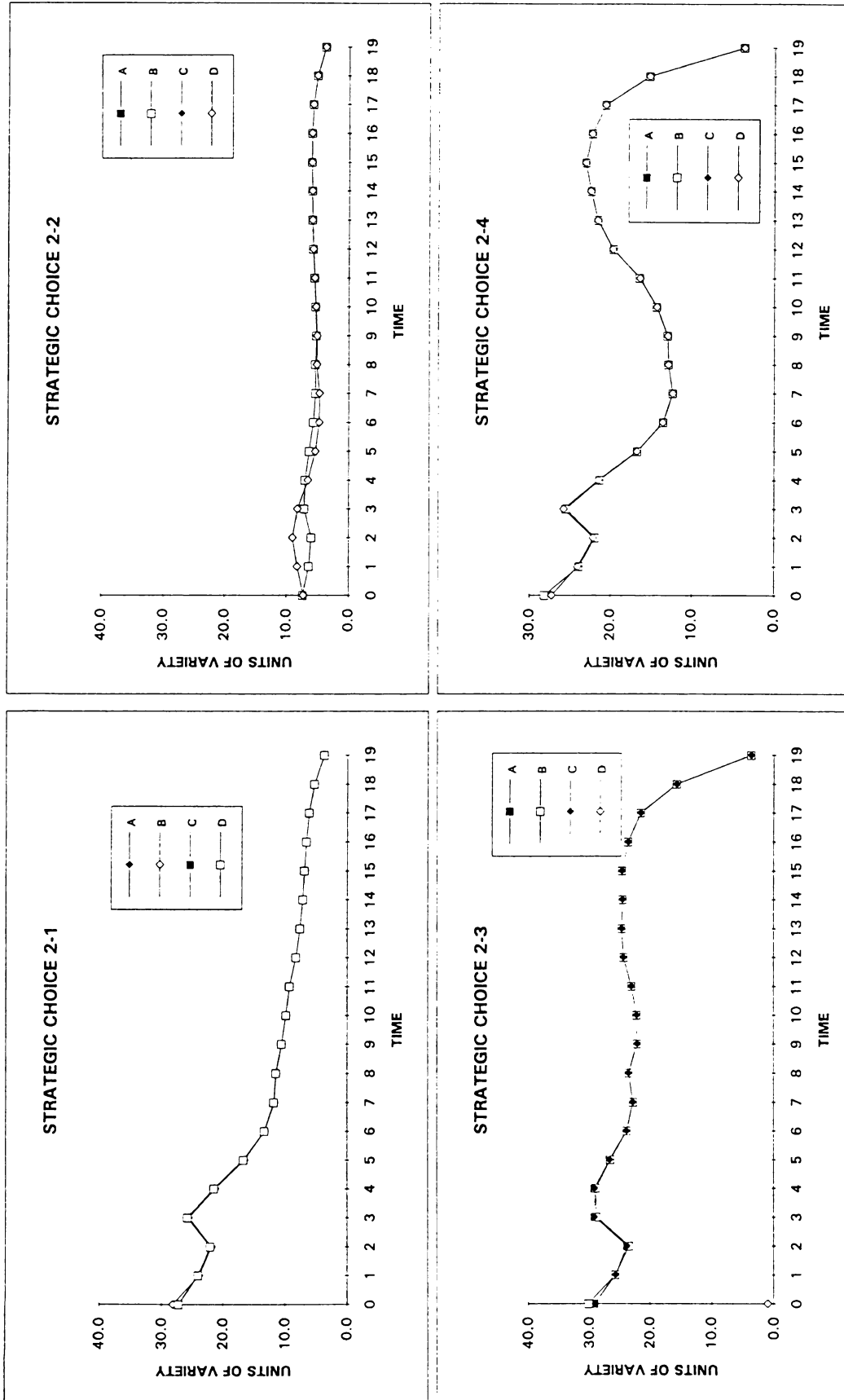


Figure 6.20 Acquisition of Flexibility with the Reversed PLC

Table 6.29
Cumulative Automation Capacity with the Reversed PLC

Strategic Choice Initial Process Technology	2-1				2-2				2-3				2-4			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
0	50	150	50	150	0	150	50	150	0	150	50	150	0	150	50	150
1	97	197	97	197	1	170	270	170	1	50	150	50	1	90	190	189
2	146	246	146	246	2	293	393	293	2	50	150	50	2	131	231	231
3	194	294	194	294	3	416	516	416	3	60	160	60	3	176	275	275
4	241	341	241	341	4	535	635	535	4	100	200	100	4	222	322	322
5	286	386	286	386	5	651	751	651	5	168	268	168	5	272	372	372
6	335	434	335	435	6	772	872	772	6	239	339	239	6	324	424	424
7	386	486	386	486	7	899	999	899	7	313	413	313	7	380	480	480
8	441	540	441	540	8	1029	1129	1029	8	392	492	392	8	438	538	539
9	497	597	497	597	9	1160	1260	1160	9	477	577	477	9	498	598	600
10	560	660	560	660	10	1298	1398	1298	10	545	645	545	10	559	659	660
11	640	739	640	739	11	1439	1539	1439	11	597	697	597	11	616	716	718
12	726	825	726	825	12	1575	1675	1575	12	632	732	632	12	666	766	771
13	826	926	826	926	13	1707	1807	1707	13	649	749	649	13	710	810	813
14	931	1031	931	1031	14	1831	1931	1831	14	690	790	690	14	752	852	853
15	1039	1139	1039	1139	15	1952	2052	1952	15	734	834	734	15	791	891	892
16	1147	1247	1147	1247	16	2068	2168	2068	16	780	880	780	16	831	931	932
17	1250	1350	1250	1350	17	2176	2276	2176	17	824	924	824	17	877	977	977
18	1342	1442	1342	1442	18	2270	2370	2270	18	857	957	857	18	912	1012	1012
19	1408	1508	1408	1508	19	2337	2437	2337	19	879	979	879	19	937	1037	1037
20	1417	1517	1417	1517	20	2346	2446	2346	20	888	988	888	20	946	1046	1046

Table 6.30
Cumulative System's Flexibility with the Reversed PLC

Strategic Choice Initial Process Technology	2-1				2-2				2-3				2-4			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
0	100	100	10	10	0	100	100	10	0	100	100	10	0	100	100	10
1	123	123	32	32	1	106	106	16	1	124	124	33	1	123	123	32
2	142	142	51	51	2	111	111	22	2	145	145	54	2	142	142	51
3	159	159	69	69	3	116	116	30	3	163	163	73	3	159	159	69
4	180	180	89	89	4	122	122	36	4	186	186	96	4	180	180	89
5	197	197	106	106	5	127	127	41	5	210	210	119	5	197	197	107
6	210	210	120	120	6	132	132	46	6	231	231	141	6	210	210	120
7	220	220	130	130	7	137	137	49	7	250	250	160	7	221	221	131
8	230	230	140	140	8	141	141	53	8	268	268	178	8	231	231	141
9	239	239	149	149	9	145	145	57	9	287	287	197	9	241	241	151
10	247	247	157	157	10	150	150	61	10	305	305	215	10	251	251	161
11	255	255	165	165	11	154	154	66	11	322	322	232	11	263	263	173
12	263	263	173	173	12	158	158	70	12	341	341	251	12	276	276	186
13	269	269	179	179	13	163	163	75	13	360	360	270	13	292	292	202
14	275	275	185	185	14	168	168	79	14	380	380	290	14	309	309	219
15	281	281	191	191	15	172	172	84	15	400	400	310	15	327	327	237
16	287	287	197	197	16	177	177	89	16	419	419	329	16	345	345	255
17	292	292	202	202	17	182	182	94	17	438	438	348	17	363	363	273
18	297	297	207	207	18	186	186	98	18	455	455	366	18	380	380	290
19	301	301	211	211	19	191	191	102	19	468	468	378	19	392	392	302
20	304	304	214	214	20	194	194	105	20	471	471	381	20	395	395	305

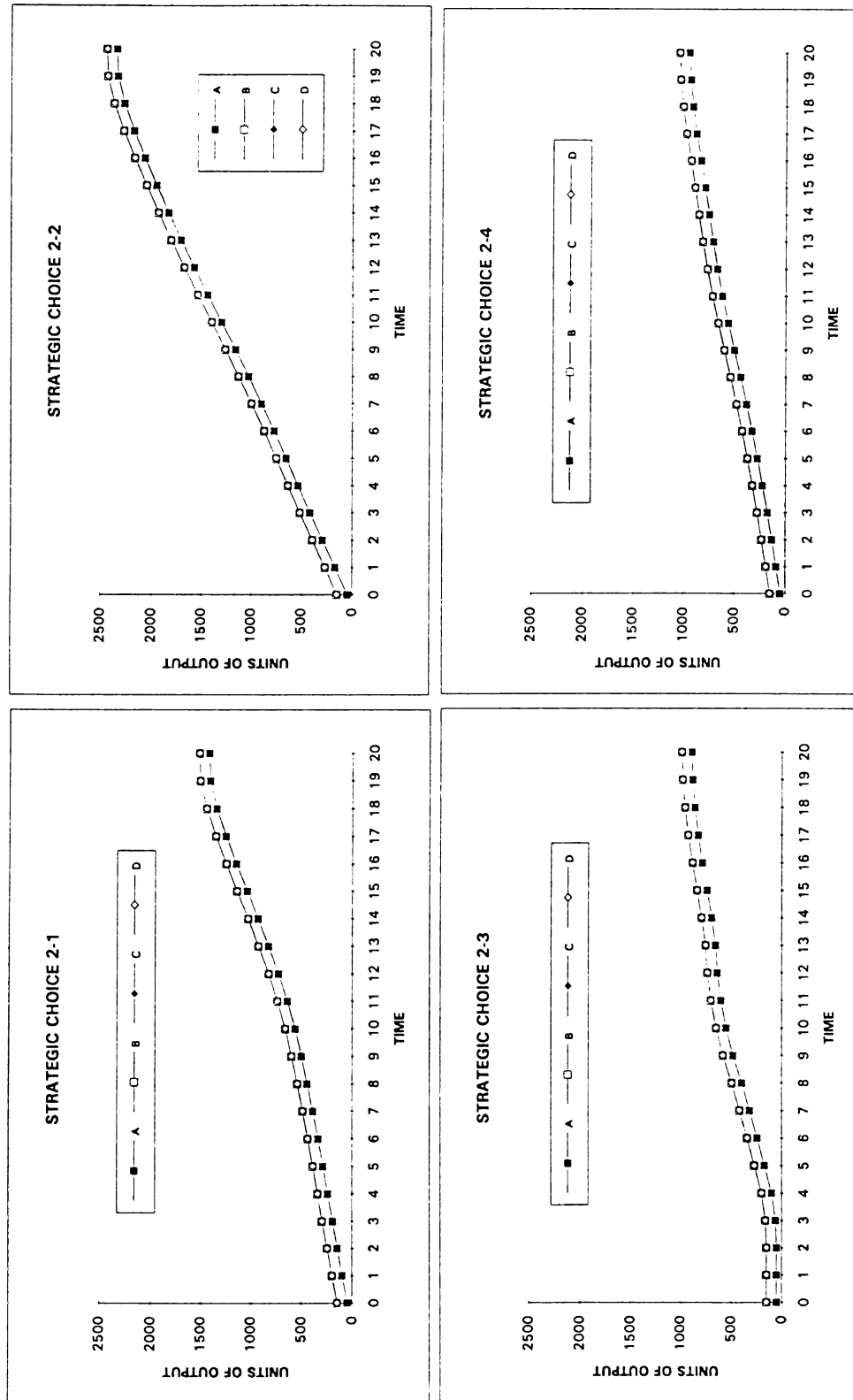


Figure 6.21 Cumulative Automation Capacity with the Reversed PLC

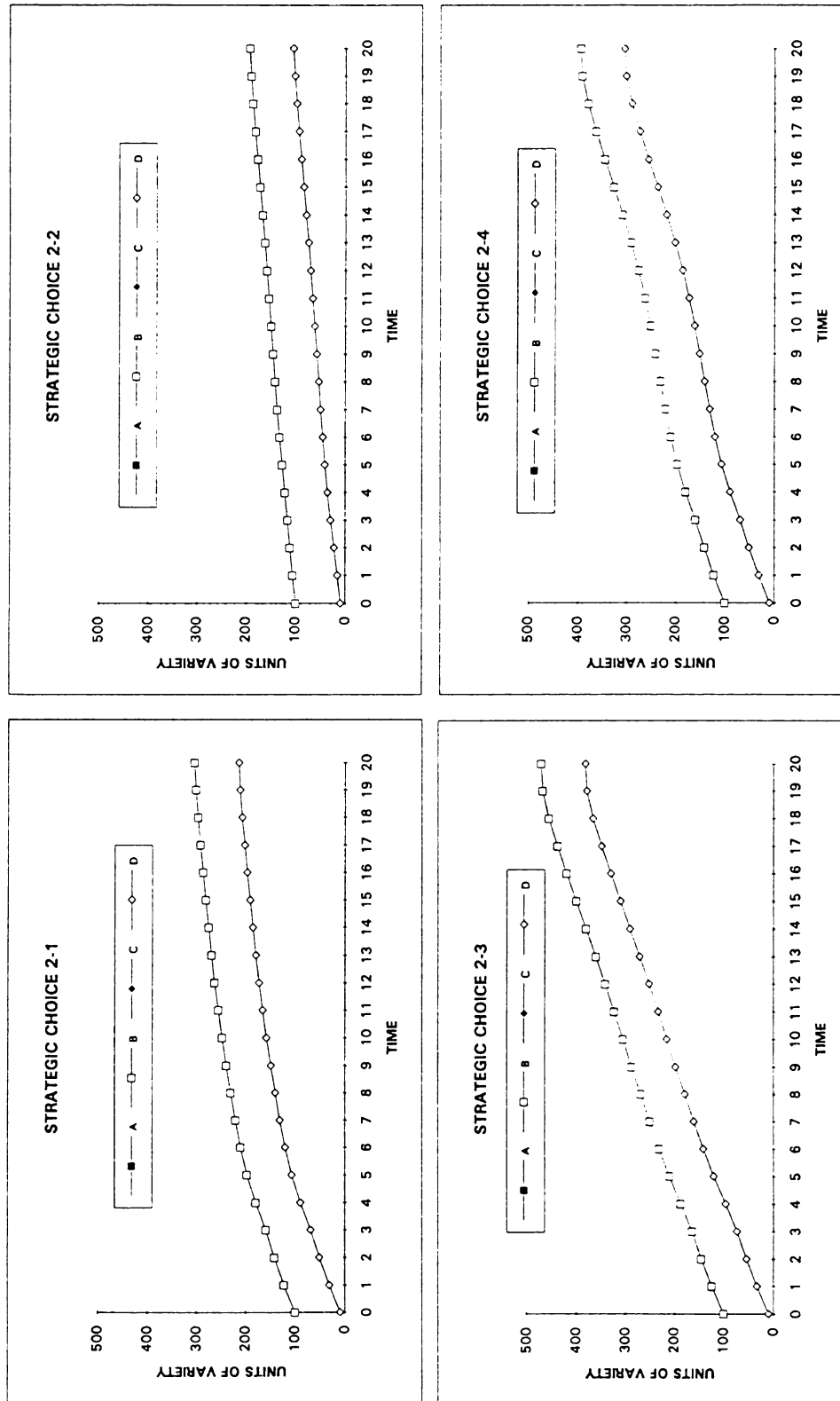


Figure 6.22 Cumulative System's Flexibility with the Reversed PLC

Table 6.31

Cost Performance

	Strategic Choice	Process Technology	G1*v(I)	G2*m(I)	G3*K(I)	G4*S(I)	C1*A*2	C2*F*2	C3*R*2	b1+b2IP	C4(p-v)*2	C5(q-m)*2	E1(v-v)*2	E2(m-M)*2	Total
Normal PLC	1-1	A	108,011	4,437	28,180	10,368	-2,919,604	-332,157	0	-149,574	-61	0	-229,235	-40,442	-3,520,077
		B	108,011	4,437	28,179	10,368	-2,919,503	-332,161	0	-141,342	-52	0	-229,316	-40,439	-3,511,818
		C	108,011	4,436	28,180	7,055	-2,919,626	-330,669	0	-137,952	-52	0	-229,215	-42,031	-3,511,864
		D	108,011	4,404	28,179	6,959	-2,919,531	-330,250	0	-129,719	-44	0	-229,290	-42,036	-3,503,319
	1-2	A	120,340	3,331	45,173	6,587	-9,272,544	-38,164	0	-118,558	-72	0	-451,658	-2,446	-9,708,010
		B	120,340	3,331	45,173	6,587	-9,272,544	-38,163	0	-118,066	-68	0	-451,657	-2,446	-9,707,514
		C	120,340	3,327	45,174	3,333	-9,272,700	-43,130	0	-97,011	-52	-6,727	-451,506	-1,293	-9,700,244
		D	120,340	3,327	45,174	3,333	-9,272,704	-43,128	0	-96,518	-48	-6,727	-451,502	-1,294	-9,699,748
	1-3	A	97,910	5,711	16,285	14,102	-1,220,170	-573,030	0	-162,399	-217,205	-26,824	-860,138	-91,241	-3,016,998
		B	97,910	5,711	16,285	14,103	-1,220,237	-572,854	0	-151,338	-217,339	-26,858	-859,888	-91,451	-3,005,956
		C	97,910	5,711	16,285	10,790	-1,220,190	-572,186	0	-152,688	-217,042	-26,825	-860,251	-92,206	-3,010,691
		D	97,910	5,711	16,285	10,790	-1,220,252	-572,174	0	-141,626	-217,177	-26,859	-860,006	-92,220	-2,999,618
Reversed PLC	2-1	A	126,552	17,926	28,816	11,183	-3,078,782	-357,510	0	-155,008	-5,058	-652	-216,861	-35,847	-3,665,240
		B	126,552	17,926	28,815	11,183	-3,078,725	-357,508	0	-146,639	-5,012	-645	-216,952	-35,850	-3,656,853
		C	126,553	17,926	28,816	7,874	-3,078,809	-356,082	0	-143,089	-5,061	-651	-216,827	-37,415	-3,656,776
		D	126,552	17,926	28,815	7,874	-3,078,745	-356,079	0	-134,729	-5,016	-645	-216,924	-37,418	-3,648,389
	2-2	A	140,974	13,423	45,905	7,121	-9,469,751	-47,453	0	-128,532	-87	0	-414,689	-1,546	-9,854,636
		B	140,973	13,423	45,905	7,121	-9,469,526	-47,454	0	-125,599	-76	0	-414,912	-1,546	-9,851,689
		C	140,974	13,421	45,905	3,872	-9,469,849	-52,264	0	-106,437	-64	-6,652	-414,592	-531	-9,846,217
		D	140,974	13,421	45,906	3,872	-9,469,711	-52,264	0	-103,500	-54	-6,652	-414,732	-531	-9,843,272
	2-3	A	116,865	25,085	19,102	17,324	-1,616,671	-783,687	0	-163,944	-706,345	-87,792	-2,279,487	-77,894	-5,537,444
		B	116,865	25,085	19,102	17,325	-1,616,684	-783,691	0	-153,362	-706,454	-87,836	-2,279,312	-77,891	-5,526,855
		C	116,865	25,084	19,102	14,015	-1,616,712	-782,366	0	-154,166	-706,077	-87,792	-2,279,697	-79,366	-5,531,110
		D	116,865	25,084	19,102	14,015	-1,616,704	-782,372	0	-143,582	-706,196	-87,834	-2,279,535	-79,364	-5,520,520
	2-4	A	118,228	21,801	20,159	14,530	-1,457,135	-512,594	0	-161,293	-32,484	-4,000	-59,514	-62,431	-2,114,733
		B	118,228	21,801	20,159	14,530	-1,457,014	-512,593	0	-151,488	-32,494	-4,004	-59,605	-62,433	-2,104,914
		C	118,221	21,801	20,161	11,221	-1,463,304	-511,338	0	-149,852	-31,231	-3,847	-53,512	-63,832	-2,105,511
		D	118,221	21,801	20,160	11,221	-1,463,136	-511,335	0	-140,070	-31,249	-3,852	-53,641	-63,836	-2,095,714

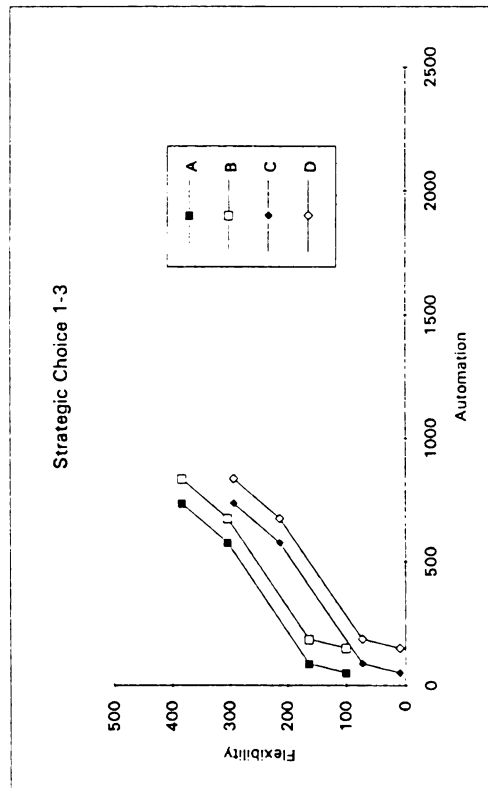
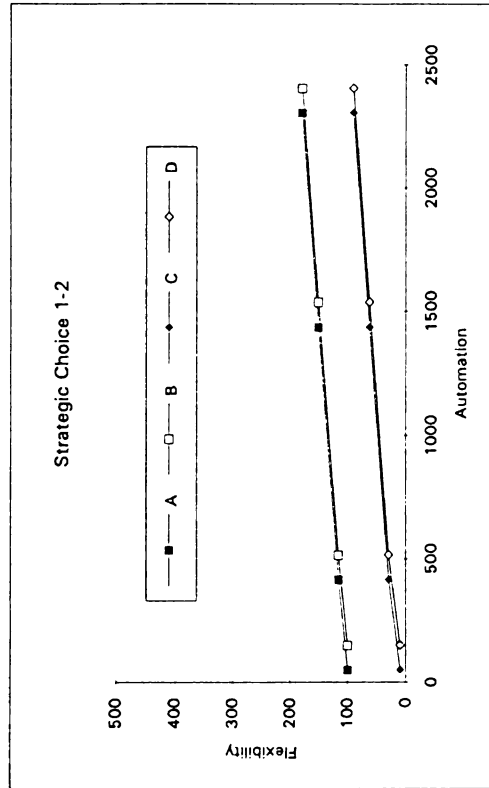
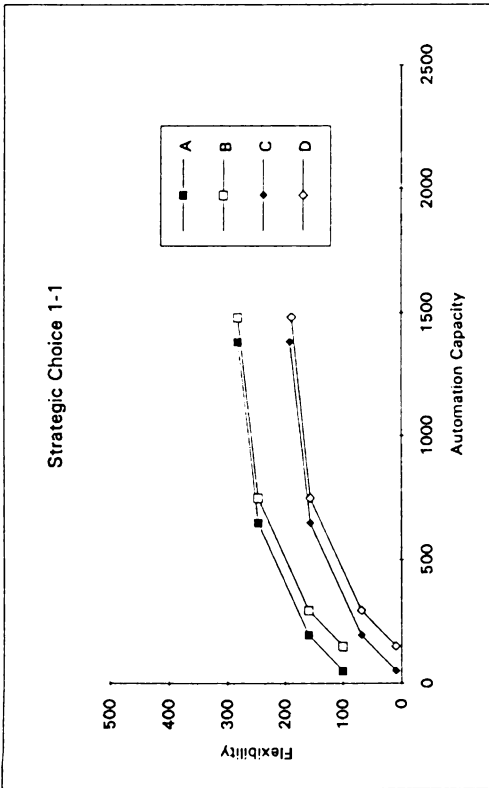


Figure 6.23 Evolution of Process Technology with the Normal PLC

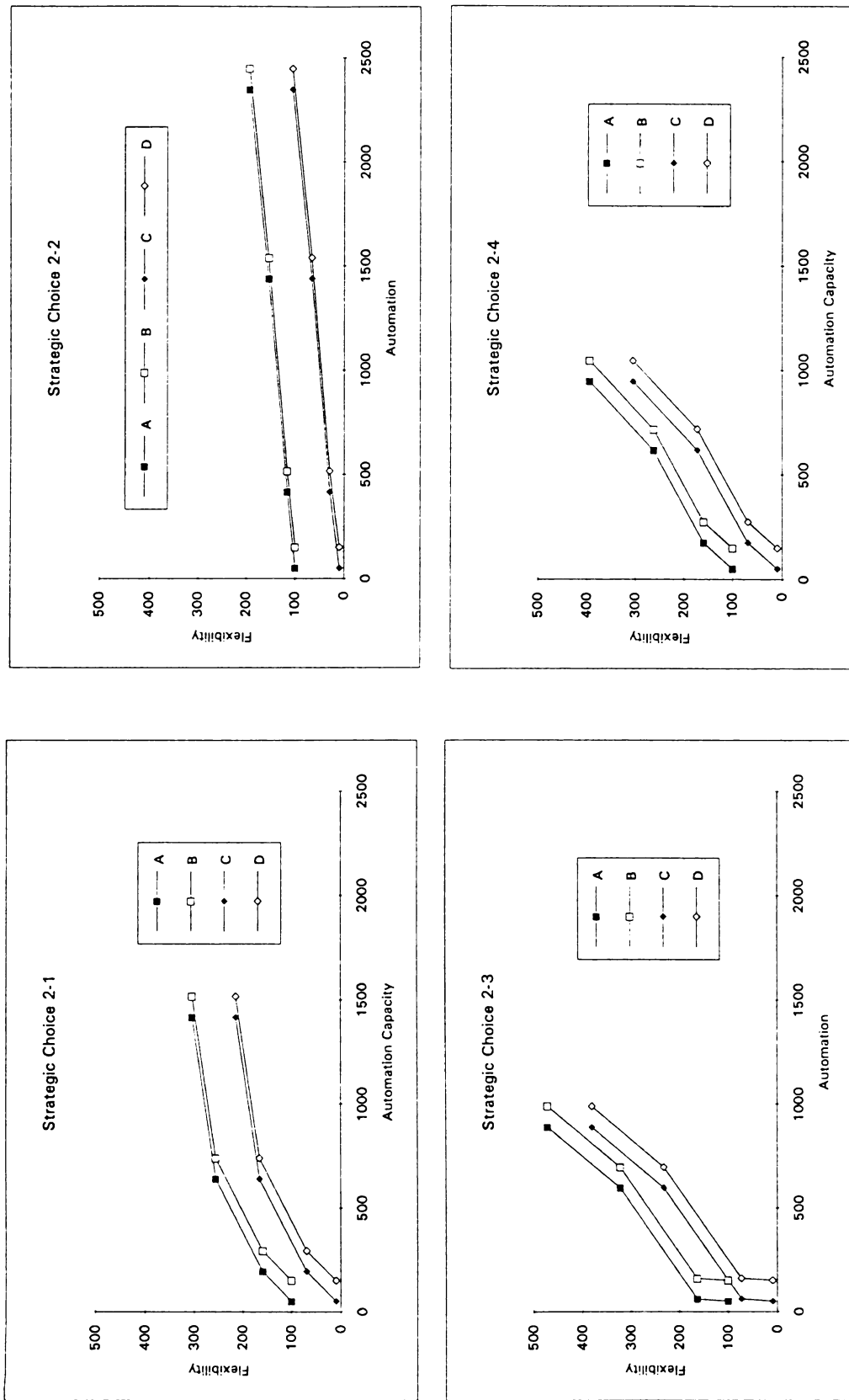


Figure 6.24 Evolution of Process Technology with the Reversed PLC

Table 6.32
Acquisition of Automation Capacity with the Normal PLC
(e1 = 10, e2 = 20)

Initial Process Strategic Choice	A			B			C			D		
	1-1	1-2	1-3	0	1-1	1-2	1-3	0	1-1	1-2	1-3	0
0	37.0	38.8	36.4	0	36.9	38.8	36.1	0	37.0	39.3	36.0	0
1	38.8	41.1	38.4	1	38.8	41.1	38.0	1	38.8	41.7	37.9	1
2	40.7	42.2	40.8	2	40.6	42.2	40.4	2	40.7	42.7	40.3	2
3	42.6	42.7	43.5	3	42.6	42.7	43.1	3	42.6	43.3	43.0	3
4	44.6	43.5	46.3	4	44.6	43.5	45.9	4	44.6	44.1	45.8	4
5	46.9	45.6	48.7	5	46.9	45.6	48.2	5	46.9	46.3	48.1	5
6	49.2	47.8	51.1	6	49.2	47.8	50.7	6	49.2	48.5	50.5	6
7	51.6	50.0	53.6	7	51.6	50.0	53.2	7	51.6	50.7	53.0	7
8	54.1	52.0	56.4	8	54.2	52.0	55.9	8	54.1	52.8	55.6	8
9	56.8	55.4	58.5	9	56.9	55.4	58.0	9	56.8	56.1	57.7	9
10	55.9	55.4	57.4	10	55.9	55.4	60.2	10	55.9	55.0	61.4	10
11	39.7	46.2	43.0	11	39.7	46.2	43.9	11	39.8	46.1	44.3	11
12	31.4	37.1	29.8	12	31.4	37.1	30.1	12	31.4	37.3	30.2	12
13	24.0	30.8	20.4	13	24.0	30.8	20.5	13	24.0	31.0	20.5	13
14	17.9	28.2	13.1	14	17.9	28.2	13.2	14	17.9	28.1	13.2	14
15	14.3	25.5	10.8	15	14.3	25.5	10.8	15	14.3	25.5	10.8	15
16	11.7	22.3	10.0	16	11.7	22.3	10.0	16	11.7	22.3	10.0	16
17	9.3	18.5	9.2	17	9.3	18.5	9.2	17	9.3	18.5	9.2	17
18	6.2	14.0	7.3	18	6.2	14.0	7.2	18	6.2	14.0	7.2	18
19	0.9	8.9	0.9	19	0.9	8.9	0.9	19	0.9	8.9	0.9	19

Table 6.33

Acquisition of Flexibility with the Normal PLC
($e_1 = 10$, $e_2 = 20$)

Initial Process Strategic Choice	A			B			C			D		
	1-1	1-2	1-3	0	1-1	1-2	1-3	0	1-1	1-2	1-3	0
0	0.0	0.0	0.0	0	0.0	0.0	0.0	0	5.9	7.4	1-3	0
1	0.0	0.0	0.0	1	0.0	0.0	0.0	1	8.1	8.5	9.6	1
2	0.0	0.0	0.0	2	0.0	0.0	0.0	2	12.9	9.2	15.3	2
3	0.0	0.0	0.0	3	0.0	0.0	0.0	3	9.2	8.3	11.1	3
4	0.0	0.0	0.0	4	0.0	0.0	0.0	4	4.2	6.2	0.0	4
5	0.0	0.0	0.0	5	0.0	0.0	0.0	5	0.0	4.1	0.0	5
6	0.0	0.0	0.0	6	0.0	0.0	0.0	6	0.0	0.0	0.0	6
7	0.0	0.0	0.0	7	0.0	0.0	0.0	7	0.0	0.0	0.0	7
8	0.0	0.0	0.0	8	0.0	0.0	0.0	8	0.0	0.0	0.0	8
9	0.0	0.0	0.0	9	0.0	0.0	0.0	9	0.0	0.0	0.0	9
10	0.0	0.0	0.0	10	0.0	0.0	0.0	10	0.0	0.0	0.0	10
11	0.0	0.0	0.0	11	0.0	0.0	0.0	11	0.0	0.0	0.0	11
12	0.0	0.6	0.0	12	0.0	0.6	0.0	12	0.0	1.9	0.0	12
13	0.0	1.0	0.0	13	0.0	1.0	0.0	13	0.0	2.1	0.0	13
14	0.0	1.3	0.0	14	0.0	1.3	0.0	14	0.0	2.3	0.0	14
15	0.0	1.7	0.0	15	0.0	1.7	0.0	15	0.0	2.5	0.0	15
16	0.0	2.1	0.0	16	0.0	2.1	0.0	16	0.0	2.7	0.0	16
17	0.0	2.5	0.0	17	0.0	2.5	0.0	17	0.0	2.9	0.0	17
18	0.3	2.9	0.0	18	0.3	2.9	0.0	18	0.2	3.1	0.0	18
19	0.5	3.3	0.0	19	0.5	3.3	0.0	19	0.5	3.3	0.0	19

Table 6.34
Cumulative Automation Capacity with the Normal PLC
(e1 = 10, e2 = 20)

Initial Process Strategic Choice	A			B			C			D		
	1-1			1-2			1-1			1-1		
	0	1	2	0	1	2	0	1	2	0	1	2
0	50.0	50.0	50.0	150.0	150.0	150.0	50.00	50.00	50.00	150.0	150.0	150.0
1	87.0	88.8	86.4	186.9	188.8	186.1	87.0	89.3	86.0	186.9	89.3	186.5
2	125.8	130.0	124.9	225.7	230.0	224.1	125.8	131.0	123.9	225.7	131.0	225.0
3	166.5	172.2	165.7	266.3	272.2	264.5	166.5	173.7	164.2	266.4	173.7	265.8
4	209.1	214.9	209.2	308.9	314.9	307.7	209.1	217.0	207.3	308.9	217.0	309.4
5	253.7	258.4	255.6	353.5	358.4	353.6	253.7	261.1	253.0	353.6	261.1	355.9
6	300.6	304.0	304.2	400.4	404.0	401.8	300.6	307.4	301.1	400.4	307.4	404.6
7	349.8	351.8	355.3	449.6	451.8	452.5	349.8	355.9	351.6	449.6	355.9	455.8
8	401.4	401.8	409.0	501.2	501.8	505.7	401.4	406.5	404.5	501.2	406.5	509.6
9	455.5	453.8	465.3	555.3	553.8	561.6	455.5	459.3	460.2	555.4	459.3	566.1
10	512.3	509.2	523.8	612.2	609.2	619.6	512.3	515.4	517.9	612.3	515.4	624.8
11	568.2	564.6	581.1	668.1	664.6	679.9	568.2	570.4	579.4	668.2	570.4	681.7
12	607.9	610.8	624.2	707.9	710.8	723.8	608.0	616.5	623.7	707.9	616.5	725.2
13	639.3	647.9	653.9	739.2	747.9	753.8	639.3	653.8	653.8	739.3	653.8	757.2
14	663.3	678.7	674.3	763.2	778.7	774.3	663.3	684.8	674.4	763.3	684.8	775.4
15	681.2	706.9	687.4	781.2	806.9	787.5	681.3	713.0	687.5	781.2	713.0	787.8
16	695.4	732.4	698.3	795.4	832.4	798.3	695.5	738.5	698.4	795.5	738.5	798.3
17	707.2	754.7	708.2	807.1	854.7	808.3	707.3	760.7	708.3	807.2	760.7	808.2
18	716.5	773.3	717.4	816.5	873.3	817.5	716.6	779.2	717.6	816.6	779.2	817.4
19	722.7	787.3	724.7	822.6	887.3	824.8	722.8	793.2	724.8	822.7	793.3	824.7
20	723.6	796.1	725.6	823.5	896.2	825.6	723.6	802.1	725.7	823.6	802.1	825.6

Cumulative System's Flexibility with the Normal PLC
(e1 = 10, e2 = 20)

Initial Process Strategic Choice	A			B			C			D											
	1-1	1-2	1-3	1-1	1-2	1-3	1-1	1-2	1-3	1-1	1-2	1-3									
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
7	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
8	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
10	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
11	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
13	100.0	100.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
14	100.0	101.3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
15	100.0	102.3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
16	100.0	103.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
17	100.0	105.3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
18	100.0	107.3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19	100.2	109.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
20	100.6	112.2	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

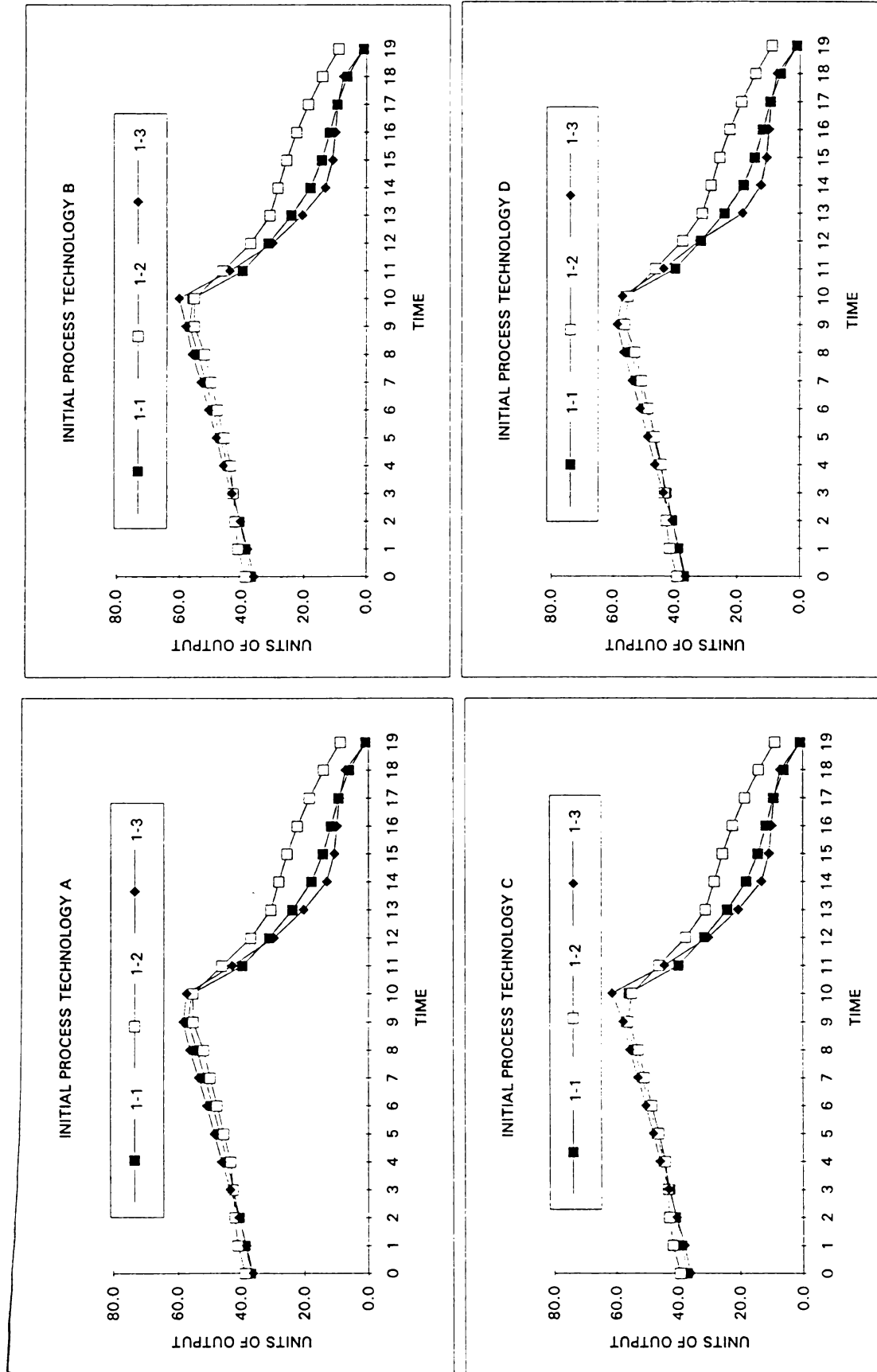


Figure 6.25 Acquisition of Automation Capacity with the Normal PLC
($e_1 = 10$, $e_2 = 20$)

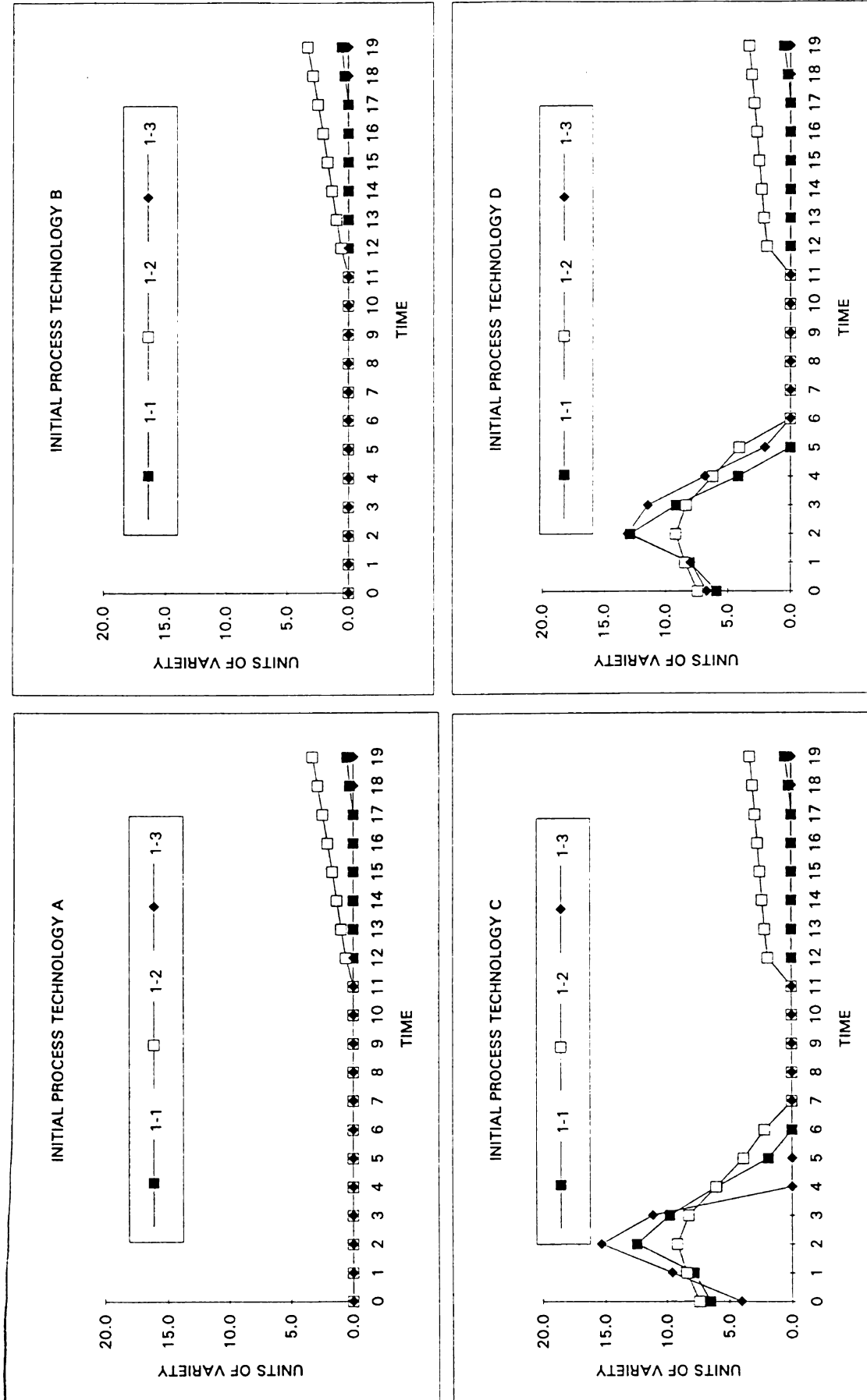


Figure 6.26 Acquisition of Flexibility with the Normal PLC
($e_1 = 10, e_2 = 20$)

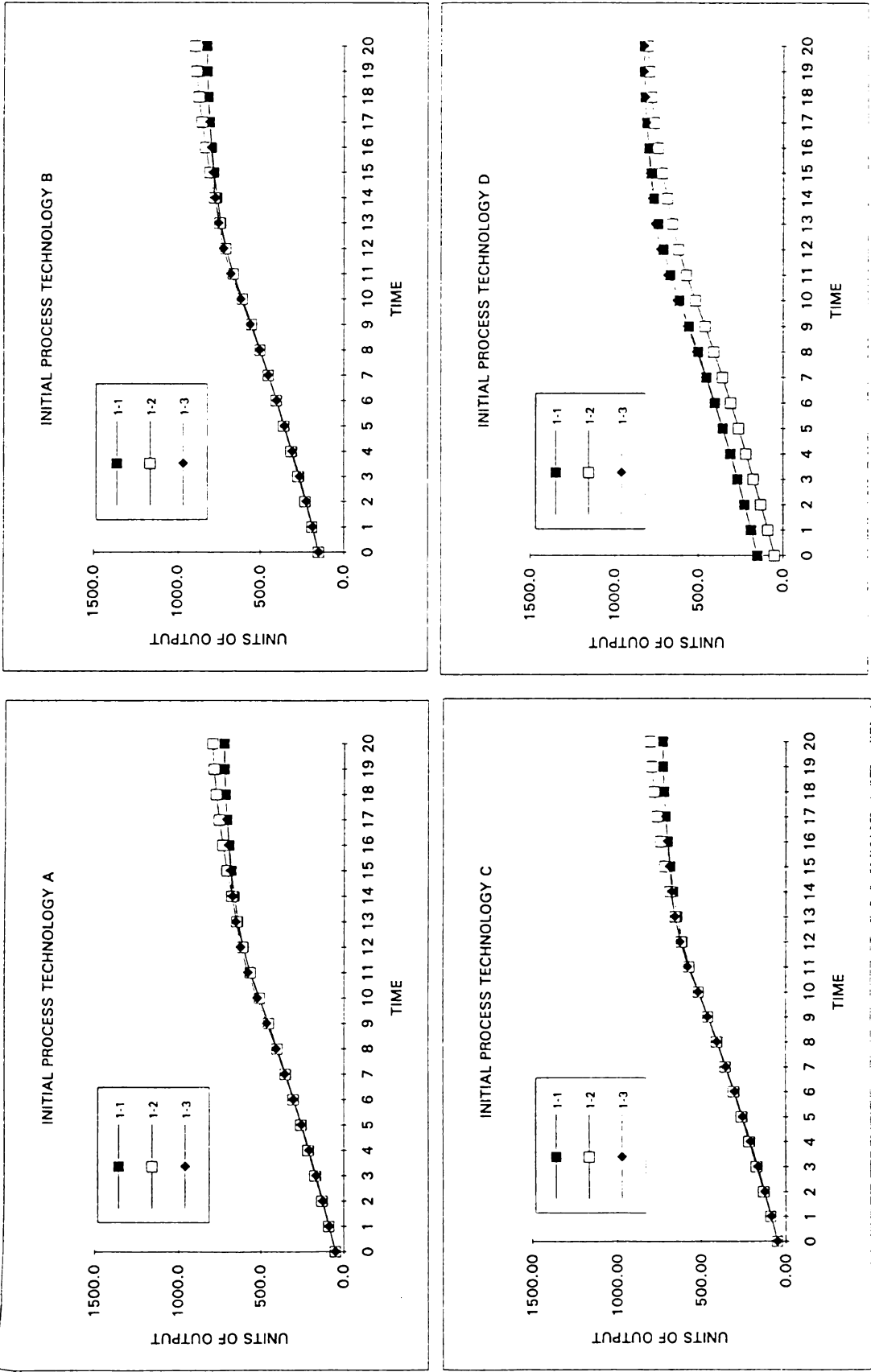


Figure 6.27 Cumulative Automation Capacity with the Normal PLC
(e1 = 10, e2 = 20)

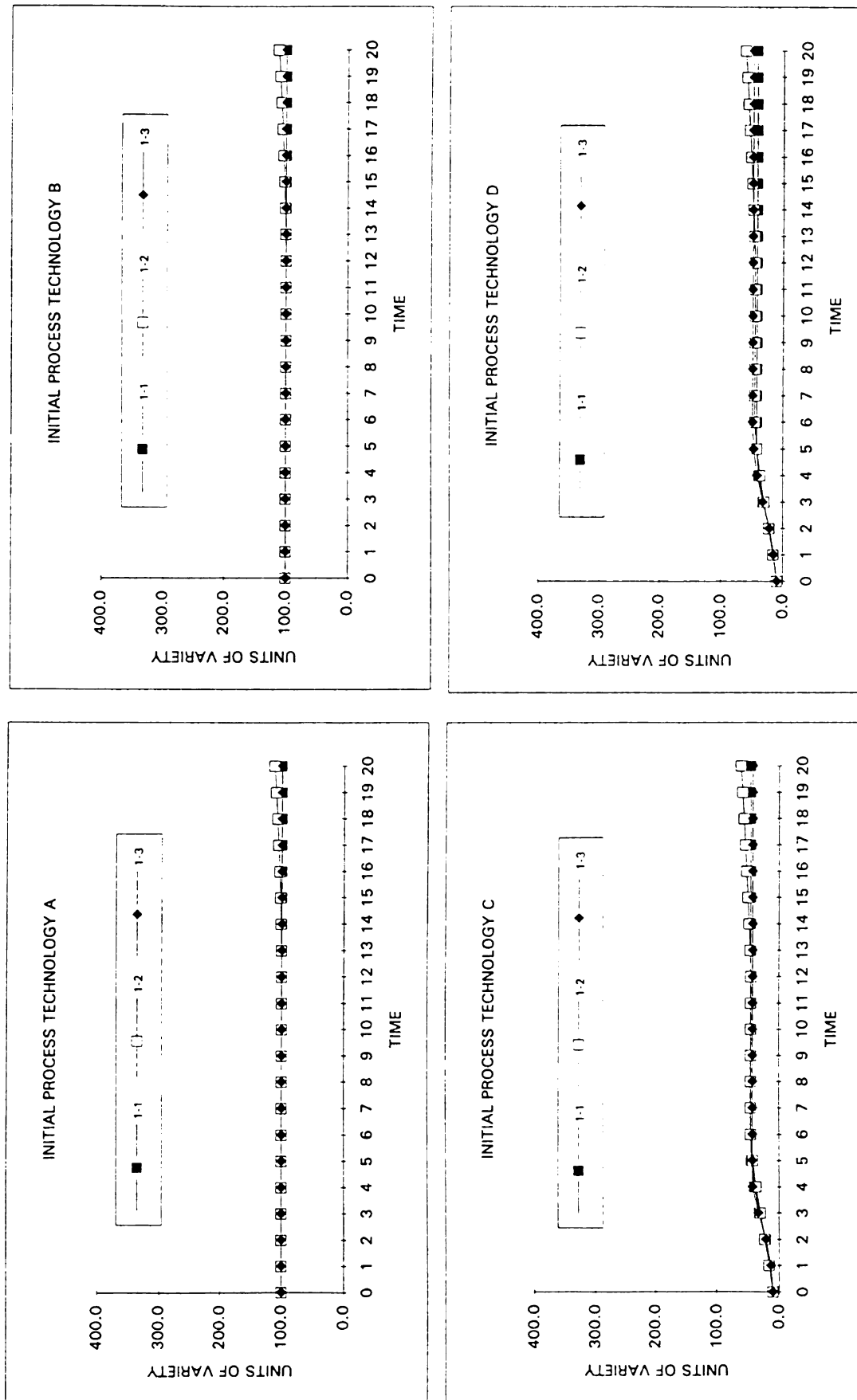


Figure 6.28 Cumulative System's Flexibility with the Normal PLC
(e1 = 10, e2 = 20)

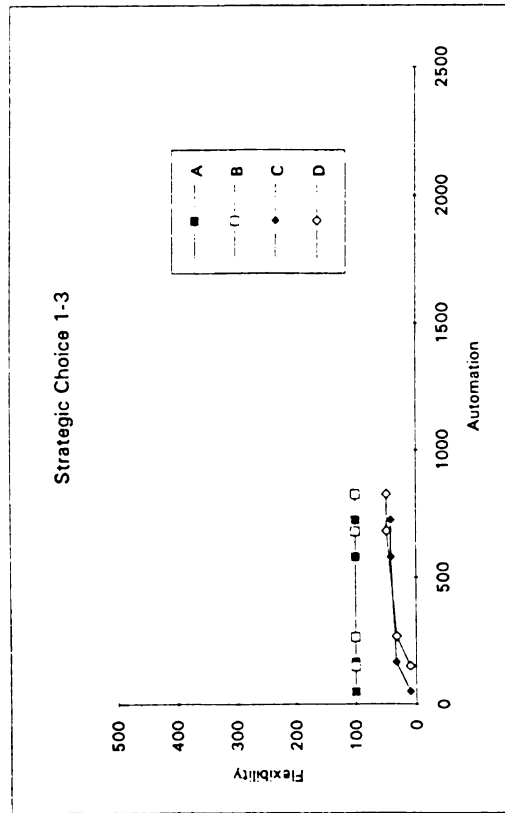
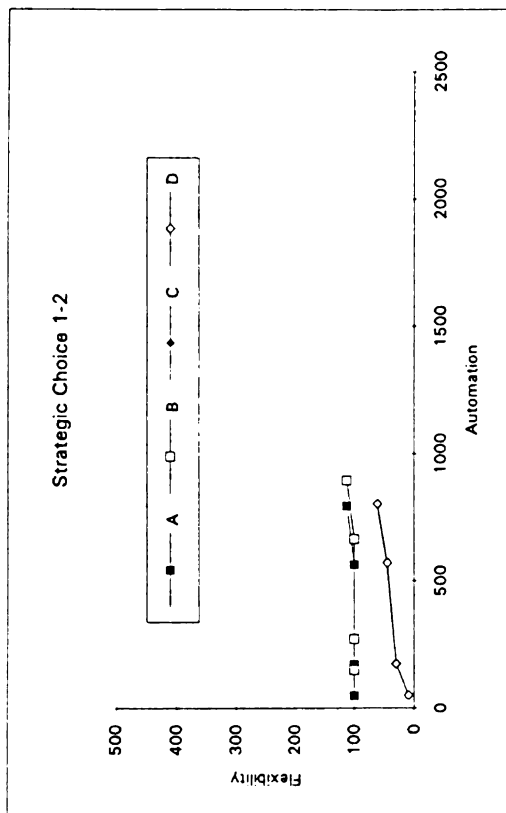
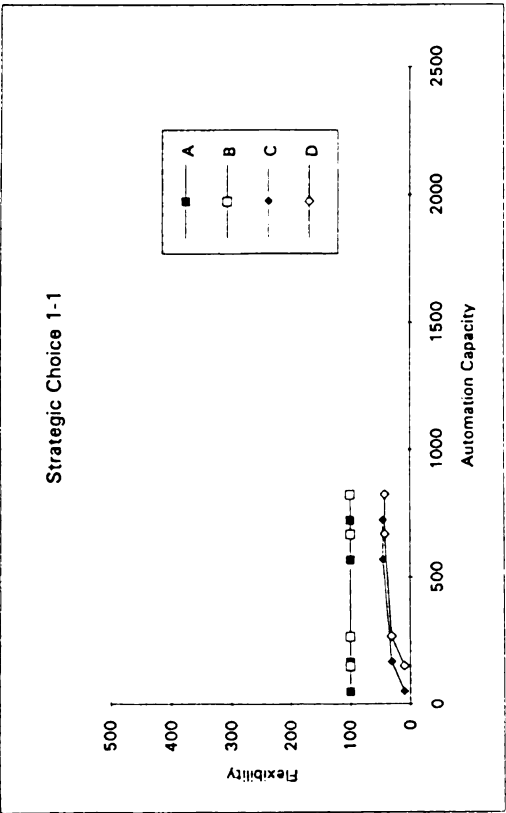


Figure 6.29 Evolution of Process Technology with the Normal PLC
($e_1 = 10, e_2 = 20$)

CHAPTER VII

SUMMARY AND CONCLUSIONS

This chapter summarizes the research conducted in this dissertation. Section 7.1 provides a brief overview of the content, focus, and findings of this research. Section 7.2 summarizes the contributions of this study. Finally, the possible future extensions of this research are suggested in Section 7.3.

7.1 RESEARCH OVERVIEW

This section summarizes the content and findings of this research. The scope and issues of this study are presented first, followed by the research model, research methodology, and, finally, a summary of the findings.

7.1.1 Research Scope and Issues

The research in this dissertation is focused on the optimal acquisition policy within the context of manufacturing strategy. The literature review in Chapter II suggests that, first, the decision process of process technology acquisition should consider two important factors: the objectives of various strategies in the hierarchy of strategy and the conditions of external market environment. Secondly, it is necessary to modify the product-process matrix theory so that it emphasizes the importance of flexibility in a fiercely competitive world of advanced technology. The research scope of this dissertation is to develop a conceptual framework for understanding the strategic implications of the effect of the two factors on the optimal acquisition of process technology within the context of the PLC theory, and to explore research issues analytically.

Two key research issues are identified in this study. The first issue is the effect of two major research factors, strategic priority and external market environment, on the

optimal acquisition of new process technology. The second issue is the effect of the two factors on the evolution of process technology throughout the various stages of the PLC.

7.1.2 Research Model

The research model developed in this dissertation is a dynamic optimal control model. It has an objective function minimizing the total cost, which includes the acquisition cost of technology, production costs, penalty costs for volume and variety flexibilities, and penalty costs for the strategic fit between an SBU's actual market position and its goal in terms of both volume and variety demand. The model has five control variables and seven state variables.

7.1.3 Research Methodology

A design for scenario analysis is developed using three research factors: (1) PLC type, (2) strategic choice (priority), and (3) the structure of initial process technology. The design has twenty-eight replications. Since the closed form solution of the problem can not be obtained, the model is converted to a discrete-time, non-linear model. The converted model is solved by using the GRG2 algorithm in a spreadsheet software, Microsoft Excel®.

7.1.4 Summary of Findings

Based on the discussions of the results of the scenario analysis, findings can be summarized as follows:

1. It is found that a firm whose strategic priority is flexibility invests high in the system's flexibility and low in automation capacity, as compared to low investment in automation capacity and high investment in flexibility for a firm whose strategic priority is cost efficiency.

2. According to the result of this study, the size of investment in process technology is larger with the Reversed PLC than with the Normal PLC.
3. There is little difference in the evolution of process technology between the Normal PLC and the Reversed PLC when a firm's strategic choice is a mixed one (flexibility-cost efficiency/flexibility-cost efficiency) or cost efficiency.
4. According to the result of this study, for total cost performance a firm with a priority of cost efficiency is greatly inferior to the one with a priority of flexibility. This holds for both types of the PLC.
5. For the optimal acquisition of new process technology in terms of flexibility and strategic fit, a firm should select its strategic priority congruent to external market conditions.
6. The acquisition policy of new process technology is found as a strategic decision. In a decision making process for technology acquisition, it is important to align the objectives of various strategies in the hierarchy of strategies with the external market environment. This alignment will optimize the long-term performance of a manufacturing system through the acquisition of new process technology.

Based on the findings in this study, it may be difficult to make generalizations from the preceding conclusions which will apply to problems in the real world. However, this study is expected to lay a cornerstone for future studies in this area. It is hoped that the future studies will further enrich the model to capture the dynamics of strategic variables.

7.1.5 Limitations of Study

This study has some limitations as follows:

1. The results of scenario analysis may be approximated solutions due to the large size of time step in the state equations.

2. The capacity of solution algorithm is not sufficient to allow more than 20 time periods for the PLC. GRG2 in Microsoft Excel® can handle a non-linear problem of up to 200 variables and 150 constraints.
3. Parameters are not industry-verified.
4. Each solution in scenario analysis may be a local optimum. There is no way to verify whether each solution is a global optimum or not.
5. The solutions may be sensitive to the initial values of some state variables.

7.2 CONTRIBUTIONS

The contributions of this study can be viewed in terms of three aspects: (1) research methodology for the study of manufacturing strategy, (2) the content of research, and (3) managerial implication of research findings. First, this study broadened the knowledge base in terms of research methodology for future research in the area of business strategy. In particular, there are few analytic studies for problems related to manufacturing strategy. Because of the dynamic interaction among variables in a strategic problem, it is indispensable to develop dynamic control models such as the one in this dissertation, in order to facilitate both academicians and practitioners understanding of the problem structure.

Second, this dissertation suggests a new conceptual framework for the study of technology acquisition. This study broadly views the problem of technology acquisition by relating the optimal acquisition policy to some strategic and environmental variables. The conceptual frameworks for the decision process of process technology acquisition and for the structure of new process technology suggested by this study are expected to guide future studies in the area of manufacturing strategy.

Finally, the findings in this study can help managers to make decisions for the acquisition of new process technology in a strategic fashion. Analytic studies for process

technology acquisition in the past generally dealt with narrowly defined problems and myopically analyzed the problems without due consideration of the strategic implications of technology acquisition decisions. This study provides managers with a direction for acquisition decisions of new process technology which will lead to the best alignment of various strategies in the hierarchy of strategies.

7.3 POSSIBLE RESEARCH EXTENSIONS

The findings in this study suggests the following research extensions in the future.

1) There should be more efforts to find an algorithm to solve a problem of reasonable size. Because of the large number of variables and constraints contained in the model the solution time and the accuracy of solution of an algorithm become critical for future extensions of this study. In fact, if each period is divided into several steps in order to attain more accurate and smooth solutions, the efficiency of the solution algorithm becomes deteriorated. An efficient algorithm will also allow an investigation of the effect of a longer planning horizon on the technology acquisition policy.

2) A sensitivity analysis with some key parameters is a possible research extension in the future. In particular, the level of initial capacity for volume and variety can be changed to analyze in more detail the effect of initial process technology. The penalty costs for the strategic fit, e_1 and e_2 , can also be included in a sensitivity analysis. From the results with several different levels of these two penalty costs, one can find how the difference in the relative importance, perceived by decision makers, between the functional strategy and the corporate and/or business strategy is affecting the optimal acquisition of process technology.

3) The model can be extended to a game theoretic one. In this study, the model considers a single firm case. With an extension of Duopoly or Oligopoly the game theoretic aspect of technology acquisition problem can be analyzed. In particular, it would

be interesting to study the interaction effect of strategic choices between two competitors or among several competitors on the optimal technology acquisition decision of a firm.

4) Finally, the parameterization of the model should be in the list of possible future research extensions. Once the parameters of this model is estimated with empirical data, it can be used to evaluate strategically the optimal acquisition problem for new process technology of a firm. The parameterization would be possible when real data become available from industry after long experience of advanced process technology,

APPENDICES

APPENDIX I

Derivation of Necessary Conditions

The first-order derivatives of adjoint variables are like the followings;

$$\lambda_1'(t) = -\delta H/\delta v = \lambda_1(t)[\pi_1 a(t) - \pi_2] - [2c_4(p(t) - v(t)) - 2e_1(v(t) - V(t))]e^{-rt}, \quad (a1-1)$$

$$\lambda_2'(t) = -\delta H/\delta m = \lambda_2(t)[\phi_1 f(t) - \phi_2] - [2c_5(q(t) - m(t)) - 2e_2(m(t) - M(t))]e^{-rt}, \quad (a1-2)$$

$$\lambda_3'(t) = -\delta H/\delta b_1 = \lambda_3(t)\alpha a(t) + p(t)e^{-rt}, \quad (a1-3)$$

$$\lambda_4'(t) = -\delta H/\delta b_2 = -\lambda_4(t)\beta s^{-1}(t)(\rho_1 f(t) - \rho_2 r(t)) + p(t)e^{-rt}, \quad (a1-4)$$

$$\lambda_5'(t) = -\delta H/\delta k = 0, \quad (a1-5)$$

$$\lambda_6'(t) = -\delta H/\delta x = 0, \quad (a1-6)$$

$$\lambda_7'(t) = -\delta H/\delta s = \lambda_4(t)\beta b_2(t)(\rho_1 f(t) - \rho_2 a(t))s^{-2}(t). \quad (a1-7)$$

APPENDIX II

T	PH2	THE2	C4	C5	DSV	DSM	DB1	DB2	DK	DX	DS	e(i)	K+Q	HAF	WP-Q
0	0.02	0.2	100	200	2.680636	2	-13.81272	0	38.36868	38.36868	0	1	195	3.837E+11	9.925E+11
1	0.04	0.5	100	200	4.8415288	6	-12.19089	0	40.003045	40.003045	0	0.9512294	232.36868	4E+11	1.02E+12
2	0.1	0.7	100	200	11.548773	12.6	-10.68173	0	41.727879	41.727879	0	0.9048374	289.37171	4.173E+11	1.039E+12
3	0.2	0.3	100	200	24.728513	9.18	-9.284277	0	43.535298	43.535298	0	0.880708	304.79969	4.354E+11	1.185E+12
4	0.3	0.1	50	100	44.28479	3.978	-8.00632	0	45.443809	45.443809	0	0.8187308	343.74489	4.544E+11	1.428E+12
5	0.3	0.01	50	100	57.978608	0.43758	-6.84521	0	47.500882	47.500882	0	0.7788008	387.1997	4.75E+11	1.871E+12
6	0.3	-0.01	50	100	75.927089	-0.441956	-5.794412	0	49.64108	49.64108	0	0.7408182	434.4818	4.964E+11	2.452E+12
7	0.3	-0.1	50	100	99.457261	-4.375362	-4.852035	0	51.866521	51.866521	0	0.7046881	484.34386	5.187E+11	3.212E+12
8	0.3	-0.4	50	100	130.31366	-15.7513	-4.016886	0	54.175432	54.175432	0	0.67032	538.38806	5.418E+11	4.207E+12
9	0.2	-0.3	50	100	115.62077	-7.088087	-3.2936	0	56.652176	56.652176	0	0.6376282	600.44914	5.688E+11	5.51E+12
10	0.1	-0.2	50	100	72.803305	-3.307774	-2.444131	0	54.420913	54.420913	0	0.6065307	661.32475	5.442E+11	6.613E+12
11	0.05	-0.1	50	100	41.771889	-1.32311	-1.366366	0	38.88979	38.88979	0	0.5769498	719.28038	3.889E+11	7.190E+12
12	0.03	-0.05	25	50	27.44377	-0.585599	-0.920198	0	31.014948	31.014948	0	0.5488116	758.98667	3.101E+11	7.58E+12
13	0.02	-0.01	25	50	19.361667	-0.113126	-0.623606	0	23.95625	23.95625	0	0.5220458	789.87049	2.4E+11	7.898E+12
14	0.01	-0.01	25	50	10.735105	-0.111966	-0.426444	0	18.150363	18.150363	0	0.4968663	813.40256	1.815E+11	8.134E+12
15	0.01	-0.01	25	50	10.366671	-0.110875	-0.315397	0	14.475366	14.475366	0	0.4723966	830.78026	1.448E+11	8.308E+12
16	0.01	-0.01	25	50	10.129836	-0.109766	-0.242981	0	11.837181	11.837181	0	0.449329	844.84889	1.184E+11	8.448E+12
17	0.01	-0.01	25	50	9.885675	-0.108868	-0.182546	0	9.3950167	9.3950167	0	0.4274149	866.54534	9.395E+10	8.666E+12
18	0.01	-0.01	25	50	9.580881	-0.107582	-0.114384	0	6.0762525	6.0762525	0	0.4066697	885.99136	6.076E+10	8.66E+12
19	0.01	-0.01	25	50	8.9188529	-0.106806	-0.016155	0	0.8795579	0.8795579	0	0.385741	872.50171	8.795E+09	8.725E+12
20	0.01	-0.01	25	50	8.8836458	-0.105441	0	0	0	0	0	0.3578794			

T	SV	SM	B1	B2	K	X	S	C1A2	C2P2	C3R2	(B1+B2)P	C4(P+V)2	C5(Q+M)2	E1(SV+LV)2	2:SM+LV2	Total
0	100	10	100	50	200	50	100	73607.733	0	0	14887.5	56.246671	2.246E-10	0	0	
1	102.69034	12	86.18728	50	238.36667	88.966668	100	76109.941	0	0	13214.881	44.106779	7.363E-09	0.3103802	27.366407	
2	107.53216	18	73.996387	50	278.37171	128.37171	100	78775.863	0	0	11995.18	34.779722	3.64E-12	1.3869071	234.53386	
3	119.09094	30.6	63.314653	50	320.09669	170.09669	100	81565.944	0	0	11558.803	27.629672	4.259E-10	3.5543636	1450.6785	
4	143.80945	39.78	54.030376	50	363.63489	213.63489	100	84539.673	0	0	12160.058	44.302828	3.755E-12	7.9167581	4145.9173	
5	188.09424	43.758	46.026744	50	409.0787	239.0787	100	87861.762	0	0	13994.946	35.907182	4.72E-10	2.8033264	6039.4363	
6	246.07317	44.19588	39.181534	50	456.57959	306.57959	100	91277.579	0	0	16198.471	29.460002	1.304E-10	0.0069087	7235.0133	
7	322.00026	43.753624	33.987123	50	506.22067	366.22067	100	94785.338	0	0	18872.351	24.5	1.119E-10	7.298866	8161.6862	
8	421.45732	39.378262	28.536088	50	558.08719	408.08719	100	98668.71	0	0	22145.716	20.671764	1.849E-09	40.737594	7483.8867	
9	551.77137	23.626657	24.518602	50	612.26362	462.26362	100	102368.52	0	0	26182.061	17.703668	9.784E-12	130.6884	3007.7364	
10	667.33214	16.53887	21.227903	50	668.9248	518.9248	100	88816.146	0	0	26570.49	1116.4177	108.70572	248.82838	1625.8875	
11	740.19544	13.231096	18.763772	50	723.34671	573.34671	100	43629.369	0	0	28543.717	12642.464	1478.1525	355.0035	1136.2717	
12	781.95731	11.907986	17.417376	50	762.2365	612.2365	100	26395.837	0	0	28092.045	7246.4524	802.63624	626.01497	996.11605	
13	809.41108	11.312987	16.497177	50	793.25045	643.25045	100	15028.968	0	0	27420.015	4883.3784	541.0185	2484.6494	939.4324	
14	828.77275	11.199461	15.873572	50	817.2457	667.2457	100	8180.178	0	0	28607.901	2932.6675	306.45284	5830.2847	900.02789	
15	839.50765	11.057467	15.447128	50	836.36666	686.36666	100	4948.9083	0	0	25683.6	889.51564	81.242283	10636.462	889.18041	
16	849.87363	10.976692	15.131731	50	849.87204	699.87204	100	3147.973	0	0	24724.99	283.59407	19.451436	16940.486	877.03003	
17	859.99995	10.886826	14.88875	50	861.70922	711.70922	100	1862.3011	0	0	23755.789	127.47887	6.2100029	24679.996	863.71125	
18	869.88603	10.798158	14.706204	50	871.04424	721.04424	100	750.54475	0	0	22782.136	154.88886	8.662161	33822.467	849.36253	
19	879.44563	10.660576	14.59182	50	877.12049	727.12049	100	14.956669	0	0	21795.36	466.19636	38.608849	44428.949	834.07609	
20	888.36458	10.54407	14.575664	50	878.00005	728.00005	100	0	0	0	0	7258184.3	2044.9944	56749.649	817.99774	
	96043.319	2227.368			16149.908		3678.7944	-1063006	0	0	-419176	-31188.57	-3391.134	-140257.8	-47667.39	-1584508

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