MANUFACTURING STRATEGY AND THE ENVIRONMENT:
AN ANALYTICAL STUDY

DISSERTATION

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By

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To My Parents

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CHAPTER I

INTRODUCTION

The research in this dissertation deals with manufacturing strategy. Manufacturing strategy guides various operation management decisions and links them with the firm's business strategy to attain competitive advantages. This dissertation analytically studies two of the most important decision areas with significant strategic implications: product planning and process design. Within the context of these two decisions, two policy issues frequently found in the manufacturing strategy literature are evaluated. One issue is the linkage between various decisions, and the other is the emphasis on manufacturing flexibility. By conducting an experimental study using analytical models, this study examines the effectiveness of strategic policies under different environments. In so doing, the dissertation research attempts to provide insights for both managers and researchers on how to manage the manufacturing function strategically to develop and sustain competitive advantages.

1.1 RESEARCH OBJECTIVES

The need for studies in manufacturing strategy is strong from both practitioner and academic perspectives. Manufacturing's weak performance throughout the last two decades contributes to the concern for the U.S. economy, and the recent progress has been uneven despite favorable foreign exchange policies. Some U.S. companies have responded by adopting approaches of foreign competitors, such as the Just-In-Time (JIT) system from Japanese companies. However, merely importing a particular managerial

concept has not been enough. A more strategic approach to manufacturing decisions may be needed, as Wickham Skinner asserted early in 1969. The concept of manufacturing strategy is therefore gaining increased attention.

Research in manufacturing strategy is taking place at three levels: conceptual, empirical, and analytical. The conceptual level has been the initial stage, providing the foundation and the research framework for future study. Empirical research shows more concern over the problem of measuring the key variables and their relationships. This dissertation attempts to contribute to the field by exploring the third stage, the analytical study phase.

Analytical study in manufacturing strategy is still in its infancy. Most variables and their relationships, coming out of the conceptual and empirical studies, have yet to be defined more precisely and confirmed with actual data. However, analytical and empirical studies should proceed in parallel rather than in sequence. An analytical model can help both practitioners and researchers to better understand the structure of problems in manufacturing strategy. Also, descriptive and prescriptive findings from an analytical study can help provide the focus and direction for future empirical research.

The above view is shared by the leaders in the manufacturing strategy field. Robert H. Hayes, during his presentation at the 1988 Decision Sciences Institute National Meeting, suggested that the research in manufacturing strategy should grow into the *stage two*. To develop the field of manufacturing strategy research into a more mature phase, Hayes asserted that there are needs to develop *transportable* and *implementable* research tools that can fill the gap between the practitioner's needs and the state of art in academia. To achieve this objective, he encouraged researchers to develop analytical tools to study the interrelationship among various components of manufacturing strategy.

The objectives of this study are therefore threefold: 1) to establish a conceptual framework of manufacturing strategy within the context of product planning and process design, 2) to develop a mathematical programming model to portray these strategic decisions, and 3) to use the decision model to assess two focal strategic concepts – linkage between decisions and emphasis on flexibility – under different environmental contexts. By doing so, this dissertation addresses some important issues in manufacturing strategy and tests the conjectures raised by the previous studies.

1.2 RESEARCH SCOPE AND QUESTIONS

Manufacturing strategy involves various decisions and numerous issues. This section provides the framework and focus of the dissertation by addressing the strategic implications of product and process decisions. Also, two critical issues for this dissertation are identified as the linkage among decisions and emphasis on manufacturing flexibility. This section then recognizes the need for more studies on the environmental aspect of manufacturing strategy. Finally, the research questions are established.

1.2.1 Manufacturing Strategy, Product Planning, and Process Design

Manufacturing strategy answers the question of how to use manufacturing strengths as a competitive weapon to achieve the corporate and business goals (Wheelwright 1984; Swamidass and Newell 1987). Within the hierarchy of strategy, manufacturing strategy reflects the goals and strategies of the business unit, and guides various decisions within the operations function to achieve them effectively.

The *product planning* decision is closely related to the basic question of what manufacturing should achieve. It reflects the business strategy by determining what

products with what features should be offered at what time in order to respond to the opportunities and threats in the market. By doing so, product planning helps determine the firm's competitive position in the market, and at the same time determines the manufacturing requirements in terms of process and capacity to meet the planned demand over time. Traditional theories in the strategy research, such as dominant orientation (Porter 1980), and competitive priorities (Skinner 1969; Buffa 1984; Wheelwright 1984; Krajewski and Ritzman 1987), consider the product planning decision as a key element of strategy.

The *process design* decision represents another fundamental aspect of manufacturing strategy. In general terms, the process design guides the organization's technological choices. More specifically, the decision specifies when to acquire and dispose of a particular manufacturing technology. The process design decision affects the competitive strength of a firm by determining how efficiently it can satisfy the process requirements. It also influences the basis on which various product planning alternatives are considered. Many concepts in strategy, such as efficiency versus flexibility (Hayes and Wheelwright 1979a, 1979b, 1984; Slack 1983; Karmarkar and Kekre 1985), and economies of scale and scope (Goldhar and Jelinek 1983; Cohen and Lee 1984), are closely linked to this process decision.

Therefore, this dissertation takes product planning and process design as two key decisions in manufacturing strategy. Chapter II further highlights the importance of the product and process decisions in developing manufacturing strategy. These two decisions are formulated as mathematical programming problems in Chapter III. Then two focal strategic issues as described below are addressed within the context of these two decisions.

1.2.2 Strategic Value of Flexibility and Linkage

Two of the most critical concepts in the *content* and *process* of manufacturing strategy are respectively represented by the emphasis given to manufacturing flexibility and the linkage between decisions. *Manufacturing flexibility* has been frequently mentioned by strategy researchers as the key element to enhance the U.S. productivity (Buffa 1984; Roth 1986). Also the recent articles on the flexible manufacturing systems (FMS) seem to suggest that developing manufacturing flexibility is essential for the U.S. companies to compete against worldwide competitors (Jaikumar 1986; Goldhar and Jelinek 1983). However, industry's implementation of FMS is still at a disappointingly low level, despite the widely hailed potential strategic advantages of such a system. Thus there is a need for studying the concept of manufacturing flexibility in more concrete, tangible terms. Answers to questions such as what it represents, how it should be pursued, and what strategic benefits are expected from higher flexibility in different environments, should provide valuable insights to managers and researchers alike.

A key concept on how manufacturing strategy should be formulated and implemented is the *linkage* among various decisions in operations management (Wheelwright 1984; Sharma 1987). The consistency in various decisions directed toward the goals and strategies of the business has been asserted as a critical element of manufacturing strategy. Particularly, the linkage between product and process decisions has been the subject of many publications (Hayes and Wheelwright 1979a, 1979b; Abernathy 1976; Utterback and Abernathy 1985; Buffa 1984; Krajewski and Ritzman 1987). In this study, the pattern of linkage between product and process decisions is interpreted as the role of manufacturing in the strategy formulation process. Wheelwright (1984) describes two types of manufacturing roles, *reactive* and *proactive*, and suggests that the performance of a firm can be improved if the manufacturing function plays a more

proactive role. Also Swamidass and Newell (1987) empirically find that, as manufacturing managers are involved more actively in the strategy formulation process, the firm's performance is improved. However, their study also finds that the participation of manufacturing managers diminishes as the environment becomes more uncertain, implying either the difficulty of linking various decisions or lower payoffs in an uncertain environment.

The analytical framework developed in Chapter III incorporates these two strategic issues within the context of the mathematical programming model. Two different decision models – linked and unlinked – are developed to reflect the linkage aspect. Also, the flexibility issue is included in the form of additional constraints.

1.2.3 Manufacturing Strategy and the Environment

Strategy theorists have suggested that the environment is a critical determinant of strategy. Particularly the organizational theory literature views the external environment of an organization as the source of events and changing trends which create opportunities and threats for individual firms. Unfortunately, the research in operations management has paid little attention to the environment-manufacturing strategy connection. Exceptions are the work by Van Dierdonck and Miller (1980) and Swamidass and Newell (1987).

One of the main premises of this dissertation is that manufacturing strategy should be understood within the specific context of the firm's environment. More specifically, the strategic policies such as linking decisions or emphasizing manufacturing flexibility should not be taken as a universal prescription for all firms. Companies in a particular manufacturing environment may need more linkages between product and process decisions than others under a different environment. Similarly, manufacturing flexibility could be a strong competitive weapon for some companies, while others under a different

environment could not afford to, or should not pursue to, enhance their manufacturing flexibility.

Therefore, this dissertation assesses the effectiveness of these strategic policies under different environments. Chapter IV provides a framework to study the environmental impact on manufacturing strategy, and presents research hypotheses regarding the strategy-environment connection. Then the experimental study presented in Chapters V and VI tests the research hypotheses by simulating the decision models under different environmental settings. This study thus attempts to build a contingency theory regarding the impact of the environment on manufacturing strategy.

1.2.4 Research Questions

The research questions center around the conjectures of several strategy researchers in conceptual and empirical studies, that have not been tested or confirmed analytically. In the context of product planning and process design, the dissertation tests the following research hypotheses:

- a. *Integrated* decisions are more effective than non-integrated decisions in achieving competitive advantages.
- b. *Flexible* manufacturing technology is more effective in achieving competitive advantages.
- c. The degree of effectiveness of the integrated decisions is contingent upon the structure of the manufacturing environment.
- d. The degree of effectiveness of manufacturing flexibility is contingent upon the structure of the manufacturing environment.

Chapter II reviews the literature on manufacturing strategy that explored the above questions. These questions are reinforced and formalized as research hypotheses in

Chapter IV with the guidance from the organizational theory literature. In addition, a small field study was conducted to examine the managerial practices dealing with the strategy-environment relationship. These research hypotheses are then tested by an experimental study presented in Chapter VI.

1.3 RESEARCH METHODOLOGY OVERVIEW

The research methodology in this dissertation consists of three segments: 1) decision models, 2) simulation, and 3) experimental analysis. *First*, in Chapter III, product planning and process design decisions are formulated into mathematical programming problems. They are formulated in two different formats: an *unlinked* model to represent the non-integrated decision-making process, and a *linked* model to represent the integrated decision-making process. The unlinked model makes the product and process decisions sequentially, while the decisions are made simultaneously in the *linked* model. In each model, the emphasis on manufacturing flexibility is reflected as additional constraints.

Second, a simulation model is developed to evaluate the consequences of different policies under various environments. The simulation model generates various parameters in the decision model to reflect the environmental structure, and simulates the decision making pattern over several periods using a *rolling schedule* procedure. Chapter III briefly describes the simulation model, and Chapter V provides the more detailed procedure of implementing various environmental factors.

Third, an experimental design allows statistical tests of the research hypotheses. Environmental factors are identified with the guidance of previous research. Realistic factor levels are established on the basis of the data from a field study. Then the decision

models, that represent different strategic policies, are simulated under different environmental settings. The results of experimentation are analyzed statistically to test the research hypotheses. The strategic implications of different policies are addressed in terms of the product and process positions generated by the decision models.

1.4 SUMMARY

This chapter briefly described the main thrust of this dissertation. Manufacturing strategy is studied analytically in this research. Two critical decisions in forming manufacturing strategy were identified as product planning and process design. Also this chapter established two focal issues in manufacturing strategy research – linkage among decisions and developing manufacturing flexibility. This chapter recognized the need for more research on the environment-manufacturing strategy connection. Thus the research hypotheses were established around the environmental impact on the performance of different policies.

The research methodology was briefly reviewed. This study develops an analytical model to assess various strategic policies. The decision model is formulated in the form of a mathematical programming problem, which is simulated over several periods using a rolling schedule procedure. The experimental study is then conducted with a realistic factor setting that is determined on the basis of the field study data. The results are statistically analyzed to test the research hypotheses.

CHAPTER II

LITERATURE REVIEW

This chapter reviews the current knowledge base on manufacturing strategy. The purpose is to classify and summarize past literature with the intent of pinpointing the gaps in our knowledge and identifying research issues. The thrust of this dissertation, as discussed in Chapter I, is to address the issues of linkage and manufacturing flexibility within the context of product planning and process design decisions. The research questions raised in this dissertation include various topics in manufacturing strategy, such as 1) product planning, 2) process design, 3) linkage between decisions, 4) manufacturing flexibility, and 5) environmental impact on manufacturing strategy. This chapter discusses the literature related to the first four issues as well as the research methodologies for studying manufacturing strategy. The last issue of environmental impact will be discussed in Chapter IV due to its large scope and complexity.

Section 2.1 reviews and summarizes the various concepts developed in manufacturing strategy. This section thus provides a conceptual framework that links various issues with manufacturing strategy. Section 2.2 then presents a discussion on the two focal decisions in manufacturing strategy – product planning and process design. It reviews the literature that specifically emphasizes the strategic implications of the product and process choices. The strategic nature of the relationship between these two decisions is highlighted. Section 2.3 reviews the literature dealing with the linkage aspect of manufacturing strategy. The pattern of linkage between the product and process decisions, as addressed in Chapter I, is portrayed to represent the role of manufacturing in the process

of business strategy formulation. Section 2.4 discusses the concept of manufacturing flexibility. It reviews the literature that defines manufacturing flexibility at the strategic, tactical, and operational levels, and discusses the strategic benefit expected from developing manufacturing flexibility. Finally, Section 2.5 reviews the research approaches used in the study of manufacturing strategy, and briefly describes the analytical research method selected for this dissertation. The main findings from the literature are summarized in Table 2.1 along with their implications for this dissertation.

2.1 CONCEPTS IN MANUFACTURING STRATEGY

As a research field, manufacturing strategy is in its early stage of development. Most of the concepts are still being developed, and many researchers are trying to define a solid research framework. For an analytical study such as this dissertation, it is crucial that the scope and objective of the study be based on a firm conceptual framework.

Manufacturing strategy refers to the basic policy for guiding operations decisions in a manufacturing organization. Many researchers approach this concept from two dimensions. First, manufacturing strategy is represented by the *fundamental choices* which influence the competitive position of a firm. Second, manufacturing strategy is understood as the *pattern of decisions* that is shaped over a period. Both dimensions of manufacturing strategy are reflected in this dissertation.

This section reviews the key concepts that define manufacturing strategy so as to build a conceptual framework. First, the fundamental decisions in formulating manufacturing strategy are discussed within the framework of strategy hierarchy. Then the literature that views strategy as a pattern of decisions is reviewed. This section concludes with a brief remark on how these perspectives are incorporated in this study.

2.1.1 Manufacturing Strategy in the Strategy Hierarchy

Most strategy researchers conceptualize strategic management on the basis of a hierarchical structure. They tend to classify strategies into three hierarchical levels: corporate strategy, business strategy, and functional strategy. Within the framework of strategy hierarchy, manufacturing strategy is understood as one of the functional strategies, along with marketing, finance, research and development, and human resource strategies. In essence, manufacturing strategy should reflect the goals and objectives of the business strategy, and direct the manufacturing function in achieving them.

2.1.1.1 The Hierarchy of Strategy

By classifying strategic decisions into hierarchical groups, the unique characteristics of the strategies at each hierarchical level can be highlighted. This view is clearly supported by Hofer and Schendel (1978). They define four *strategic components*: scope, distinctive competence, competitive advantage, and synergy. Hofer and Schendel then contend that the relative importance of each component depends on the hierarchical level of the strategy. For example, the notion of scope and competitive advantage are more emphasized when a business strategy is formulated, while the concepts of distinctive competence and synergy are more important at a functional strategy level.

Wheelwright (1984) defines the concept of manufacturing strategy within the context of the strategy hierarchy. At the highest level, the *corporate strategy* determines the areas of business to be involved in, and acquisition/allocation of various resources. Next the *business strategy* defines the ranges or boundaries for each strategic business unit, and specifies the basis on which the business unit will achieve a competitive advantage. *Functional strategies*, such as marketing, finance, and manufacturing, then develop policies to implement the tasks defined by the higher level strategies. The functional strategy thus specifies how that function will support the desired competitive

advantage set by the business strategy and how it will complement the other functional strategies.

According to this hierarchical point of view, manufacturing strategy is understood as one branch of the functional strategies. As a functional strategy, it defines manufacturing's tasks to achieve the goals set by the business strategy. Swamidass and Newell (1987) accordingly define manufacturing strategy as "the effective use of manufacturing strengths as a competitive weapon for the achievement of business and corporate goals." Summarizing the viewpoints of Skinner (1985) and Wheelwright and Hayes (1985), Swamidass and Newell contend that manufacturing strategy should reflect the goals and strategies of the business, and enable the manufacturing function to contribute to the long-term competitiveness of the strategic business unit.

Reflecting this hierarchical perspective of the literature, manufacturing strategy is defined in this dissertation in terms of a combination of two major decisions: *what* tasks should be achieved by the manufacturing function, and *how* manufacturing should achieve these tasks. Figure 2.1 schematically describes this view.

2.1.1.2 Strategic Tasks of Manufacturing Function

One of the key concepts in strategic management is the notion of *distinctive competence*, and it has been well received at the level of corporate strategy. Porter (1980) recognizes that firms have discovered many different approaches to create a competitive advantage, and the best strategy for a given firm is ultimately a unique construction reflecting its particular circumstances. As a part of building a generalizable theory for the competitive strategy field, Porter proposes three internally consistent generic strategies that can provide a long-run defensible position for a company. They are: 1) overall cost leadership, 2) differentiation, and 3) focus.

The concept of distinctive competence at the corporate strategy level is translated accordingly to the lower hierarchy strategy, such as manufacturing strategy. Regarding the question of what tasks should be achieved by the manufacturing function to contribute to the business goal, Skinner (1969) proposed a term *manufacturing mission*. Skinner asserts that a manufacturing firm can compete in several dimensions such as low cost or high quality. By determining the target level or the relative priority of performance in each dimension, a firm can define the tasks that should be achieved by the manufacturing function. Thus manufacturing strategy can be represented as a *vector of competitive priorities*. Skinner asserts that a firm has to define this manufacturing mission in such a way that the firm's distinctive competence can be effectively exploited.

Wheelwright (1984) formalizes this concept of competitive priorities into four dimensions: cost, quality, dependability, and flexibility. Most of the past literature in this field, such as Fine and Hax (1985), Cohen and Lee (1985), Schroeder et al. (1986), and Swamidass and Newell (1987), adopt similar concepts to represent the strategic tasks of manufacturing. Later Krajewski and Ritzman (1987) summarize this concept of competitive priorities into seven dimensions. They include low cost, high-performance design, fast delivery, consistent quality, on-time delivery, product flexibility, and volume flexibility.

2.1.1.3 Decisions in Manufacturing Strategy

The question regarding *how the tasks should be achieved* encompasses the *whole* set of decision areas in operations management. The literature seems to suggest, however, that some decisions have more strategic importance than others.

Wheelwright (1984) divides strategic decisions in the manufacturing function into two large categories: *structural* decisions and *infrastructural* decisions. He contends that the structural decisions are more strategic, while the infrastructural decisions are more

tactical in nature. He lists the eight key decisions to achieve the strategic tasks of manufacturing. Among them, capacity, facility, technology, and vertical integration decisions are in the structural category, while the infrastructural category includes work-force, quality, production planning and control, and organization decisions. Wheelwright (1981) contends that, even though the infrastructural decisions seem to have less strategic meaning, Japanese companies have demonstrated that the operational decisions, if managed with consistent strategic perspective, could become a real strategic weapon.

Fine and Hax (1985) contend that a manufacturing strategy must be comprehensive, but at the same time, the complex web of decisions must be broken down into analyzable pieces. They divide the manufacturing decisions into nine categories; facilities, capacity, vertical integration, processes and technologies, scope and new products, human resources, quality, infrastructure, and vendor relations. Similar views are reflected, with minor differences, by the previous studies, such as Cohen and Lee (1985), Anderson et al. (1986), and Schroeder et al. (1986).

2.1.2 Pattern of Decisions as Manufacturing Strategy

According to the traditional perspective, a strategy is defined as a deliberate conscious set of guidelines that determine decisions into the future. Accordingly, a strategy is viewed as explicit, developed consciously and purposefully, and made in advance of the specific decisions to which it applies. Some researchers, however, have paid more attention to the pattern of decisions as a key feature of strategy. They contend that the traditional definition of *strategy as plan* is incomplete for organizations and nonoperational for researchers (Mintzberg 1978).

An alternative perspective is to define the strategy with more focus on the *process* rather than the *content* alone. Mintzberg (1978) discriminates the *intended* strategy (as defined traditionally) and the *realized* strategy, and defines a realized strategy as "a pattern

in the stream of decisions." According to his definition, when a sequence of decisions in some area exhibits *consistency* over time, a strategy is considered to have formed. Mintzberg argues convincingly that defining strategy as a pattern arising from a stream of decisions enables researchers to consider both sides of the strategy formation coin: strategies as *intended* (a priori guidelines) as well as strategies as *evolved* (a posterior consistencies). He goes further to contend that this definition operationalizes the concept of strategy for the researchers, because research can now focus on a tangible phenomenon – the decision stream.

Wheelwright (1984) adopts this view and contends that, in order to lead to the kind of manufacturing strategy required for the business strategy, the decisions must be made *consistently* with the decisions made at other points in time. He goes further to say "It is this pattern of structural decisions over time that constitutes the manufacturing strategy of a business unit. More formally, a manufacturing strategy consists of a sequence of decisions intended to enable a business unit to achieve its desired competitive advantage."

Adopting these perspectives for this research, manufacturing strategy is understood as the result of evolving decisions. At a particular time, the firm makes strategic decisions based on the estimation of its market opportunity and competency, with the intention of developing a certain competitive advantage. This intention is realized, either as expected or differently, by the interaction of its decisions, competitor's reaction, and changes in the firm's business environment. The results can be either close to what was intended or far from it. The firm then evaluates the results and makes subsequent decisions. This cyclical process is repeated over time, and the resulting strategic position is seen as the strategy of the firm. Thus what is meaningful and important is the way the decisions are made, and this is captured by many researchers as the pattern of decisions which represents the strategy (Mintzberg 1978; Wheelwright 1984).

2.1.3 Summary and Implications

This section reviewed the literature that provides a research paradigm for manufacturing strategy. Two generic approaches of viewing manufacturing strategy are considered: 1) manufacturing strategy as the fundamental choices made in the manufacturing function, and 2) manufacturing strategy as a pattern of decisions.

As shown in Figure 2.1, the first view is reflected in this research by modeling the *product* and *process* decisions as key strategic decisions answering two fundamental decisions: *what tasks* should be achieved by manufacturing, and *how* the tasks should be achieved. The literature dealing with the product and process decisions is further discussed in the following section. The second view of defining *strategy as a pattern of decisions* is reflected in this study by simulating a decision model over several periods. As will be described in Chapter III, the decision model is solved repeatedly in a rolling schedule format, making decisions at each period based on the past period's decisions and additional information available. The results over the experimental periods are then analyzed to evaluate the pattern of decisions and resulting performance.

2.2 PRODUCT-PROCESS DECISIONS AND MANUFACTURING STRATEGY

In the previous section, the concept of manufacturing strategy was discussed within the framework of the strategy hierarchy. Two key questions were accordingly specified as: 1) what tasks should be achieved by the manufacturing function, and 2) how the tasks should be achieved. In this section, the previous studies in *product* and *process decisions* are discussed relative to these key questions. The impact of these two decisions on competitive advantage is particularly emphasized.

2.2.1 Product Planning and Manufacturing Strategy

In general terms, the *product planning* decision specifies what products should be offered with what features at what time in order to respond to opportunities and threats in the market. In so doing, product planning reflects the goals of business strategy and helps determine the firm's competitive position in the market. At the same time, product plans specify the manufacturing requirements in terms of process and capacity to meet the planned demand over time. Therefore, the product planning decision is closely related to the basic question of what tasks the manufacturing function should achieve. Traditional theories in strategy research, such as dominant orientation (Porter 1980), and competitive priorities (Skinner 1969; Buffa 1984; Wheelwright 1984; Krajewski and Ritzman 1987), consider the product planning decision as a key element of strategy.

In the hierarchy of strategy, it seems that the product planning decisions take place primarily at the corporate-strategy level. However, some researchers contend that the product decision is the logical starting point for formulating operations strategy (Krajewski and Ritzman 1987). When a firm knows its product characteristics, it can effectively design and operate the production system.

In the literature, product decisions are understood mostly within the framework of product life cycle. Wasson (1978) summarizes the strategic relationships between the product life cycle and the dynamic nature of competitive strategy. Hayes and Wheelwright (1984) suggest that, while the product life cycle is useful primarily in planning a firm's marketing strategy, its concept can be indirectly related to the firm's manufacturing strategy. They contend that different product life cycle stages imply different tasks to manufacturing in terms of production volume, product variety, and dominant form of competition. As products and markets evolve, Hayes and Wheelwright (1984) argue, the priorities that govern the manufacturing function need to change.

Adopting this linkage between the product life cycle and manufacturing strategy, Krajewski and Ritzman (1987) describe product planning as the whole spectrum of activities leading up to the introduction, revision, and dropping of products. Thus the primary decisions to be made in the product planning process include: 1) whether or not to enter the market with a certain product, 2) when to enter the market, and 3) when to exit the market. Related to these questions, Hayes and Wheelwright (1979a) contend that a firm can choose from various possible *entrance-exit strategies*.

2.2.2. Process Design and Manufacturing Strategy

The *process design* decision is another fundamental choice in manufacturing strategy. In general terms, the process design decision guides the organization's choice of process technology. More specifically, the decision determines when to acquire and dispose of a particular production technology, as well as how much. The process design decision affects the competitive strength of a firm by determining how efficiently it can perform various processes. Many concepts in manufacturing strategy, such as efficiency versus flexibility (Hayes and Wheelwright 1979a,b, 1984; Slack 1983; Karmarkar and Kekre 1985), and economies of scale and scope (Goldhar and Jelinek 1983), are closely linked to this process decision.

Traditionally in the operations management field, manufacturing processes have been described on the basis of the process flow characteristics. The general consensus seems to classify the manufacturing process types into five generic groups: 1) project, 2) job shop, 3) batch process, 4) assembly line, and 5) continuous flow. The key idea for this classification is that most operating characteristics –such as layout, work-force, materials/information flow, and operating controls– vary along the spectrum. In order to compete effectively, therefore, a manufacturing firm should choose a particular process

type that fits with the product and market requirements (Hayes and Wheelwright 1979a, 1979b, 1984).

As for the key process decisions to be made, Krajewski and Ritzman (1987) describes *four facets of process design* as: 1) degree of capital intensity, 2) resource flexibility, 3) vertical integration, and 4) customer involvement. In each of these facets, process design decisions involve the choice regarding the trade-off between efficiency and flexibility. A firm should find an *optimal* point on the trade-off curve by deciding the appropriate levels of these facets. The decisions should be made in such a way that the goals and objectives of the higher-level strategies can be effectively achieved.

2.2.3 Integrating Product–Process Decisions

The integration of product plans and process choices has been a frequent subject in the manufacturing strategy literature. The literature on this linkage is found in three general areas: 1) product and process innovation, 2) product-process matrix, and 3) positioning strategy.

2.2.3.1 Product and Process Innovation

Utterback and Abernathy (1975) report a close linkage between the development history of product and process technologies. Using a dynamic model of process and product innovation, they explain the tendency in process development from an *uncoordinated* process to a *systematic* process, and the tendency in product development to go from a *product performance maximizer* to a *product cost minimizer*. The authors then hypothesize that the characteristics of the process innovation systematically correspond with the stage of product development. They also contend that the firm's production process technology should follow closely its strategy for competition and growth.

Abernathy (1976) then examines the correlations between the product/market changes and process technology changes based on historical data from the Ford Motor Company. His main argument is that as products evolve from more diversified ones to more standardized ones, the production processes evolve from a more *fluid* system (with more general-purpose equipment and jumbled flow of materials) to a more *specialized* system (with more special-purpose equipment and line flow of materials).

2.2.3.2 Product–Process Matrix

Hayes and Wheelwright (1979a; 1979b) initiate the concept of the *product-process matrix*, and suggest how the matrix can be applied for the strategic management of manufacturing. They point out that using *only* the product life cycle concept in strategic planning can be inadequate because it neglects the manufacturing implications of the decision. They suggest that using the concept of a process life cycle together with the product life cycle can help a company choose among its various manufacturing and marketing options.

The main thrust of the product-process matrix is that a firm positioned on the *diagonal* of the matrix can compete more effectively in the market, supported by the structural match between the product requirements and the process capabilities. However, Hayes and Wheelwright (1979a) imply that firms off the diagonal can also find a unique niche and develop a distinctive competence, as long as their distance from the main diagonal is not too great. Hayes and Wheelwright also propose that the matrix can be used to explore various strategic issues, such as 1) the concept of distinctive competence, 2) the managerial implications of selecting a particular product-process combination, and 3) the organization of focused operating units so that they can specialize on different parts of the total manufacturing task.

In the follow-up paper, Hayes and Wheelwright (1979b) examine the possible effects of change in either products or production processes on the firm's competitive advantage. They contend that, if a company ignores the changes brought about by maturing markets or technology developments, serious internal problems can result from the mismatch between product and process technologies. The authors conclude this series of papers by suggesting that the product-process matrix can be applied as a useful tool that can explicitly involve both marketing and manufacturing in coordinating and implementing a firm's competitive goals.

2.2.3.3 Positioning Strategy

The above theories and observations support the need for consistency between product decisions and process decisions. Some researchers go further to argue that the nature of relationships between these decisions determines the competitive position of a firm. They suggest the term *positioning strategy* for the choice on how the product and process decisions are linked together.

Buffa (1984) contends that the positioning decision is one of the most important tasks to be mastered by American manufacturing managers. He argues that it is of considerable strategic importance to position the production system to match the market requirements. By matching the product strategies with the production system types, a firm can develop a competitive edge over the other firms which do not.

Krajewski and Ritzman (1987) contend that corporate strategy connects with operations through positioning decisions. They suggest that if positioning decisions are properly linked to other manufacturing decisions (such as design, capacity and location, and operating decisions), operations becomes a competitive weapon rather than a millstone. Thus the positioning decisions serve as the linchpin between corporate (or business) strategy and manufacturing functional strategy.

2.2.4 Summary and Implications

From this literature, it is clear that product and process decisions, and the linkage between them, are crucial components in manufacturing strategy. In this dissertation, as shown in Figure 1, the product decision is conceived as a key decision that answers what tasks should be achieved by manufacturing, and the process decision is conceived as the answer to how manufacturing should achieve these tasks.

Each of these two decisions has a critical impact on a firm's competitive position. More important, however, is the integration between these two decisions. The literature dealing with the product-process innovation, the product-process matrix, and the positioning strategy, all emphasizes close linkage between product and process decisions. The research questions in this dissertation, as discussed in Chapter I, thus center around the product-process linkage. The next section further discusses the linkage aspect in manufacturing strategy.

2.3 LINKAGE OF DECISIONS IN MANUFACTURING STRATEGY

One of the key concepts on how manufacturing strategy should be formulated and implemented involves the *linkage* among various decisions in operations management (Wheelwright 1984; Sharma 1987). Consistency in decisions directed toward the goals and strategies of the business has been asserted as a critical element of manufacturing strategy.

Consistency in decisions involves two dimensions. First, decisions made over time should be consistent with others. This dimension of consistency was already examined in Section 2.1, where strategy is conceptualized as the pattern in a stream of decisions. The

linkage notion that will be discussed in this section is concerned with a second dimension – the consistency among the components of manufacturing strategy.

2.3.1 Various Concepts of Linkage

Wheelwright (1984) defines four areas of consistency that should be achieved in the strategy formation process. They include: 1) consistency between the manufacturing strategy and the overall business strategy, 2) consistency among the manufacturing strategy and the other functional strategies within the business, 3) consistency among the decision categories that make up the manufacturing strategy, and 4) consistency between the manufacturing strategy and the business environment (such as resources and competitive behavior). He contends that the more consistent the pattern of decisions is in supporting the desired competitive advantage, the more effective the manufacturing strategy.

The importance of consistency is shared by most researchers. Richardson et al. (1985) suggest that firms having a congruent corporate mission and manufacturing task will outperform those where the two are mismatched. Based on a study using data from 64 Canadian electronics companies, they conclude that an important factor in corporate success is the degree to which the perceived corporate mission matches the measures of performance of the manufacturing function.

Swamidass (1986), in his study on the assessment of the manufacturing strategy practiced by 35 firms, finds a considerable mismatch of emphasis between the chief executives and manufacturing managers. He observes that while chief executives stressed quality and technology, which would contribute to a business strategy based on product differentiation, manufacturing managers stressed cost and keeping delivery promises. He contends that this mismatch could be a sign of problems in the effective use of manufacturing.

More recently, Sharma (1988) empirically examines the linkages between product, process, and demand. Using data from 121 manufacturing firms, he finds that the greater the product diversity, the less likely the processes are organized as production (or continuous) line. His empirical analysis thus supports the relationship implicitly hypothesized in the product-process matrix by Hayes and Wheelwright (1979).

Other researchers, such as Van Dierdonck and Miller (1980) and Miller (1981), study the linkage between manufacturing strategy and infrastructural system design, such as the production planning and control system. They contend that the design of production planning and control systems should be determined on the basis of the tasks given to the manufacturing function by the corporate and business strategies.

2.3.2 Differing Roles of Manufacturing in Linkages

This study focuses on the linkage between the product planning and process design decisions. As discussed in Section 2.2, this product-process linkage has been studied by several researchers, most prominently by Hayes and Wheelwright (1979a,b) within the framework of the product-process matrix.

This dissertation research approaches the product-process linkage from a different perspective. The pattern of linkage between product and process decisions is interpreted as the role of manufacturing in strategy formulation process. As discussed earlier, product planning decisions are primarily determined at the business (or corporate) strategy level. By defining the business segments in which the company chooses to compete and consequently the range of products it opts to offer, corporate strategy influences what types of manufacturing capabilities should be developed. Conversely, the types of manufacturing capabilities, that are determined by the process design decisions, can also influence the choice of business segments (or products) in corporate strategy. Therefore, *two-way relationships* seem to exist between the product planning and process design

decisions. The former relationship can be classified as a *top-down* linkage, while the latter one can be described as a *bottom-up* linkage.

Regarding the above relationship, Hayes (1985) provides a profound insight. He succinctly compares two opposite approaches in strategic management. The first approach, named as the *ends-ways-means* approach, selects the objects or *ends* first, then defines the strategies or *ways* of accomplishing them, and lastly develops the necessary resources or *means*. He contends that by adopting this formal strategy formation process, corporate strategists spend most of their time worrying about the structural means of achieving their objectives. According to his argument, however, real strategic advantage often comes from changing the way a company behaves, such as performance evaluation systems and information systems. He also argues that the formalized strategic planning processes reduce a company's flexibility in reacting to the fast changes in the competitive environment. Hayes thus proposes an alternative planning process, named as *means-ways-ends* approach, that builds the corporate strategy on the basis of the company's distinctive competence in the manufacturing function.

Wheelwright (1984) more formally defines two types of manufacturing roles in the process of strategy formation. In the mode of the *reactive* roles of manufacturing, corporate and business strategies define the desired competitive advantages, and manufacturing simply responds with what is required to deliver on that advantage. He contends that, "although this approach might be a worthy first step for many firms, recent competitive performance suggests that manufacturing can and should take a more *proactive* role in defining the desired competitive advantage if manufacturing is to become a significant competitive weapon." According to Wheelwright, a proactive role can be viewed as the manufacturing function taking an *equal* role as compared with other functions. He argues that the marketing function has traditionally dominated the strategy

formulation process in most firms. Wheelwright suggests that the performance of a firm can be improved if the manufacturing function plays a more proactive role.

Swamidass and Newell (1987) empirically find that, as manufacturing managers are involved more actively in the strategy formulation process, the performance of the firm is improved. However, their study also finds that the participation of manufacturing managers diminishes as the environment becomes more uncertain, suggesting either the difficulty of linking various decisions or lower payoffs in uncertain environments. Though Swamidass and Newell did not explicitly explain why manufacturing's role differs depending on the environmental uncertainty, this finding is significant in that it is the first empirical result on the strategic value of manufacturing's role.

2.3.3 Summary and Implications

This dissertation research examines the product-process linkage using mathematical programming models. Particularly, it attempts to test and confirm the arguments of Hayes (1985) and Wheelwright (1984) regarding manufacturing's role in strategy formation. Also, the empirical findings of Swamidass and Newell (1987) are examined by the experimental study.

In Chapter III, two types of decision models are developed to portray the two approaches referred to above. First, product planning and process design decisions are formulated as separate problems. They are solved sequentially to represent the *reactive* role of manufacturing. The product decisions are made first, and the consequent manufacturing requirements are resolved by the process decisions. Then two decisions are formulated as one integrated problem and solved simultaneously. The second model thus represents the *proactive* role of the manufacturing function. In this linked model, manufacturing implications of various product alternatives are evaluated *before* the actual

product planning decisions are made. By comparing the performance of the two models, the effectiveness of reactive and proactive approaches is examined.

Later in Chapter VI, an experimental study is conducted to evaluate the effectiveness of integration under different environmental settings. While Swamidass and Newell (1987) examined the relationship between environmental uncertainty and manufacturing's role, this study attempts to expand the notion of the environment to include more dimensions. A contingency theory is proposed with respect to the relationship between the manufacturing environment and integration.

2.4 MANUFACTURING FLEXIBILITY

Buffa (1984), among others, recently noticed a significant new trend common to many business segments. Competition is forcing many manufacturers to provide more diverse customized products. At the same time, the fast developing new technologies, such as computer aided design (CAD) and the flexible manufacturing system (FMS), reduce the time and cost of introducing a new product into market. As a result, the product life cycle becomes shorter, and manufacturers are forced to develop the capability to respond promptly to market changes, that is, develop more flexibility (Buffa 1984). Accordingly, the concept of manufacturing flexibility is gaining increased attention from both industry managers and academic researchers. Some researchers go even further to say that "flexibility is the next battle ground in the international industrial competition." (De Meyer et al. 1989) However, as many researchers have agreed, the level of understanding of this new concept is still low (Jaikumar 1986).

In this section, the concept and strategic value of manufacturing flexibility are discussed. First, the concept of flexibility is described at three levels; strategic, tactical, and operational. Then the literature that emphasizes the strategic value of manufacturing

flexibility is reviewed. Finally, the linkage between manufacturing flexibility and the product planning decision, which is the focus of this dissertation, is briefly described.

2.4.1 Definition of Flexibility

The term flexibility is widely used by many researchers in many different areas of operations management. Depending on where it is used, the meaning of flexibility seems to vary considerably. In this section, therefore, the concept of flexibility is discussed at three different levels.

2.4.1.1 Flexibility at the Strategic Level

At the most strategic level, flexibility is defined as the capability of a system to respond to changes in the environment (Karmarkar and Kekre 1980). It seems that there is general consensus with this definition of flexibility, as the system's responsiveness to environmental changes (Zelenovic 1982; Gerwin 1987; Slack 1983). A unique perspective is proposed by Slack (1983), who suggested that "flexibility is an indication of potential rather than performance."

Graham and Rosenthal (1986) argue that there are two motivations for manufacturing flexibility. The first motivation is protection against undesirable or threatening contingencies that can occur in short, medium, or long term. The second motivation is the anticipation for enhanced performance or improved service leading to expanded markets. They suggest that the first motivation is rather reactive in nature, while the second is more aggressive.

2.4.1.2 Flexibility at the Tactical Level

In much of the operations management literature, *changes in environment* means either changes in product mix or changes in demand volume. Thus the concept of

flexibility takes the form of product flexibility and volume flexibility. *Product flexibility* represents the ability to make quick design changes or introduce new products quickly, while *volume flexibility* means the ability to quickly accelerate or decelerate the rate of production to handle large fluctuation in demand (Krajewski and Ritzman 1987).

At this tactical level, the concept of *flexibility* is compared to the concept of *efficiency* (De Meyer et al. 1989). Traditional wisdom suggests that there exists a trade-off relationship between flexibility and efficiency: In order to gain flexibility, a firm has to lose some of its efficiency. The emerging technologies such as FMS, however, allow firms to gain flexibility without sacrificing too much efficiency. As a result, the choice between flexibility and efficiency becomes much more complex with many alternatives provided by the new technologies.

Some researchers view this trade-off using the contrast between economies of scale and economies of scope. Cohen and Lee (1985) describe that scale economies arise due to fixed cost, specialized equipment, and price breaks for inputs, while scope economies occur due to shared input (such as common process equipment) that can be allocated over different products. Goldhar and Jelinek (1983) suggest that new manufacturing technologies are advantageous because they possess considerable economies of scale and scope simultaneously.

Other researchers have attempted to offer typologies to classify and measure the concept of flexibility. Among them, the classifications by Gerwin (1983) and Slack (1983) seem to focus on the tactical level of flexibility. Gerwin (1983) proposes to group the various features of flexibility into five categories; mix, volume, parts, design-change, and routing flexibilities. Slack (1983) proposes a framework which includes new product, product mix, quality, volume and delivery flexibilities.

2.4.1.3 Flexibility at the Operational Level

Flexibility at the operational level is often studied with regards to FMS technology. There is general agreement in the literature that this new production technology has been designed to attain the efficiency of well-balanced transfer lines, while maintaining the flexibility of job shops which simultaneously produce multiple part types. Thus the concept of flexibility is heavily emphasized in the environment where various parts of medium-size volume have to be produced simultaneously (Groover 1980; Brown et al. 1984). Consequently, the *variety* of parts that can be processed simultaneously seems to represent the concept of flexibility at the operational level.

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 The most comprehensive survey of operational flexibility can be found in the work by Brown et al. (1984). They define eight types of flexibilities as: 1) *Machine* flexibility : the ease of making the changes required to produce a given set of part types; 2) *Process* flexibility : the ability to produce a given set of part types, each possibly using different materials in several ways; 3) *Product* flexibility : the ability to changeover to produce a new set of products economically and quickly; 4) *Routing* flexibility : the ability to handle breakdowns and to continue producing the given set of part types; 5) *Volume* flexibility : the ability to operate a manufacturing system profitably at different production volume; 6) *Expansion* flexibility : the capability of building a system, and expanding it as needed, easily and modularly; 7) *Operations* flexibility : the ability to interchange the ordering of several operations for each part type; 8) *Production* flexibility : the universe of part types that a manufacturing system can produce. These operational concepts of flexibility are frequently discussed in the other studies related to FMS technology (Roth 1986; Monahan and Smunt 1989).

2.4.2 Strategic Value of Manufacturing Flexibility : A Broader View

In this dissertation, the concept of manufacturing flexibility is mostly understood at the strategic or tactical level. As discussed earlier, manufacturing flexibility is understood at these levels as the capability of a manufacturing system to respond promptly and economically to the changes in its environment. The changes are related with either the product mix or the demand volume, or both.

Little research has addressed the strategic value of manufacturing flexibility beyond the conceptual level. Jaikumar (1986) in his highly regarded paper strongly argues that this lack of strategic perspective in the U.S. manufacturers could seriously damage their effort to compete against Japanese companies. Rather than realizing the distinctive strategic premises of the FMS technology, the U.S. manufacturing managers "mastered narrow-purpose production on expensive FMS technology designed for high-powered flexible usage."

In this section, the strategic value of manufacturing flexibility is discussed within the hierarchical relationships among competitive advantages, competitive priorities, and process design decisions. Then the dynamic relationships between product planning and process design decisions are described with the intention of capturing the strategic benefit of manufacturing flexibility.

2.4.2.1 Competitive Priorities and Manufacturing Flexibility

From the manufacturing strategy perspective, the value of manufacturing flexibility should be understood as the competitive advantage it provides a company. Within the strategy hierarchy, the competitive advantage of the strategic business unit is attained by appropriately defining the competitive priorities of its manufacturing function. The competitive priorities which are closely related with manufacturing flexibility are product flexibility and volume flexibility.

A more flexible manufacturing system can provide a more diverse range of products economically (product flexibility), and it can also handle the fluctuating demand more efficiently (volume flexibility). However, these strategic benefits of flexibility come at the expense of lost efficiency. Usually flexible systems cannot handle the high volume of demand as efficiently as more rigid systems such as highly automated production lines (Groover 1980).

The process design decision has to resolve this trade-off between efficiency and flexibility. As discussed earlier in Section 2.2, a process design decision is made by selecting the mix of different process technologies (which possess different levels manufacturing capabilities in terms of efficiency and flexibility). Therefore, the choice of process technologies is a critical decision in manufacturing strategy formation.

2.4.2.2 Product Decision and Manufacturing Flexibility

This dissertation approaches the strategic value of manufacturing flexibility from the relationship between the product planning and process design decisions. The relationships between these two decisions are not one-dimensional (or sequential) but two-dimensional (or circular). On the one hand, when product decisions are made and the production requirements are determined for the manufacturing function, the process decision has to be made such that the production requirements can be accomplished most efficiently. On the other hand, when the process decisions are made and the cost structure of the manufacturing function is thus determined, the product decisions have to be made such that the profits from various products can be maximized with the given manufacturing cost structure. Figure 2.2 describes this two-dimensional relationships between product and process decisions.

When the manufacturing process is designed to achieve a high level of efficiency with more special-purpose equipment, the consequent product decision could be *strictly*

constrained to a narrow scope of alternatives that can be manufactured efficiently with the given production system. In contrast, if the manufacturing process is designed to achieve a high level of flexibility with more general-purpose equipment, the product decisions can be made more *freely* over a wider range of possibility. Therefore, it can be conjectured that, by having flexible process technologies, a firm can better exploit the new product opportunities occurring in the market.

This viewpoint is consistent with what Graham and Rosenthal (1986) considered as the important strategic motivation when a firm acquires FMS technology. They argue that manufacturing flexibility provides not only the protection against undesirable changes (such as unforecasted change in product demand and frequent engineering changes), but also the capability to exploit the potential opportunities (such as new product line development).

2.5 RESEARCH METHODS IN MANUFACTURING STRATEGY

The early research in manufacturing strategy has been *conceptual* in nature. Case analysis supported by the expertise and intuitive insights of the researchers, has been the main method of research. As the concept of manufacturing strategy is becoming more clearly defined, and as research issues are gradually raised, quantitative methods are starting to be applied. However, compared to other areas in operations management, the manufacturing strategy field has relied on less rigorous research methodologies.

In this section, the manufacturing strategy literature is reviewed on the basis of research methodology. First, three approaches in this field –conceptual, empirical, and analytical– are discussed. Then the research methods applied in this dissertation are briefly described.

2.5.1 Three Levels of Manufacturing Strategy Research

Research in manufacturing strategy is taking place at three levels: conceptual, empirical, and analytical. This subsection briefly reviews the major concerns of the two earlier phases – conceptual and empirical – and discusses the need for analytical research in this field.

2.5.1.1 Conceptual Studies of Manufacturing Strategy

At the conceptual level, the insights of a few leaders in this field, such as Skinner, Hayes, and Buffa, have been the starting point. Based on their experience and expertise, these researchers raised the need for a more strategic approach in managing the manufacturing function. Hayes and Wheelwright (1984) confessed that their main objective of writing the highly publicized book *Restoring Out Competitive Edge: Competing Through Manufacturing*, was to alarm American managers to the danger of ignoring manufacturing function in the strategic decision-making process.

Then researchers attempted to provide a conceptual framework for defining manufacturing strategy and its linkage with other functional areas. Also the linkages among various design and operations decisions in production management were studied. Wheelwright (1984) and Hayes and Wheelwright (1984) thus present a framework for the strategic management of manufacturing. These frameworks also help researchers to define the structure of the problem and to identify possible research questions.

The results of these conceptual studies are *conjectures* regarding what aspects of manufacturing management are strategic and how they should be managed. These conjectures need to be validated and tested in order to become a generalizable theory.

2.5.1.2 Empirical Studies of Manufacturing Strategy

Empirical studies followed the conceptual stage of manufacturing strategy research. Researchers are starting to use various statistical procedures to validate and support the concepts and propositions in manufacturing strategy. The key conjectures raised by the pioneers of the field are tested by surveys of company practices and statistical analysis.

For example, the Boston University Manufacturing Roundtable (Miller et al. 1988) has been conducting surveys on the strategic aspects of manufacturing in North America, Western Europe, and Japan. The surveys report trends in manufacturing strategies and the consequent performance. The issues include competitive priorities, top management concerns, and various actions to enhance manufacturing competitiveness. A few other researchers recently conducted surveys on various aspects of manufacturing with different sample sizes (Schroeder et al. 1986; Swamidass and Newell 1987; Sharma 1988).

On the basis of such surveys, researchers do statistical analysis to clarify and validate the conjectures in manufacturing strategy. Some of them are *exploratory* in nature (Schroeder 1986; Swamidass 1986). Rather than statistically testing formal hypotheses, these studies attempt to find how the manufacturing function is viewed by managers, and how various concepts of manufacturing strategy are implemented by the practitioners. These exploratory studies contribute to defining the research issues that are worth pursuing.

More rigorous *confirmatory* statistical methods were applied to formally test various hypotheses and build a theory. Regression analysis (Van Dierdonck and Miller 1980; Richardson et al. 1985), path analysis (Swamidass and Newell 1987), factor analysis (Roth 1987; Sharma 1988) and covariance structure analysis (Sharma 1988) have been used to study the relationships among components of manufacturing strategy. These studies also contribute to the field of manufacturing strategy by providing the measurement schemes for the key variables and defining the relationships among them.

2.5.1.3 Analytical Studies of Manufacturing Strategy

Traditionally, the production and operations management area has enjoyed an abundance of rigorous analytical research methodologies. However, due to their limited assumptions and narrow problem definition, the previous analytical studies have been confined to more operational problems rather than strategic issues.

Many analytical methods provide *optimal* solutions. The optimality is certainly a strength of these methods. However, in order to attain this optimality, many unrealistic assumptions have to be made. The previous analytical research has been frequently criticized due to their unrealistic assumptions. As soon as one or few of these assumptions is relaxed, most solutions lose the strength of optimality. The meaning of optimality is particularly weak in more strategic decision problems, where the problems cannot be defined clearly enough for the analytical methods. The environment dealt with by strategic decisions has considerable uncertainty, while analytical methods usually are best when there is certainty in decision environment. Therefore, it is not surprising that the traditionally popular analytical methods are not used in manufacturing strategy research.

Researchers started to apply various analytical methods to examine more *tactical* decisions such as technology acquisition (Gaimon 1985; Roth 1985), capacity expansion (Luss 1984), and more recently the flexible manufacturing systems (FMS) investment decisions (Monahan and Smunt 1988). These problems, however, are single dimensional because only one category of decision is involved. In contrast, manufacturing strategy seems to be multi-dimensional, with more importance given to the relationships between several decisions.

2.5.2 Research Methodology : An Analytical Approach

In this section, the research approach of this dissertation is briefly described. First, the need for analytical approach in manufacturing strategy research is discussed. Then the following subsection briefly describes the research approach that uses a mathematical programming model as a tool to evaluate strategic policies.

2.5.2.1 Need for Analytical Study in Manufacturing Strategy Research

As discussed above, analytical approaches have been used sparingly in manufacturing strategy research. Two reasons stand out for this unpopularity: First, gaining optimality of solutions by making unrealistic assumptions is not appealing to many researchers or practitioners. Second, the decisions in manufacturing strategy are too complex to be represented by any analytical models and the decision environment is too uncertain.

Nevertheless, it is the author's belief that empirical and analytical studies should proceed in parallel. Researchers applying the empirical approaches are starting to measure the decision variables and validate the relationships among them. Researchers are more capable of defining the concepts which were previously vague at most. Variables can now be defined and measured quantitatively. The results from these empirical studies thus help formulate the problems using analytical models.

Analytical research, both descriptive and normative, now can help researchers identify new critical decision variables and linkages among them. Richer experimental study is possible with the analytical approaches. The analytical models also help both managers and researchers to understand their problems. The relationships among various decision variables can be better understood within the framework of analytical models, using an objective function and constraints. Traditionally in the operations management

field, analytical models have helped enhance managerial practices particularly at the operational level. Similar contributions might be possible at the strategy level.

2.5.2.2 Research Method Overview

In this dissertation, a mathematical programming model is developed as a *tool* to evaluate various strategic policies. Then the model is simulated under various environments to examine when a certain strategic policy is more effective than others. The role of the mathematical programming model applied in this research is *not* to provide an optimal solution for the problem. Rather the model is used as an experimental tool, which portrays the managerial policy regarding the strategic decisions.

First, the product planning and process design decisions are formulated as mathematical programming problems. Different formulations are developed to represent different strategy formulation processes. As will be discussed in Chapter III, a *linked* model is formulated to represent the policy of making product and process decisions simultaneously. An *unlinked* model is developed to represent the case where product decision is made first and process decision is made next. Then the models are revised to represent a policy where manufacturing flexibility is mandated by the management. For each model, additional sets of constraints are enforced to represent this flexibility policy. The details are explained in Chapter III.

Second, strategic policies are simulated using the decision models over some period of time under a particular manufacturing environment. The environment is defined by different sets of parameters for the decision model. The performance of the different models is compared to examine the impact of different environments. The results are studied using statistical methods.

Figure 2.1

Manufacturing Strategy in Strategy Hierarchy

Figure 2.2

Two-Dimensional Relationships between
Product and Process Decisions

Table 2.1
Literature Review Summary

Section	Dissertation Feature	Literature	Implications to Dissertation
2.1	Manufacturing strategy concept	<p>Hofer&Schendel (1978) Wheelwright (1984) Swamidass&Newell (1987)</p> <p>Porter (1980) Skinner (1969) Wheelwright (1984) Fine and Hax (1985) Cohen and Lee (1985) Schroeder et al. (1986) Krajewski & Ritzman (1987)</p> <p>Mintzberg(1978) Wheelwright (1984)</p>	<p>•Define manufacturing strategy as a functional strategy in the <i>strategy hierarchy</i></p> <p>•Define two key decisions for manufacturing strategy: 1) <i>What tasks</i> should be achieved? and 2) <i>How</i> to achieve these tasks?</p> <p>•Capture the pattern in the stream of decisions as strategy</p>
2.2	Product and Process Decisions	<p>Porter (1980) Skinner (1969) Buffa (1984) Wheelwright (1984) Wasson (1978) Hayes& Wheelwright (1979a) Hayes& Wheelwright (1984) Krajewski& Ritzman (1987)</p> <p>Hayes&Wheelwright (1979a) Hayes& Wheelwright (1984) Slack (1983) Karmarkar& Kekre (1985) Goldhar& Jelinek (1983) Krajewski& Ritzman (1987)</p> <p>Utterback& Abernathy(1975) Abernathy (1976) Hayes& Wheelwright(1979a) Hayes& Wheelwright(1979b) Buffa (1984) Krajewski& Ritzman (1987)</p>	<p>•Define <i>product planning</i> to represent the <i>tasks</i> to be achieved by manufacturing function</p> <p>•Define <i>process design</i> to represent <i>how</i> manufacturing achieves the tasks</p> <p>•Emphasize the <i>linkage</i> between product and process decisions as the key issue in manufacturing strategy</p>

Table 2.1 (Continued)

Section	Dissertation Feature	Literature	Implications to Dissertation
2.3	Linkage of Decisions in Manufacturing Strategy	Wheelwright (1984) Sharma (1987) Richardson et al. (1985) Swamidass (1986) Van Dierdonck & Miller (1980) Miller (1981) Hayes (1985) Swamidass & Newell (1987)	<ul style="list-style-type: none"> •Highlight the <i>role of manufacturing</i> in the process of strategy formulation as the <i>pattern of linkage</i> between product and process decisions •Develop an <i>analytical model</i> to represent two different patterns of linkages •Conduct an <i>experimental</i> study to evaluate the value of linkage under different environments
2.4	Manufacturing Flexibility	Buffa (1984) De Meyer et al. (1989) Jaikumar (1986) Karmarkar & Kekre (1980) Zelenovic (1982) Gerwin (1987) Slack (1983) Graham & Rosenthal (1986) Krajewski & Ritzman (1987) Cohen & Lee (1985) Goldhar & Jelinek (1983) Groover (1980) Brown et al. (1984) Roth (1986) Monahan & Smunt (1989) Jaikumar (1986) Swamidass & Newell (1987)	<ul style="list-style-type: none"> •Highlight flexibility as a strategic weapon to exploit dynamic market opportunities •Define <i>strategic value</i> of manufacturing flexibility in the context of product-process interrelationship •Model the strategic relationship between <i>product opportunities</i> and <i>manufacturing flexibility</i> •Evaluate strategic value of flexibility under different <i>environments</i> by simulating the decision model

Table 2.1 (Continued)

Section	Dissertation Feature	Literature	Implications to Dissertation
2.5	Research Method in Manufacturing Strategy	<p>Hayes& Wheelwright(1984) Wheelwright (1984) Miller et al. (1988) Schroeder et al. (1986) Swamidass& Newell (1987) Sharma (1987) Roth (1987) Swamidass (1986) Van Dierdonck & Miller (1980)</p> <p>Cohen & Lee (1985) Gaimon (1985) Luss (1984) Roth (1986) Monahan& Smunt (1988)</p>	<p>•Reflect findings from conceptual and empirical studies to develop an <i>analytical model</i></p> <p>•Highlight the <i>need for analytical research</i> in manufacturing strategy in parallel with empirical studies</p> <p>•Propose an <i>analytical</i> approach that uses a <i>mathematical programming problem formulation</i> as an experimental <i>tool</i> to evaluate strategic policies under different environments</p>

CHAPTER III

THE MODEL

In this chapter, product and process decisions are formulated as mathematical programming problems. Key decision variables and parameters are defined in the model such that the strategic policies can be reflected properly. Also, a simulation model is developed in order to evaluate the consequences of different strategic policies.

Section 3.1 provides a brief description of the model's scope, assumptions, and notation. Then Section 3.2 presents two types of decision models – unlinked and linked models – that formulate the product planning and process decisions into mathematical programming problems. Section 3.3 discusses the simulation model which is used to evaluate the different decision models under uncertain environments.

3.1 INTRODUCTION

As mentioned in Chapter II, few studies have considered the product decision and process decision in a combined model. This section begins by conceptualizing the basic rationale for the proposed model. Then, the assumptions in the model are described, followed by a brief description of the notation used in the model.

3.1.1 General Description of the Models

Product planning decides when, if ever, to introduce and/or withdraw products to or from the market. Several alternative products can be offered to the market with different features, and each product can be introduced and withdrawn at several different times depending on alternative entrance-exit strategies. Each product's demand level and profitability depend on when it is introduced to the market. The decision model seeks to maximize the total contribution from all possible products over the planning horizon. Also, each product requires different types and amounts of production processes. By deciding the mix of various products to be offered over time, the processing requirements for manufacturing are determined.

Process design decides what types of process technologies should be acquired and disposed of over time. Production technologies differ as to their capabilities. A particular technology could be very efficient in performing a particular process, while another is more flexible in the sense that it can perform various processes even though not very efficiently. Process design decides the mix of technologies at a particular time period, thus determining the manufacturing system's flexibility and efficiency.

These two decisions are closely related, as shown in Figure 3.1. Product planning decisions determine the requirements for different processes, while process design decisions determine the manufacturing system's capability to perform different processes. The match or mismatch between process requirements and capability depends on how these two decisions are made.

As discussed in Chapter II, the above relationship is highly strategic (Hayes and Wheelwright 1984). By deciding to introduce more diverse products to the market, the firm requires a more flexible manufacturing system that can perform various processes. On the other hand, if a firm decides to pursue a high-volume strategy with limited number of products, it asks for a more efficient manufacturing system. This product-process

interrelationship can also be understood in the opposite direction. For example, when a firm maintains more flexible capability in the manufacturing function, it has a distinctive ability to introduce more product variety to the market.

The relationships between product and process decisions are represented by two different decision models in this research. First, an *unlinked decision model* is formulated to represent the two decisions separately. A product planning model (P1) is formulated as a profit maximizing problem. The model P1 estimates the contribution margin of each product based on the *current* mix of process technologies, not considering what changes in process design decisions might be planned for the future. Then, a process design model (P2) solves a cost minimization problem, to satisfy the process requirements generated by the *current* product plan. Again, the model P2 does not consider what new products might be contemplated for the future. These two models are solved sequentially, and the unlinked model therefore represents the case where the manufacturing function plays a *reactive* role in strategy formation process.

Second, a *linked decision model* (I) is introduced that makes both product planning and process design decisions simultaneously. In this model, the decision variables for product planning and process design are integrated into one mathematical programming problem. Thus, the impact of different product strategies on the process requirements, and vice versa, is explicitly considered before any choice is made. The model I represents the case where manufacturing function plays a *proactive* role in strategy formation process.

3.1.2 Assumptions

In the product-process decision models, several assumptions are made. They simplify problem complexity, as well as provide the deterministic decision environment for the mathematical programming formulation.

- 1) The system attempts to optimize within a given planning horizon.
- 2) The unit contribution for each product is known for each period.
- 3) Demand for each product, and for each introduction strategy, can be forecast perfectly for each planning period .
- 4) The standard processing time per unit of each product is known.
- 5) The efficiency of each technology in performing a particular process is known.
- 6) The acquisition cost and salvage value of a process technology are known for each period.
- 7) The amount of process technology that can be acquired and disposed of is continuous.
- 8) Acquisition and disposal of technology are made at the beginning of each period, and there is no lead time in implementing a new process technology.

Some of these assumptions are relaxed later when uncertainties are introduced with the simulation model. More specifically, forecast errors are introduced to 1) the demand for each product, 2) the standard processing time, and 3) the efficiency of process technology. Chapter V provides a detailed description for the implementation of uncertainty.

3.1.3 Notation

Throughout this research, the following notation is used. It is classified into decision variables and parameters for product and process decisions. Particular attention is paid in this section to how each variable and parameter represents the strategic decision-making process. First, the indexes are defined. Then, decision variables for product planning and process design decisions are explained. Last, parameters in the models are described. Table 3.1 summarizes the notation.

3.1.3.1 Indexes

The following indexes are maintained in the model:

- a) i = product, $i = 1, 2, \dots, I$
- b) j = process, $j = 1, 2, \dots, J$
- c) k = process technology, $k = 1, 2, \dots, K$
- d) m = product introduction strategy, $m = 1, 2, \dots, M_i$
- e) t = time period, $t = 1, 2, \dots, T$

3.1.3.2 Decision Variables for Product Planning

The main decision for the product planning problem is the level of demand for a product i a firm plans to satisfy in period t , which is represented by D_{it} . The value of D_{it} is determined by two variables, P_{im} and $Q_{ii'mt}$, as described below.

- D_{it} = units of product i *actually* demanded in period t as a result of product planning, taking into account the interaction effect with other product decisions
- P_{im} = $\begin{matrix} 1 & \text{if product } i \text{ is introduced/withdrawn following strategy } m \\ 0 & \text{otherwise} \end{matrix}$
- $Q_{ii'mt}$ = proportion of demand for product i with strategy m lost in period t due to the existence of similar product i' in the market

3.1.3.3 Decision Variables for Process Design

The main decision for the process design problem is the level of process technology k to be maintained in period t , which is represented by Z_{kt} . The value of Z_{kt} is determined by X_{kt} and Y_{kt} as described below.

- X_{kt} = additional capacity of technology k acquired at the beginning of period t , expressed in machine hours per period

Y_{kt}	=	capacity of technology k disposed of at the beginning of period t, expressed in machine hours per period
Z_{kt}	=	capacity of technology k held in period t, expressed in machine hours per period
A_{kjt}	=	capacity of technology k to be allocated to perform process j in period t, expressed in machine hours per period
L_{it}	=	units of demand for product i that cannot be met due to the shortage of capacity in period t

3.1.3.4 Parameters for Product Planning

Parameters that are included in the product planning problem are forecasted demand for each product, estimated contribution of unit product, interrelationships among similar products, and product investment cost and available capital. They are described below.

a) Demand Forecast for Each Product

d_{imt}	=	number of units of product i to be demanded in period t if introduction strategy m is pursued
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The demand for a particular product is estimated by the manager based on various strategic choices, such as emphasis on low price or high-performance design. For a particular product i the manager also evaluates alternative timings of introduction, as represented by the index m, and estimates the demand level in each period.

For example, d_{imt} can be represented for several products as shown in Table 3.2. In this example, product 1 represents a standard product that goes through the full life cycle, while products 2 and 3 represent revised versions of product 1 with some extra features added, or excluded, respectively. In other words, product 2 puts more emphasis on high quality design with extra features among the dimensions of competitive priorities,

and pursues a smaller market than product 1. It is also shown in the table that these revised-version products are offered during a limited portion of the product life cycle.

Also Table 3.2 shows different strategies of introducing a product in the market. The strategy 1 for product 1 represents an early-entry late-exit alternative, while strategy 2 represents late-entry pursuing high-volume demand in the maturity stage of the product life cycle, and strategy 3 represents a policy of not going for that particular product market. As shown, the level of demand in each period is estimated differently for each alternative introduction strategy. Studies in marketing suggest that early entry into a market usually provides a firm with a larger market share (Urban et al. 1986).

Each product's demand level is closely related with the contribution margin parameters that are described next. The model assumes that managers can evaluate alternative products with different features, and estimate demand levels and contribution margins expected from each product over the period.

Also, in order to model the interaction between products, a zero-one parameter k_{imt} is defined as:

$$k_{imt} = \begin{array}{ll} 1 & \text{if } d_{imt} > 0 \\ 0 & \text{if } d_{imt} = 0 \end{array}$$

b) Contribution Margin of Each Product

$$c_{it} = \text{discounted unit contribution of product } i \text{ in period } t$$

This parameter represents the profitability of each product in each period throughout the life cycle. In order to reflect the *time value of money*, c_{it} is represented in the decision model as a discounted value.

In the product planning model **P1**, the value of c_{it} represents the difference between market price and sum of materials, labor, and variable overhead costs. Thus,

$$c_{it} = p_{it} - m_{it} - v_{it} \quad (3.1)$$

where, p_{it} = price per unit of product i in period t

m_{it} = materials cost per unit of product i in period t

v_{it} = labor and variable overhead cost per unit of product i in period t

The unit price, p_{it} , is closely related to the particular features of the product as described above. In this model, it is assumed that the unit materials cost, m_{it} , is constant and not affected by any product or process decisions. Generally, v_{it} depends on the processing requirement for the particular product i . But it is also affected by the efficiency of the production technologies used to perform the necessary processes for the product. When the product planning decision is made separately from the process design decision, however, the future process technology to be used is unknown, thus leaving v_{it} as a blind spot in product planning. The most reasonable assumption in such cases is that v_{it} will be estimated from accounting data, based on the *current* mix of process technology. The procedure for this estimation will be elaborated more in Section 3.2.1.

The c_{it} for several products can be illustrated by the example shown in Table 3.3. It shows that the profitability of product 1 changes over its life cycle, as the competitive environment in the market evolves. Wasson (1978) explains that as a product goes through its life cycle, the nature of competition changes from a more feature-based competition to a more price-based one. Consequently, the price level decreases, and so does the contribution margin. The c_{it} values for product 2 show higher price and higher profit margin for a modified product with additional features introduced in the late stage of the life cycle.

c) Impact of Introducing Similar Products Simultaneously

$q_{ii'}$ = proportion of demand for product i lost due to the existence of similar product i'

When similar products are available in the market at the same time, the demand for each one can be diminished or enhanced depending on the relationship with others. The traditional microeconomics concepts of *substitute* and *complementary* products play important roles in product portfolio development (Devinney and Stewart 1988). This effect should be considered in the product planning decision so as to correctly gauge future demands.

The q_{ij} parameters are illustrated with the example in Table 3.4. In this example, offering products 1 and 2 during the same period does not reduce each other's demand as much as offering products 2 and 4 simultaneously to the market. Note that q_{ij} matrix is not necessarily symmetric, so one product can have more of a negative impact on a second one than the other way. Also, some q_{ij} could be negative in case of complementary products.

d) Product Development Investment Cost and Capital Budget Available

h_{imt} = capital investment required for product i in period t if strategy m is pursued

KP_t = total capital budget available for product development in period t

When a new product is to be introduced to the market, some fixed investment cost is necessary. Also, a limit on the product investment for each period t is introduced as KP_t . This budget limit is affected by the financial position of the firm, which is a function of the results of past product and process decisions, and the policy which allocates the capital budget between product development and process investment. As will be discussed later in Chapter V, KP_t is determined in the simulation process such that a portion of total net cash flow in period $t-1$ can be invested for the product development. Accordingly, when a firm makes poor decisions in a period, it will have a more limited fund for its investment in the following period.

3.1.3.5 Parameters for Process Design

Parameters in the process design decision include the process requirement for each product, each technology's capability and efficiency of performing a process, various costs of process technologies, and capital investment cost. They are briefly described below.

a) Process Requirement for Each Product

r_{ij} = number of machine hours required to perform process j per unit of product i

Each product requires different manufacturing processes, and in different amounts. This parameter thus provides the link between product planning and process design.

Table 3.5 illustrates r_{ij} for an example case. It shows that, compared to the standard product 1, the high-quality product 2 with more features requires an additional process 5, while the low-quality product 3 doesn't even require process 2.

b) Process Capability of Each Technology

s_{kj} = efficiency of technology k in performing process j
 $0 \leq s_{kj} \leq 1$

If $s_{kj} = 0$, technology k cannot perform process j .

If $s_{kj} = 1$, technology k is most efficient in performing process j .

This parameter represents the efficiency and flexibility of each technology. For example, Table 3.6 shows different capabilities of different technologies. Technology 1 represents a specialized equipment for process 1, which however cannot perform any other processes, while technology 2 represents a general-purpose equipment that is versatile but inefficient. Technologies 3 and 4 represent new technologies such as FMS that are capable of performing various processes rather efficiently.

By this parameter, the process design choice between an efficient system and flexible system is incorporated in the model. As will be shown next, this parameter also has a close relationship with costs, so that the choice between expensive but efficient system and less expensive but inefficient system can be reflected in the model.

c) Costs Related to Each Technology

a_{kt}	=	discounted unit acquisition cost of technology k in period t
b_{kt}	=	discounted unit salvage value of technology k in period t
f_{kt}	=	discounted fixed overhead cost to keep unit of technology in period t
u_{kt}	=	discounted variable overhead and labor cost to operate unit of technology in period t

The above four parameters determine the cost of maintaining different types of process technologies. As with the contribution margin, these cost parameters are represented as discounted values in the objective function reflecting the time value of money.

The above parameters represent the decision choice between various manufacturing systems. For example, a combination of high a_{kt} and low u_{kt} represents a technology that is highly automated thus requiring less operating cost, while low a_{kt} and high u_{kt} combination represents a conventional technology that is not automated and requires high variable costs.

d) Capital Budget Available for Process Investment

KR_t	=	total capital budget available for technology investment in period t
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As the product investment case, a limit on technology investment during period t is introduced. As with KP_t , the parameter KR_t is also affected by past decisions and allocation policy during the simulation process.

e) Penalty for Not Meeting Projected Demand

$$M_{it} = \text{penalty for lost sales per unit of product } i \text{ in period } t$$

Due to the limit on the capital budget for process investment, there is a chance that the demand projected by product planning cannot be satisfied with the process technology capacity. This parameter M_{it} thus assigns priorities to different products regarding the allocation of the processing capacity to the products.

3.2 THE DECISION MODEL

In this section, product and process decisions are formulated as mathematical programming problems. First, the decision models are presented separately to represent *unlinked* decisions in strategy formulation. Second, an integrated model is developed to make the two decisions simultaneously. Then, a set of side constraints are introduced to reflect the particular emphasis on manufacturing flexibility as a competitive weapon.

3.2.1 Product Planning Decision Model (P1)

The model **P1** represents the product planning decision that does not consider its impact on process design and future technological choices *a priori*. Without considering future manufacturing choices on process design, the product planning attempts to maximize the total contribution from the product mix to be offered to market. In other words, it does not consider manufacturing's future technology, but makes decisions based on the contribution margin of each product estimated with the current process technology. The model **P1** is described below:

$$\text{Maximize } \sum_t \sum_i c_{it} D_{it} - \sum_t \sum_i \sum_m h_{imt} P_{im} \quad (3.2)$$

s. t.

$$D_{it} = \sum_m P_{im} d_{imt} - \sum_{i'} \sum_m Q_{ii'mt} d_{imt} \quad (3.3)$$

$$i=1,2,\dots,I ; t=1,2,\dots,T$$

$$Q_{ii'mt} \geq [\sum_{m'} P_{i'm'} k_{i'm't} + P_{im} k_{imt} - 1] q_{ii'} \quad (3.4)$$

$$i,i'=1,2,\dots,I ; i \neq i' ; m=1,2,\dots,M_i ; t=1,2,\dots,T$$

$$Q_{ii'mt} \leq P_{im} k_{imt} q_{ii'} \quad (3.5)$$

$$i,i'=1,2,\dots,I ; i \neq i' ; m=1,2,\dots,M_i ; t=1,2,\dots,T$$

$$Q_{ii'mt} \leq [\sum_{m'} P_{i'm'} k_{i'm't}] q_{ii'} \quad (3.6)$$

$$i,i'=1,2,\dots,I ; i \neq i' ; m=1,2,\dots,M_i ; t=1,2,\dots,T$$

$$\sum_m P_{im} = 1 \quad (3.7)$$

$$i=1,2,\dots,I$$

$$\sum_i \sum_m h_{imt} P_{im} \leq KP_t \quad (3.8)$$

$$t=1,2,\dots,T$$

$$P_{im} = (0,1) \quad i=1,2,\dots,I ; m=1,2,\dots,M_i \quad (3.9)$$

$$Q_{ii'mt} \geq 0 \quad i,i'=1,2,\dots,I ; i \neq i' ; m=1,2,\dots,M_i ; t=1,2,\dots,T \quad (3.10)$$

$$D_{it} \geq 0 \quad i=1,2,\dots,I ; t=1,2,\dots,T \quad (3.11)$$

The objective function (3.2) maximizes the total contribution from all products over the planning horizon less the total investment for product development. Note that unit contribution c_{it} is multiplied by the expected demand from the product planning decision, D_{it} . As noted earlier, c_{it} is estimated as

$$c_{it} = P_{it} - m_{it} - v_{it} \quad (3.12)$$

in this model P1, and the unit variable overhead and labor cost v_{it} is estimated based on the current manufacturing technology, such that

$$v_{it} = \sum_j r_{ij} \left(\frac{\sum_{k \in K_j} [f_{kt} + u_{kt}] [Z_{k0} / s_{kj}]}{\sum_{k \in K_j} Z_{k0}} \right) \quad \left. \begin{array}{l} i=1,2,\dots,I ; t=1,2,\dots,T \\ K_j = \{ k \mid s_{kj} > 0 \} \quad j=1,2,\dots,J \end{array} \right\} ? \quad (3.13)$$

The above equation (3.13) estimates the unit product cost by summing all the process requirements r_{ij} multiplied by average cost for performing unit of process j , that is expressed in the fraction, assuming that the production technology of the last period is maintained in the future. If no technology is currently available to perform a particular process, its estimate is made based on the average cost over all current technologies.

D_{it} , the expected demand for each product in each period, is determined by constraints (3.3 - 3.7). When a particular P_{im} is set to 1, the demand for the product i in period t is d_{imt} . However, if any product i' whose $q_{ii'}$ is greater than zero is also introduced in the period t , then the demand for product i is reduced by $q_{ii'}$ times d_{imt} as in constraint (3.4 - 3.6).

Constraints (3.8) set the limit on the new product development. In every decision period t , the result of past decisions in period $t-1$ is evaluated by the simulation model, and the total capital available for investment in period t (KT_t) is calculated. Then for the model P1 and P2, KT_t is allocated into KP_t and KR_t . Then the value of KP_t is assumed to be constant over the periods $t=1,2,\dots,T$ in the constraints (3.8).

As shown above, the product planning model **P1** does not consider its impact on the requirements of process technology, nor does it reflect the future technologies being considered by manufacturing. The only considerations are paid on the market opportunities, and the manufacturing aspect remains as a blind spot. This model thus represents a marketing-dominated case in the strategy formation process.

3.2.2 Process Design Decision Model (P2)

The process design model answers the question of how to meet the product plan most efficiently. In the framework of unlinked decision making, a process decision is made after the product plan determines the future demand for various products. As the product planning decision in the model **P1** does not consider what the future manufacturing will be capable of, process design in this model **P2** does not consider any new products which are planned to be introduced in the future. It considers only the products that are offered at the current decision period, and attempts to optimize with the given output requirements projected into the future. The process design decision model is formulated as follows:

$$\text{Minimize } \sum_t \sum_k (a_{kt} X_{kt} - b_{kt} Y_{kt} + f_{kt} Z_{kt} + u_{kt} \sum_j A_{kjt}) + \sum_t \sum_i M_{it} L_{it} \quad (3.14)$$

s.t.

$$Z_{k0} = z_{k0} \quad k=1,2,\dots,K \quad (3.15)$$

$$Z_{k,t-1} + X_{kt} - Y_{kt} = Z_{kt} \quad (3.16)$$

$$t=1,2,\dots,T ; k=1,2,\dots,K$$

$$\sum_{i \in I_1} (D_{it} - L_{it}) r_{ij} \leq \sum_k s_{kj} A_{kjt} \quad (3.17)$$

$$t=1,2,\dots,T ; j=1,2,\dots,J$$

$$I_1 = \{ i \mid D_{i1} > 0 \}$$

$$\sum_j A_{kjt} \leq Z_{kt} \quad (3.18)$$

$$t=1,2,\dots,T ; k=1,2,\dots,K$$

$$\sum_k a_{kt} X_{kt} \leq KR_t \quad (3.19)$$

$$t=1,2,\dots,T$$

$$X_{kt}, Y_{kt}, Z_{kt} \geq 0 \quad k=1,2,\dots,K ; t=1,2,\dots,T \quad (3.20)$$

$$A_{kjt} \geq 0 \quad k=1,2,\dots,K ; j=1,2,\dots,J ; t=1,2,\dots,T \quad (3.21)$$

$$L_{it} \geq 0 \quad i=1,2,\dots,I ; t=1,2,\dots,T \quad (3.22)$$

The objective function (3.14) minimizes the total cost of acquiring and operating cost minus the total salvage value of all technologies throughout the planning horizon. Note that the fixed cost f_{kt} is multiplied by Z_{kt} , while the variable cost u_{kt} is multiplied by the total capacity actually utilized $\sum_j A_{kjt}$.

Constraints (3.15 - 3.16) represent the capacity balance equations. Constraints (3.17) define the process requirements in that the total effective capacity (taking into account the efficiency of particular technology in performing a particular process, s_{kj}) allocated to a certain process should be at least as large as the total process requirements from all products during each period. Constraints (3.18) set the upper limit on capacity allocation. Constraints (3.19) define the limit on the process investment for each period in the same way as explained in section 3.2.1.

Note that the demand for each product, D_{it} , is determined by the product planning model **P1**, and therefore is *exogenous* for the process design model **P2**. Furthermore, constraints (3.17) show that the process design model considers only the products that are offered in the upcoming period $t=1$. Any other products that are part of the product planning to be introduced sometime in the future are not included in estimating the future process requirements. It shows the lack of linkage between two decision models.

Also, since the product planning decisions are made without considering the process capacity aspect, there is no guarantee that the projected demand can be satisfied even though acquisition lead times are assumed to be zero. With the limit on capital investment as shown in constraints (3.19), the process design model may generate infeasible solutions if the constraints (3.17) are applied *tightly* without the additional variable L_{it} . By defining the constraints as above, the model allows the process design to experience capacity shortfalls if the capital budget is not enough. The parameter M_{it} in the objective function assign priorities to the demands for different products. The decision

model **P2** thus only tries to meet the given demand most efficiently, portraying manufacturing in a reactive role.

3.2.3. Product-Process Linkage Model (I)

The two separate decision models presented above represent the unlinked decisions in strategic management, and they portray the reactive role for manufacturing in strategy formulation process. Two decisions are made sequentially, and when each decision is made, the other decision remains as a blind spot. In other words, product planning decisions are made without considering the changes being contemplated in future manufacturing technology, and process design decisions are made without reflecting new products being considered in the product plans. Figure 3.2 describes the process of sequential decision making.

Since future process planning is not considered in product planning, the firm tends to introduce various products only to capture the market opportunities, and it may cause inefficient process investments. Also, the process decisions are made shortsightedly without considering its impact on the future competitive position of the firm, such as the capability of introducing new products to the market, thus causing the manufacturing system to become a millstone rather than a competitive weapon. Unlinked decisions thus could result in myopic investment in process technology and ineffective product plans to exploit the market opportunities.

The *linked* model (I) makes these two decisions simultaneously. More linkage and integration between decisions are pursued, so that the product planning considers its impact on process design and vice versa. Also, the total capital budget can be more wisely allocated to product and process investment as necessary, rather than the arbitrary allocation to KP_t and KR_t as described in the separate decision case. The *linked* model I is presented below:

$$\begin{aligned} \text{Maximize } \sum_t \sum_i c_{it} D_{it} - \sum_t \sum_i \sum_m h_{imt} P_{im} \\ - \sum_t \sum_k (a_{kt} X_{kt} - b_{kt} Y_{kt} + f_{kt} Z_{kt} + u_{kt} \sum_j A_{kjt}) \end{aligned} \quad (3.23)$$

s. t.

$$D_{it} = \sum_m P_{im} d_{imt} - \sum_{i'} \sum_m Q_{ii'mt} d_{imt} \quad (3.24)$$

$$i=1,2,\dots,I ; t=1,2,\dots,T$$

$$Q_{ii'mt} \geq [\sum_{m'} P_{i'm'} k_{i'm't} + P_{im} k_{imt} - 1] q_{ii'} \quad (3.25)$$

$$i,i'=1,2,\dots,I ; i \neq i' ; m=1,2,\dots,M_i ; t=1,2,\dots,T$$

$$Q_{ii'mt} \leq P_{im} k_{imt} q_{ii'} \quad (3.26)$$

$$i,i'=1,2,\dots,I ; i \neq i' ; m=1,2,\dots,M_i ; t=1,2,\dots,T$$

$$Q_{ii'mt} \leq [\sum_{m'} P_{i'm'} k_{i'm't}] q_{ii'} \quad (3.27)$$

$$i,i'=1,2,\dots,I ; i \neq i' ; m=1,2,\dots,M_i ; t=1,2,\dots,T$$

$$\sum_m P_{im} = 1 \quad (3.28)$$

$$i=1,2,\dots,I$$

$$Z_{k0} = z_{k0} \quad k=1,2,\dots,K \quad (3.29)$$

$$Z_{k,t-1} + X_{kt} - Y_{kt} = Z_{kt} \quad (3.30)$$

$$t=1,2,\dots,T ; k=1,2,\dots,K$$

$$\sum_i D_{it} r_{ij} \leq \sum_k s_{kj} A_{kjt} \quad (3.31)$$

$$t=1,2,\dots,T ; j=1,2,\dots,J$$

$$\sum_j A_{kjt} \leq Z_{kt} \quad (3.32)$$

$$t=1,2,\dots,T ; k=1,2,\dots,K$$

$$\sum_i \sum_m h_{imt} P_{im} + \sum_k a_{kt} X_{kt} \leq KT_t \quad (3.33)$$

$$t=1,2,\dots,T$$

$$P_{im} = (0,1) \quad i=1,2,\dots,I ; m=1,2,\dots,M_i \quad (3.34)$$

$$Q_{ii'mt} \geq 0 \quad i,i'=1,2,\dots,I ; i \neq i' ; m=1,2,\dots,M_i ; t=1,2,\dots,T \quad (3.35)$$

$$D_{it} \geq 0 \quad i=1,2,\dots,I ; t=1,2,\dots,T \quad (3.36)$$

$$X_{kt}, Y_{kt}, Z_{kt} \geq 0 \quad k=1,2,\dots,K ; t=1,2,\dots,T \quad (3.37)$$

$$A_{kjt} \geq 0 \quad k=1,2,\dots,K ; j=1,2,\dots,J ; t=1,2,\dots,T \quad (3.38)$$

The objective function (3.23) includes both the contribution from product planning and the costs from process design decisions. In contrast to the case of separate decision models of **P1** and **P2**, the contribution parameter c_{it} is now estimated *without* allocating the process cost f_{kt} and u_{kt} into v_{it} , thus c_{it} is defined as

$$c_{it} = p_{it} - m_{it} \quad (3.39)$$

When these two decisions are integrated into one model, there is no need to estimate the variable overhead cost v_{it} for each product by allocating the operating cost f_{kt} and u_{kt} of process technology to each product. Thus, labor and overhead costs are now *correctly* represented in decision model, in comparison to the *approximation* required in the separate decision model. This procedure reflects the arguments of many researchers who have contended that the improper cost accounting system has contributed to the recent deterioration of the U.S. manufacturing industry (Kaplan 1983; Cooper and Kaplan 1988; Hiromoto 1988).

The constraints that link two decisions into one are constraints (3.31). Note that D_{it} is not an exogenous parameter anymore, as it was in the model **P2**. Now D_{it} must be decided in the model, and its impact on the process requirements must be considered *a priori*. In other words, each alternative product strategy is evaluated not only from the market perspective but also from the manufacturing perspective. The impact of each process alternative on the product planning is also considered before the process design decisions are made. The model **I** therefore represents a proactive role of manufacturing in strategy formulation process.

Constraints (3.31) show that the process design now considers all products that are planned to be introduced during the planning horizon, not only the products to be

introduced in the upcoming period as the case in the unlinked model. Furthermore, there is no need for the additional variable for lost sales, L_{it} , since the product planning now considers the capacity of the process technology.

In addition, note that in constraints (3.33), the capital investment for product development and technology acquisition are now summed together, and limited by the total capital KT_t available for the firm. There is no need for making an allocation of total capital into KP_t and KR_t , and more effective resource allocation is expected by the linked model. Again the value of KT_t is determined in the simulation process, and remains constant over the periods $t=1,2,\dots,T$.

3.2.4 Emphasis on Resource Flexibility

The process design model presented above does not explicitly consider the concept of manufacturing flexibility. All decisions are guided by the cost minimizing objective, and the model finds a solution that meets the given demand most efficiently. Thus, the strategic value of flexibility is not reflected in the models.

Manufacturing flexibility was defined in Chapter III as the capability of manufacturing system to react effectively to the changes in the environment, such as changes in the product mix or demand volumes (Karmarkar and Kekre 1985; Slack 1983). Manufacturing's responsiveness to changes can be enhanced by two general approaches. First, the firm can respond to changes better if the plan looks further ahead into the future, thus by anticipating the future changes, and reflecting them in the current decision making process. The decision models presented here foresee some periods into the future, thus implicitly incorporate this approach.

This first approach, however, gives the system a capability of responding only to the *expected* changes. *Unexpected* changes cannot be incorporated in the decisions, no matter how long the planning horizon is. Thus, another approach is needed to enhance the

flexibility of the system in order to respond to this unexpected uncertainty, and it is pursued in this study by resource flexibility. Resource flexibility can be explicitly pursued by forcing the firm to acquire more technologies that can perform wider range of processes. By including a side constraint in the decision model, the model can force the system to enhance its flexibility. The procedure to implement this extra emphasis on flexibility is described below.

Based on the s_{kj} parameter that represents the capability of a particular technology, a binary parameter u_{kj} is defined such that

$$u_{kj} = \begin{cases} 1 & \text{if } s_{kj} > 0 \\ 0 & \text{if } s_{kj} = 0 \end{cases}$$

That is, u_{kj} indicates whether technology k can perform process j or not. A technology that can perform more diverse processes is more flexible. Therefore, the flexibility of a particular technology k can be represented by the following index:

$$F_k = \frac{\sum_j u_{kj}}{J}, \quad 0 \leq F_k \leq 1 \quad (3.40)$$

In the above equation (3.40), $\sum_j u_{kj}$ represents the number of different processes that can be performed by a technology k . Thus, the index F_k reflects the proportion of total processes that can be performed by a particular technology. This definition is consistent with the definition of process flexibility presented by Brown et al. (1984). The most flexible technology can perform all the processes, and its index F_k is 1, while less flexible technology has F_k close to 0.

The flexibility of a manufacturing system during period t is measured by the proportion of more flexible technology in the whole manufacturing system, that can be represented in the model as

$$\frac{\sum_k F_k Z_{kt}}{\sum_k Z_{kt}} \quad t=1,2,\dots,T \quad (3.41)$$

As seen above, if the system maintains a larger amount of flexible technology, its flexibility is higher, and vice versa. Then, the side constraint to reflect the emphasis on the manufacturing flexibility can be defined as:

$$\sum_k (F_k Z_{kt}) \geq FL_t (\sum_k Z_{kt}) \quad t=1,2,\dots,T \quad (3.42)$$

where, FL_t = desired level of flexibility in period t

The above constraints are added to model **P2** and **I** to represent the strategic policy which emphasize the manufacturing flexibility as a competitive priority.

3.3 THE SIMULATION MODEL

The proposed models represent a framework of strategic decisions with regards to product planning and process design. However, due to the abstractness of the variables and large scope of the problem, it is less likely that the proposed model could be used as a decision support tool directly. Rather in this dissertation research, the model is applied as a tool to address the important strategic issues related to the problems.

A simulation model, that includes the decision models as submodules, is developed to evaluate the consequences of different policies regarding the product-process decisions. In the simulation model, two particular aspects of implementing the decision model are highlighted. First, uncertainty in the decision environment is reflected in the simulation procedure. Second, the decision model is simulated over the experimental periods using the concept of rolling schedules.

3.3.1 Uncertainty in Decision Environment

Even though the decision models assume a deterministic environment, the actual decision environment is far from it. All parameters in the model are exposed to a great deal of uncertainty, particularly because they deal with long-term decisions.

Uncertainty in the decision environment has a significant impact on strategy formulation process. Swamidass and Newell (1987) found that firms tend to ignore manufacturing's participation in strategic decision making when uncertainty in the environment is high. It implies that the value of linked decisions may diminish with increasing uncertainty. Also, the value of resource flexibility in part comes from the uncertainty. A more flexible system seems to be more capable of reacting to the unexpected events, such as changes in market demand or a particular process requirement of a product. Therefore, this study intends to test the efficacy of each decision policy under various environmental settings with different level of uncertainties.

Uncertainty is reflected in this study by introducing forecast errors to the parameters in the decision models, such as d_{imt} , r_{ij} , and s_{kj} . The degree of uncertainty is controlled by the percentage errors between the actual value and forecasted value. Also, since the model deals with long-term planning, the *time* aspect of uncertainty is reflected: Uncertainty in the more distant future is set at a higher level than that of near future. In other words, the degree of uncertainty is larger as the firm must forecast further out to the future.

Another important aspect of environmental uncertainty in strategic management is the firm's capability of reducing the uncertainty by learning. For example, the newer the technology introduced, the greater the uncertainty in estimating its efficiency of performing various processes. This uncertainty is reduced as the firm gets more experience and understands the technology better. This phenomenon applies in the same way to the products and markets.

In the simulation model, the uncertainty is incorporated in the process of parameter generation. First, the decision environment is formulated to generate the actual values of parameters. Then at each period, forecasted values of the parameters are generated using Monte Carlo method depending on the level of uncertainty which is controlled by the

experimental design. Then product and process decisions are made with the forecasted values of each parameters. The decisions made for the current period are implemented with the actual parameter values and their results are evaluated. Thus, even though the decision models provide the *optimal* solution, they may not be optimal for the problem with the actual parameter values. Chapter V provides a more detailed description of this simulation procedure.

3.3.2 Rolling Scheduling Scheme of Model Implementation

In Chapter II, it was discussed that strategy is formulated through a dynamic process over a long time period. Decisions are made with the forecasted values of parameters and the results are determined by the interactions of various factors such as the reaction of competitors and development of new technology. Then the results are evaluated and the forecasts are modified to be reflected in the next-period decision making process. This cyclic process of forecasting, decision, and evaluation of results, continues and the patterns in the stream of decisions are captured as strategy.

The simulation model incorporates this dynamic process of strategy formulation with the rolling scheduling scheme which is found in much of the production planning literature (Baker 1977). In period t , all the necessary parameters are forecasted, and product-process decisions are made for the periods covered in the planning horizon. Then the decisions for the current period t is implemented, and the results are obtained with the actual values of the parameters. New forecast is made for the period $t+1$, and this procedure will continue.

The series of decisions made in this rolling schedule scheme are not necessarily the *global* optimum, which could be obtained in certain environments if the entire experimental periods are included at one time in the model. Thus, even though the unlinked model looks

to provide an inferior solution to the linked solution, this rolling schedule procedure can affect the expected result.

3.3.3 The Simulation Model

A simulation model is developed to incorporate the above two aspects. It includes four key submodules: 1) actual parameter generation, 2) parameter value forecast, 3) product-process decision making, and 4) calculating the results from the decisions with actual parameter values. These four modules will be repeated as the planning schedule is rolled from one period to another.

The decision models are embedded in the simulation as a submodule, providing the solution for product and process decisions based on the forecasted values of parameters. Then the next submodule evaluates the current-period decisions with the actual parameter values, and the results are recorded. A simple flow chart of the simulation model is described in Figure 3.3, and the detailed procedure of implementation is further explained in Chapter V.

Figure 3.1

Relationship between Product Planning and Process Design

A. Sequential Decisions of Product and Process (Unlinked Model)

B. Simultaneous Product-Process Decision (Linked Model)

Figure 3.2

Two Decision Models for Product and Process Decisions

Figure 3.3

Flow Chart of Simulation Model

Table 3.1
Summary of Notation

1. Indexes

i = product, $i = 1, 2, \dots, I$

j = process, $j = 1, 2, \dots, J$

k = process technology, $k = 1, 2, \dots, K$

m = product introduction strategy, $m = 1, 2, \dots, M_i$

t = time period, $t = 1, 2, \dots, T$

2. Decision Variables for Product Planning

D_{it} = units of product i *actually* demanded in period t as a result of product planning, taking into account the interaction effect with other product decisions

P_{im} = 1 if product i is introduced/withdrawn following strategy m
0 otherwise

$Q_{ii'mt}$ = proportion of demand for product i with strategy m lost in period t due to the existence of similar product i' in the market

3. Decision Variables for Process Design

X_{kt} = additional capacity of technology k acquired at the beginning of period t , expressed in machine hours per period

Y_{kt} = capacity of technology k disposed of at the beginning of period t , expressed in machine hours per period

Z_{kt} = capacity of technology k held in period t , expressed in machine hours per period

A_{kjt} = capacity of technology k to be allocated to perform process j in period t , expressed in machine hours per period

L_{it} = units of demand for product i that cannot be met due to the shortage of capacity in period t

Table 3.1 (Continued)

4. Parameters for Product Planning

d_{imt}	=	number of units of product i to be demanded in period t if introduction strategy m is pursued
k_{imt}	=	1 if $d_{imt} > 0$ 0 if $d_{imt} = 0$
c_{it}	=	discounted unit contribution of product i in period t
p_{it}	=	price per unit of product i in period t
m_{it}	=	materials cost per unit of product i in period t
v_{it}	=	labor and variable overhead cost per unit of product i in period t
$q_{ii'}$	=	proportion of demand for product i lost due to the existence of similar product i'
h_{imt}	=	capital investment required for product i in period t if strategy m is pursued
KP_t	=	total capital budget available for product development in period t

5. Parameters for Process Design

r_{ij}	=	number of machine hours required to perform process j per unit of product i
s_{kj}	=	efficiency of technology k in performing process j ($0 \leq s_{kj} \leq 1$)
a_{kt}	=	discounted unit acquisition cost of technology k in period t
b_{kt}	=	discounted unit salvage value of technology k in period t
f_{kt}	=	discounted fixed overhead cost to keep unit of technology in period t
u_{kt}	=	discounted variable overhead and labor cost to operate unit of technology in period t
KR_t	=	total capital budget available for technology investment in period t
M_{it}	=	penalty for lost sales per unit of product i in period t

Table 3.2

Demand level for each product (d_{imt})

i	m	t					
		1	2	3	4	5	6
1	1	10	20	40	60	60	30
	2	0	0	30	50	50	30
	3	0	0	0	0	0	0
2	1	0	0	0	0	0	0
	2	0	0	0	40	50	40
	3	0	0	0	0	40	40
3	1	0	0	0	0	0	0
	2	10	20	20	0	0	0

Table 3.3

Contribution margin of each product (c_{it})

i	t					
	1	2	3	4	5	6
1	2.0	2.0	2.0	1.8	1.0	0.6
2	0.0	0.0	3.0	3.0	3.0	2.0
3	1.6	1.6	1.0	0.0	0.0	0.0

Table 3.4

Impact of offering similar products simultaneously ($q_{ii'}$)

i	i'			
	1	2	3	4
1	0	0.2	0.4	0.3
2	0.2	0	0.5	0.7
3	0.3	0.7	0	0.6
4	0.2	0.5	0.6	0

Table 3.5

Process requirement of each product (r_{ij})

i	j					
	1	2	3	4	5	6
1	0.4	0.3	0.5	1.0	0	0
2	0.4	0.3	0.5	1.0	1.2	0
3	0.3	0	0.5	1.0	0	0

Table 3.6

Process capability of each technology (s_{kj})

k	j					
	1	2	3	4	5	6
1	1.0	0	0	0	0	0
2	0.2	0.3	0.3	0.4	0.3	0.2
3	0.9	0.8	0.7	0	0	0
4	0.7	0.7	0.8	0.9	0.7	0.6

CHAPTER IV

MANUFACTURING STRATEGY AND THE ENVIRONMENT: A FRAMEWORK AND HYPOTHESES

Strategy formulation is an interactive process between an organization's environment and its decisions. A constantly changing environment provides different opportunities and threats to a manufacturing firm, and the firm reacts to these changes by making various strategic decisions. Many strategy researchers thus define strategy as a pattern of decisions emerging from this dynamic interactive process of change and reaction (Mintzberg 1980). Therefore, manufacturing strategy should be understood within the specific context of the firm's environment.

The main thrust of this dissertation, as discussed in Chapter I, is that a firm may need a different manufacturing strategy depending on its environment. In other words, the strategic value of integrating product and process decisions, and/or developing manufacturing flexibility, is contingent upon the environmental structure. By simulating the decision models with different parameter settings, this study intends to test the conjectures listed in Chapter I.

The goal of Chapter IV is to develop a conceptual framework to represent the manufacturing environment. There is little guidance in the literature on how to define environmental factors that may affect manufacturing strategy. The term *environmental factors* encompasses a large number of variables. Without a framework that summarizes or synthesizes these factors, a rigorous analytical study can hardly evaluate the

environmental impact. Therefore, Chapters IV and V attempt to develop several *clusters* of environmental factors so as to represent the most critical aspects of the manufacturing environment.

Three steps are taken to form the environmental clusters for the experimental research. *First*, the literature in corporate and manufacturing strategy that deals with the environment is reviewed, with the intention of gaining some insights on how the environment should be conceptually structured. *Second*, a field study is conducted at three companies to explore managerial practices regarding the environment-strategy connection. *Third*, a preliminary experiment examines the behavior of the decision models under different parameter settings, with the intention of winnowing out factors which are less important. The first two steps are reported in this chapter, while the third step is discussed in Chapter V. The clusters of environment factors thus formed are used in an experimental study reported in Chapter VI, which more rigorously tests the environmental impact on manufacturing.

Section 4.1 reviews the literature on the environment in both the strategic management and manufacturing strategy areas. Drawing on these past studies, Section 4.2 proposes four clusters of environmental characteristics, that are expected to affect the effectiveness of each strategic policy. Section 4.3 then presents the results of a field study that was conducted to reinforce the conceptual framework and to establish the factor settings for this dissertation. The chapter concludes with research hypotheses regarding the environment's impact on manufacturing strategy, which will be experimentally tested in Chapter VI.

4.1 ENVIRONMENTAL STUDY IN MANUFACTURING STRATEGY: A LITERATURE REVIEW

Strategy theorists have suggested that the environment is a critical determinant of strategy. Particularly in the organization theory literature, the external environment of an organization is viewed as the source of events and changing trends which create opportunities and threats for individual firms (Lenz 1980). Unfortunately, the operations management (OM) area has paid little attention to the environment-manufacturing strategy connection. Exceptions are the work by Van Dierdonck and Miller (1980) and Swamidass and Newell (1987).

This section thus reviews the literature in the corporate strategy field on the environment. Also the studies by Van Dierdonck and Miller (1980) and Swamidass and Newell (1987) are reviewed to explore how the environmental structures have been viewed by the OM researchers. The insights from these studies are applied to develop the environmental settings under which manufacturing strategy will be tested.

4.1.1 Past Environmental Study in Corporate Strategy

Most previous studies on the environment have been conducted at the corporate strategy level. There have been numerous arguments and debates on how to succinctly capture the complex nature of the business environment. From many various studies, the following seem representative.

Aldrich (1979), in summarizing the current state of organizational theory regarding the environment, comments on two major theoretical approaches to perceive the environment. One approach, characterized as an *information perspective*, "considers the impact of environmental uncertainty on the organizational participants' ability to make decisions, and on the consequent organizational restructuring to cope with uncertainty."

The second approach, characterized as a *resource perspective*, "treats the environment as consisting of resources for which organizations compete." According to this perspective, "the level of resources and the terms under which they are made available" represent the critical factors in organizational changes (Aldrich 1979, pp.110-111).

Lawrence and Dyer (1983), studying the process of readaptation in seven American industries during the last several decades, attempt to synthesize these two perspectives. They propose a two-dimensional representation of the environment, consisting of information complexity and resource scarcity. *Information complexity* is defined as "the degree of variations in an organization's immediate environment which influence its choice of which goods and services to supply." The information domain includes competitive, technical, customer, product, and government regulatory variations. *Resource scarcity* is defined as "the degree of difficulty an organization experiences in securing the resources it needs to survive and grow." The resource domain includes availability of various types of resources, and the impact that the customers, competitors, government, and organized labor have on resource availability. Then Lawrence and Dyer propose a two-dimensional matrix, as shown in Figure 4.1, to capture the information and resource domains simultaneously. Explaining the changes of organization structure in different industries, they helped reduce the gap between the information perspective and the resource perspective.

These studies show that the environmental context can be divided into several dimensions. Most strategy researchers seem to choose a two-dimensional approach. They include information factors (such as complexity and uncertainty) and resource factors (such as competition and materials abundance). Researchers in the corporate strategy area use this *dimensional approach* to summarize the complex nature of environment. By this approach, they are able to reduce the analytical complexity of the environment, that otherwise would include a limitless number of factors.

4.1.2 Past Environmental Study in Manufacturing Strategy

In contrast to the production planning and control field, where abundant studies of the environmental impact can be found, the manufacturing strategy field has few studies on the environmental aspect. Van Dierdonck and Miller (1980) and Swamidass and Newell (1987) recently recognize the need for environmental study, and provide insight on how to do it.

Van Dierdonck and Miller (1980), while proposing a model to guide the design of production planning and control systems under different environments, divide the environmental context into two dimensions: uncertainty and complexity. They define the *uncertainty* as the reliability of information and assumptions. Demand, production, supply, and goal uncertainties were the main components. *Complexity* is defined as the maximum amount of data required to make effective decisions. Included in this dimension are volume, diversity, repetitiveness, and the interdependency of manufacturing tasks.

Guided by a limited number of samples, Van Dierdonck and Miller contend that a more *integrated* planning and control system is required to cope with higher task uncertainty, while higher task complexity should be managed by enhanced *information processing system involvement (IPSI)*. They also suggest that the need for integrativeness and IPSI can be reduced by more *tolerance for slack* and a more effective *organizational context*.

Their contribution, though yet to be confirmed with a larger sample and more rigor, is commendable because it represents one of few attempts to conceptualize the manufacturing environment and to link it with the manufacturing planning and control system. Also, while their main subject area is more closely related to the operational decisions, their approach to conceptualize the environmental context is applicable to the more strategic decisions considered in this research.

Swamidass and Newell (1987) provide another framework of environmental study for research in manufacturing strategy. They captured the environmental context by a single variable – *environmental uncertainty*. Using a path analytic model based on executive survey data, they find that environmental uncertainty negatively affects the degree to which manufacturing managers are involved in the strategic decision making process. Also, they find that the concept of flexibility is emphasized more in manufacturing strategy when environmental uncertainty is perceived higher.

They deserve credit for considering environmental factors in the study of manufacturing strategy. Their findings provide a considerable contribution to this field of study. However, their study is still primitive in that they did not explicitly identify the *factors* that contribute to environmental uncertainty. Moreover, other dimensions of the environment need to be examined, such as environmental complexity.

4.1.3 A Summary

From the brief review of previous studies on the environment, the following three points emerge. *First*, environmental research has advanced more at the corporate strategy level, mostly in the organizational theory field. Despite the contributions from Van Dierdonck and Miller (1980) and Swamidass and Newell (1987), there still exists a great need to examine how the content and process of manufacturing strategy match with the environmental context.

Second, the environment consists of numerous factors with complex relationships among them. In order to evaluate their impact on the performance of a certain policy, these complex factors need to be synthesized by some key concepts. A framework is needed that can succinctly represent the various factors composing the environment.

Third, a multi-dimensional approach such as the framework by Lawrence and Dyer (1983) seems appropriate. Compared to the single-dimensional approach as adapted by

Swamidass and Newell (1987), the multi-dimensional approach would provide a richer analysis of various environmental factors, including the interactions among them.

Therefore, this study develops four clusters of environmental factors. First, in section 4.2, the clusters are formed drawing upon the past studies. Then section 4.3 reinforces the clustering framework by presenting the results of a field study. This study was conducted to examine how managers deal with the environmental factors in their strategy formation process.

4.2 ENVIRONMENTAL CLUSTERS: A PROPOSED FRAMEWORK

There are two conflicting research motivations in defining the environment. On the one hand, the complex nature of the environment should be captured as comprehensively as possible. The more factors a study includes, the more comprehensive the result can be. Any missed factor can either mislead the result or limit the contribution of the study. On the other hand, the scope of research should be controlled as tightly as possible so that in-depth analysis of a particular factor is feasible. As more factors are included in a study, the analysis becomes more complex and the results might not be fully explained. This conflict of motivations can be resolved partially by the multi-dimensional approach as reviewed in the previous section. By grouping several factors into a *dimension* of the environment, this approach reduces the complexity of a study. Also by examining multiple dimensions and their interactions, a study can provide comprehensive findings.

This study applies the concept of *cluster* to represent the environment. Several factors, that seemed to have a similar impact on the strategy, are grouped into a single cluster. Thus, rather than studying numerous factors individually, only a handful of clusters need to be experimentally tested. More specifically, *four clusters of environmental characteristics* which have been drawn from the literature are proposed as follows:

- 1) Environmental complexity
- 2) Environmental uncertainty
- 3) Environmental tightness
- 4) Organizational learning

The following four subsections define each cluster and provide a list of individual factors that are grouped in each cluster. Table 4.1 summarizes the environmental factors and clusters established in this section.

4.2.1 Environmental Complexity

Environmental complexity refers to the size and difficulty of product-process decisions. As a wider array of products are to be considered and more diverse process technologies are available, the decision process of choosing a particular product or a particular technology becomes more difficult. The following seven factors are chosen to represent environmental complexity:

- a. Number of product lines
- b. Number of products per product line
- c. Length of product life cycle
- d. Variability of demand over product life cycle
- e. Total number of different processes in the plant
- f. Average number of different processes required for each product
- g. Total number of different process technologies

Within the context of the decision model described in Chapter III, higher environmental complexity is hypothesized to enhance the value of *integration*. Van Dierdonck and Miller (1980) suggest that more *information processing system involvement* (IPSI) might be needed with higher task complexity. Also Lawrence and Dyer (1983)

suggest a "tighter control" when task complexity is high. In the context of this dissertation, more IPSI and "tighter control" translate into the use of the *linked* decision model.

Also, higher environmental complexity is hypothesized to increase the strategic value of manufacturing flexibility. Flexibility-related studies (Groover 1980; Brown et al. 1984) suggest that a more complex mix of products and process requirements motivates more flexible manufacturing technology. Actually, the concept of flexible manufacturing systems comes from an environment in which various types of parts must be produced with low volume, thus making the process flow very complex. The generally accepted inverse relationship between product diversity and process efficiency (Krajewski and Ritzman 1987) also suggests a similar result.

Therefore, the following two hypotheses are established regarding environmental complexity:

- a. Linked decision making outperforms unlinked decision making, particularly when environmental complexity is *higher*.
- b. Emphasizing manufacturing flexibility is a better strategy when environmental complexity is *higher*.

4.2.2 Environmental Uncertainty

Environmental uncertainty represents the degree of errors in estimating the future status of an operation's tasks and capability. Formally, the following factors are hypothesized to compose environmental uncertainty:

- a. Percentage error in forecasting demand for each product (d_{imt})
- b. Percentage error in estimating process requirements for each product (r_{ij})
- c. Percentage error in estimating process efficiency for each technology (s_{kj})

High environmental uncertainty would seem to reduce the relative superiority of the linked model over the unlinked model. Since the linked model pursues a global optimality

while the unlinked model results in an local optimality, it cannot be inferior under conditions of complete certainty and an appropriate planning horizon. However, when decisions are made based on imperfect or false information due to the high uncertainty, the difference between the two models might diminish. The finding of Swamidass and Newell (1987), that manufacturing managers participated less in the strategy formulation process under highly uncertain environments, also implies a reduced strategic value of integrated decision making.

Meanwhile, higher environmental uncertainty is hypothesized to enhance the value of flexibility. The main motivation for manufacturing flexibility comes from the uncertainty in the future status of environment. Flexibility provides the risk-pooling effect: Variance in process requirements coming from unstable demand can be cancelled out by the common resources provided by flexible process technology. Empirically, Swamidass and Newell (1987) found out that more flexibility is introduced into manufacturing strategy when the environment is perceived more uncertain.

Therefore, the following two hypotheses are established regarding environmental uncertainty:

- a. Linked decision making outperforms unlinked decision making, particularly when environmental uncertainty is *lower*.
- b. Emphasizing manufacturing flexibility is a better strategy when environmental uncertainty is *higher*.

4.2.3 Environmental Tightness

Environmental tightness represents how fierce the competition is in the market, and it also reflects how critical the *right* decision making is for the survival of a manufacturing firm. Low contribution margins coming from severe price competition could make any *wrong* decision fatal. Also, the availability of investment capital, which is determined in

part as a function of the net cash flow during the prior period, reflects how critical the current period's decision is to the future position of the company. Two factors included in this study to represent the environmental tightness are:

- a. Average contribution margin (c_{it}) as a proportion of average process cost
- b. Availability of capital for product and process investment (KP_t , KR_t , KT_t)

Environmental tightness is similar to the concept of *tolerance for slack* proposed by Van Dierdonck and Miller (1980). Conditions of fierce competition and low profit margin would seem to require more integrated decision making. The difference between the linked and unlinked models might be greater when the environmental tightness is higher with less slack.

The impact of environmental tightness on manufacturing flexibility has not been studied before. Within the context of the decision model, however, it can be hypothesized that, the tighter the environment, the harder to compete with flexible technology, since the flexibility comes with the loss of efficiency. Krajewski and Ritzman (1987) suggest that a firm operating with tight profit margins tends to emphasize top-notch efficiency as a competitive priority.

Therefore, the following two hypotheses are established regarding environmental tightness:

- a. Linked decision making outperforms unlinked decision making, particularly when environmental tightness is *higher*.
- b. Emphasizing manufacturing flexibility is a better strategy when environmental tightness is *lower*.

4.2.4 Organizational Learning

Organizational learning represents a firm's ability to reduce environmental uncertainty by accumulating experiences with a particular product or process technology.

They are represented by the following three factors:

- a. Degree to which the uncertainty in demand (d_{iml}) is reduced as experience with the product accumulates
- b. Degree to which the uncertainty in process requirement (r_{ij}) is reduced as experience with the product accumulates
- c. Degree to which the uncertainty in process efficiency (s_{kj}) is reduced as experience with the technology accumulates

Organizational learning represents the ability of management to reduce the uncertainty in the environment. A higher level of organizational learning reduces the effect of environmental uncertainty. Thus when a firm has a higher learning capability, the value of linked decisions over unlinked ones would seem to be enhanced, while the value of manufacturing flexibility would seem to be reduced.

Therefore, the following two hypotheses are established regarding organizational learning:

- a. Linked decision making outperforms unlinked decision making, particularly when organizational learning is *higher*.
- b. Emphasizing manufacturing flexibility is a better strategy when organizational learning is *lower*.

4.3 A FIELD STUDY: EXECUTIVE SURVEY

The importance of empirical studies in manufacturing strategy cannot be overemphasized. Models not applied to realistic settings make at most questionable

contribution to the field. The results are meaningful to both academic researchers and practitioners only when the experiment is performed with realistic factor settings. Particularly, the characteristics of this research, including the abstractness of the decision model and the wide scope of the environmental study, require some level of empirical verification.

A limited field study was conducted, therefore, to assure that the general framework of the model is meaningful. As discussed earlier in this chapter, there is little guidance from the literature on how to define the environmental context. This survey explores the managerial perspectives on the environment-strategy connection. It helps clarify the cluster concepts and reinforce the research hypotheses. The field study also helps set the experimental factors at realistic values.

First, an overview of the field study is presented. Then, the questions asked and the data sought are described, followed by a brief summary of survey results. The specific numerical values of each answer are used in the next chapter when the experimental factors are established.

4.3.1 Field Study Overview

The purpose of this field study is threefold: 1) to help verify the decision models, 2) to explore managerial practices regarding the environment-strategy connection, and 3) to help identify important experimental factors and determine their levels. These objectives are presumed to be achievable by conducting a brief survey of manufacturing managers at three companies in a specific industry.

The industry group involving metal fabrication processes is selected as a target industry. The machine tool industry, which is classified as the Major Group 34 (fabricated metal products) in the Standard Industrial Classification (SIC) code, is chosen. Recently, researchers have paid increasing attention to this industry because of the rapid development

of new technology. The machine tool industry is being exposed to a wide array of new manufacturing technologies and fast growing foreign competition (Buffa 1984). The dynamic nature of the machine tool market seems to require a more strategic approach to its manufacturing decisions.

Out of 17 companies solicited, three companies agreed to participate. Table 4.2 presents a brief profile of these companies. As shown, their annual sales volume is between 10 to 50 million dollars, and they employ between 240 and 500 workers. All the companies rely heavily on metal fabrication processes. The managers interviewed are the highest ranked manufacturing managers, with a title such as Vice President of Manufacturing. They have been with the company at least 4 years, one manager having more than 20 years of experience. They appeared to have a solid understanding of their manufacturing processes, as well as the role of manufacturing function played in the company's business strategy. Each interview was conducted based on a structured questionnaire, but the conversations covered a wide range of topics.

4.3.2 Content of Executive Survey

The questionnaire was designed with two parts. The first part concentrates on the strategic decision-making process of the particular company and its business environment. The second part, which concentrates on the numerical characteristics of manufacturing operations, helped set up the experiments. The questionnaire itself is shown in Appendix A.

The questions in the *first* part of the survey are designed to assess how manufacturing managers perceive their firm's strategic position in the market and how their own decisions are made in relation to other business functions such as marketing. The questions are classified into the following four groups:

- 1) *Business and Manufacturing Strategy* : How are the functional strategies linked, i.e. bottom-up or top-down? Particular attention is given to the marketing-manufacturing relationship.
- 2) *Product Planning* : Is the firm's manufacturing capability considered when the product decision is made? Also basic questions are asked about the firm's competitive priorities in the market.
- 3) *Process Design* : How efficient and flexible are the firm's process technologies? The purpose of automation is also questioned, to see whether the primary motivation is efficiency or flexibility.
- 4) *Environmental Uncertainty* : How do the managers perceive their environmental uncertainty? Also, their strategic response to cope with the uncertainty is queried.

The *second* part of the survey specifically asks for the numerical characteristics of the firm's operating environment. Questions regarding the company's products, processes, and technologies are asked to acquire reasonable factor settings. To avoid the need for the managers to reveal proprietary information, the questions ask for the high and low value of the related *industry* (rather than for the firm itself).

The questionnaire for the second part of the survey is divided into 7 subgroups as follows:

- 1) *Demand diversity* : Questions ask the scope of products produced by the company, and the dynamic changes in products over time.
- 2) *Demand uncertainty* : Questions ask the uncertainties in forecasting demand in the near and distant future, for both existing and new products.
- 3) *Process characteristics* : Questions ask the scope of processes that are performed by the plant.
- 4) *Technology characteristics* : Questions ask the characteristics of both conventional and automated process technologies. Also the distinction is made between the

specialized and general-purpose equipment. The main interests are in the process capability, efficiency in performing processes, and various types of costs involved.

- 5) *Process uncertainty* : Questions ask the uncertainties in estimating process requirements for each product. Also the uncertainties in estimating the efficiency of each conventional and new technology are queried.
- 6) *Investment characteristics* : Questions ask about the investment level of each company with regards to product development and technology acquisition.
- 7) *Profitability and market competition characteristics* : Questions ask about the average level of product profitability and average length of their life cycles.

4.3.3 Summary of Survey Results

This section briefly describes the survey results. Particular emphasis is paid to the first part of survey. The manager's perception of the company's competitive environment and their strategic decision-making process is studied to reinforce the research hypotheses established in Section 4.2. The hypothesized environmental clusters and their relationships with strategic policies are examined with the manager's responses. Then the responses to the second part of the survey will be used in Chapter V for setting the factor levels in the experimental study.

Table 4.3 shows the responses from the managers of two companies to the questions in the first part of survey. The manager from *Company C* agreed to an interview, but his responses could not be acquired. The responses in the table are analyzed, and Table 4.4 summarizes some of the more interesting ones.

The three companies are distinctively different from each other with regards to their market stability, market leadership, and manufacturing's role in the strategy formation process. The differences between their operating environments and their strategic decision-making processes appear to reinforce the conjectures elaborated in the previous section.

Company A is experiencing a very competitive market where foreign competition is also strong. Its competitive position in the market is not as strong as the other two companies. The product technology in this industry is changing fast, and most of the orders are one-of-a-kind. Uncertainties in predicting demand, as well as estimating process requirements, are thus extremely high. As a result, manufacturing does not exert a strong influence on the strategic decision-making process, while marketing apparently dominates the business strategy. As expected, the company maintains more flexible, rather than efficient, process technology, that can handle a wide variety of process requirements.

In contrast, *Company C* is an industry leader with a stable market condition. The product technology in its market is stable, and the products are more standardized than in the case of *Company A*. Its competitive priority is devoted more toward a high quality product, rather than low cost. Uncertainties in estimating future demand and process requirements for the product are relatively low. The manager stated clearly that its manufacturing function plays a major role in the company's strategic decision-making process.

Company B falls between companies *A* and *C*. The market is relatively stable, and although the company is a leader in market share, it is not as strong as *Company C*. The uncertainty in demand for the final product is rather high, but the demand for major components and their process requirements appear to be more easily estimated than the case of *Company A*. The company maintains relatively coordinated efforts between manufacturing and marketing in its strategy formation process.

These contrasts suggest that firms in different strategic environments need a different approach in strategic decision making. Also the four environmental clusters presented earlier are fairly well observed from the field study data. *Companies A* and *B* responded quite differently to the questions on environment. *Company A* operates under

the environment with high uncertainty, high complexity, high tightness, and low organizational learning. *Company C* operates under an environment at the opposite end.

As a consequence, *Company A* is strategically managed with high marketing dominance, and the integration between the marketing and manufacturing decisions are low. Manufacturing reacts to the marketing strategy, and maintains a flexible process technology. In contrast, at *Company C*, manufacturing plays a more important role in strategic decisions. The decision making is more integrated and process technology is more efficient.

In summary, the decision model and environmental framework presented earlier appear to fit relatively well with this sample of industry practice. Thus in the next chapter, the environmental settings found from this field study will be accordingly implemented into the experimental study, and the results from the experiment will be statistically analyzed to test the research hypotheses.

4.4 RESEARCH HYPOTHESES

In the previous sections, four clusters of environmental characteristics were established guided by the past studies, and their impact on manufacturing strategy was speculated. The managerial practices observed in the field study seemed to support the proposed framework of the environment. This section concludes Chapter IV by formally stating the research hypotheses. Within the context of the decision model, the impact of each environmental cluster on manufacturing strategy is hypothesized as follows:

A. Linkage and the Environment

- H1: Linked decision making outperforms unlinked decision making, particularly when environmental complexity is *higher*.
- H2: Linked decision making outperforms unlinked decision making, particularly when environmental uncertainty is *lower*.
- H3: Linked decision making outperforms unlinked decision making, particularly when environmental tightness is *higher*.
- H4: Linked decision making outperforms unlinked decision making, particularly when organizational learning is *higher*.

B. Manufacturing Flexibility and the Environment

- H5: Emphasizing manufacturing flexibility is a better strategy when environmental complexity is *higher*.
- H6: Emphasizing manufacturing flexibility is a better strategy when organizational learning is *lower*.
- H7: Emphasizing manufacturing flexibility is a better strategy when environmental uncertainty is *higher*.
- H8: Emphasizing manufacturing flexibility is a better strategy when environmental tightness is *lower*.

The following two chapters present experimental studies that test these research hypotheses. First, in Chapter V, a preliminary analysis examines the behavior of different decision models under different settings of *individual* factors. The purpose of this preliminary study, as will be elaborated later, is to synchronize the individual factors within each cluster. It is conducted more in the spirit of an exploratory procedure, rather than attempting to draw any conclusions. Then, Chapter VI presents a complete experimental

study. It rigorously tests the impact of environment (in the form of clusters) on manufacturing strategy. The research hypotheses are statistically tested based on the simulation results.

INFORMATION DOMAIN Competitive variations Technical variations Customer variations Product variations Government regulation variations	High			
	Intermediate			
	Low			
		Low	Intermediate	High
		RESOURCE SCARCITY RESOURCE DOMAIN Availability of raw materials, human resources, capital Customer impact on resource availability Competitor impact on resource availability Government impact on resource Organized labor impact on resource availability		

Source : Lawrence, P.R. and D. Dyer, *Renewing American Industry*,
 The Free Press, New York, 1983, (p.6)

Figure 4.1

Analytical Framework of Environment:
 Lawrence and Dyer (1983)

Table 4.1

Environmental Factors and Clusters : A Conceptual Framework

1. Environmental Complexity Cluster (C)

- C1. Number of product lines
- C2. Number of products per product line
- C3. Variability of demand over product life cycle
- C4. Length of product life cycle
- C5. Total number of different processes in the plant
- C6. Average number of different processes required for each product
- C7. Total number of different process technologies

2. Environmental Uncertainty Cluster (U)

- U1. Percentage error in forecasting demand for each product
- U2. Percentage error of process requirement for each product
- U3. Percentage error of technology efficiency estimation

3. Environmental Tightness Cluster (T)

- T1. Average contribution margin as a proportion of average process cost
- T2. Availability of capital for product and process investment

4. Organizational Learning Cluster (L)

- L1. Learning in demand forecast
 - L2. Learning in process requirement estimation
 - L3. Learning in technology efficiency estimation
-

Table 4. 2
Profile of Three Companies

Company	A	B	C
Products	Assembly line equipment	Metal conveyor system	Laundry equipment
Major markets	Automotive & appliance manufacturers	Distribution industry	Hospitals & hotels
Annual sales	\$10-50 million	\$10-50 million	\$10-50 million
Number of employees	240	400	495
Production system	Make-to-order	Assemble-to-order	Make-to-order
Product mix	10% standard 90% special	60% standard 40% special	75% standard 25% special
Environmental uncertainty	High	Moderate	Low
Market Share	Second to leader w/ fierce competition	Leader w/ 35% share	Leader w/ 60% share
Competitive priorities	Quality & performance	Fast delivery & low price	Quality & performance

Table 4.3
Responses to the Executive Survey

	Company	
	A	B
A. Business and Manufacturing Strategy		
1. The current business strategy helps us compete effectively in the marketplace. ----	[3]	[5]
2. Manufacturing strategy is pursued with high consistency with business strategy. [3]	[3]	[3]
3. Marketing strategy is pursued with high consistency with business strategy. -----	[3]	[5]
4. Marketing and manufacturing strategies are consistent to each other. -----	[5]	[3]
5. Manufacturing strategy follows from marketing strategy. -----	[5]	[4]
6. Marketing strategy follows from manufacturing strategy. -----	[1]	[2]
B. Product Planning		
1. Product decisions are made mainly to respond to the market opportunity. -----	[3]	[5]
2. Product decisions are made mainly to exploit the manufacturing capability.-----	[3]	[1]
3. We offer more standardized product at a lower price than our competitors. -----	[3]	[4]
4. We offer more customized product at a higher price than our competitors. -----	[5]	[4]
C. Process Design		
1. Our manufacturing system is very efficient. -----	[1]	[2]
2. Our manufacturing system is very flexible. -----	[5]	[5]
3. Our manufacturing system can effectively handle the fluctuation in demand. -----	[5]	[3]
4. Our manufacturing system can effectively handle the changes in products. -----	[5]	[4]
5. We purchase automated process technology because they are more labor-efficient. [3]	[3]	[3]
6. We purchase automated process technology because they are more flexible. -----	[3]	[1]
D. Environmental Uncertainty		
1. We operate our company in a very uncertain environment. -----	[5]	[3]
2. We have particular difficulty in forecasting future demand for the existing product.[5]	[5]	[2]
3. We have particular difficulty in forecasting future demand for the new product. ---	[5]	[3]
4. There exist high level of uncertainty regarding to the process capability of our manufacturing system. -----	[1]	[1]
5. The coordination between marketing and manufacturing is crucial to cope with the environmental uncertainty. -----	[5]	[5]

*Measures: strongly disagree (1), disagree (2), neutral (3), agree (4), or strongly agree (5).

Table 4.4

Summary of Executive Survey :
Environment and Strategic Decision Making Process

Company	A	B	C
Market condition	Unstable & highly competitive	Stable & competitive	Stable & less competitive
Product technology	Fast changing	Stable	Stable
Uncertainty in demand forecast	Very high	High	Relatively low
Uncertainty in process req't	Very high	Low	Low
<hr/>			
Competition	Very fierce	High	Low
Competitive priorities	High quality & product flexibility	Fast delivery	High quality
<hr/>			
Dominance in strategy formulation	Marketing-dominated	Coordinated effort	Manufacturing-dominated

CHAPTER V

PRELIMINARY ANALYSIS OF ENVIRONMENTAL FACTORS

Chapters V and VI investigate the impact of the environment on manufacturing strategy by simulating the decision model under various environments. The effectiveness of different strategies, such as *linked* versus *unlinked* decision making and whether to emphasize *flexibility* or not, has been hypothesized to be contingent upon the manufacturing environment. The experimental study in these two chapters examines this contingency.

This chapter reports the result of a preliminary analysis on whether the clustering of environmental factors as discussed in Chapter IV is appropriate. Since there is little guidance from past studies in the manufacturing strategy field, the initial clusterings of environmental factors proposed in the last chapter need to be checked, at least in an exploratory way, before proceeding to the fuller analysis of Chapter VI. The objective here is to winnow out factors which seem less important or which do not behave in unison with the other factors in the same cluster.

For this preliminary analysis, each *individual* environmental factor is set at HIGH and LOW levels, and the simulation results from the linked and unlinked models are compared across different factor settings. By analyzing the impact of each individual environmental factor on the decision models, the initial assignment of factors to the four clusters is verified. The experimental factors which survive this preliminary analysis are then carried forward to Chapter VI for the complete experimental design.

First, Section 5.1 overviews the purposes of this preliminary study, and briefly describes the design of the sensitivity analysis. Then, Section 5.2 discusses the procedures used to implement the environmental factors within the context of the proposed model. Section 5.3 presents the result of a preliminary study, and discusses the findings. Finally, Section 5.4 describes how the results from this preliminary test are reflected in the complete experimental study in Chapter VI.

5.1 PRELIMINARY STUDY OVERVIEW

This section discusses the purpose of the preliminary analysis. It emphasizes the need for this preliminary step, and explains the basic rationale for selecting the particular method chosen. Also, the design of the preliminary experiment is briefly presented.

5.1.1 Purpose of Preliminary Analysis

The main thrust of this dissertation research is to evaluate the environmental impact on the effectiveness of manufacturing strategy. It was suggested earlier that, to investigate the environmental impact rigorously and comprehensively, various individual factors should be grouped into four environmental clusters – complexity, uncertainty, tightness, and organizational learning. (See Table 5.1 for the summary of clusters and factors in each cluster.)

These clusters are at most hypothetical. It is not clear at this point whether each *factor* (for example, total number of different processes) contributes to the respective environmental *cluster* (for example, environmental complexity) as proposed. Also, it is not known yet whether a factor in a particular cluster would behave in unison with others in the same cluster. For example, the HIGH level of the particular factor *total number of different*

processes may not affect the decision model in the same direction as the HIGH level of the factor *length of life cycle*, which is assigned to the same *environmental complexity* cluster.

Many studies in other fields of operations management, such as production planning and control, use a preliminary analysis to validate their experiments. Krajewski et al. (1987) is one example that uses a preliminary study to define the clusters of environmental factors. They simulated different production planning and control systems under different setting of several *individual factors* (such as scrap rate, equipment failure, worker flexibility, and systematic capacity imbalances), then combined them into a *cluster* (such as process characteristics). The authors imply that, by applying this preliminary analysis, the complex nature of environmental impact can be better understood.

The objectives of this preliminary study are twofold. *First*, it attempts to find any factors or clusters which are unimportant for the experimental study. Excluding unimportant factors improves the efficiency of the experimental study. The decision model, which is solved repeatedly in every decision period, is a mixed integer linear program (MILP), and each decision problem requires considerable computing time to solve. Simulating the decision model over several periods thus requires a significantly large amount of data processing and computing time. Special care must be exercised in order to control the efficiency of the experiment.

Second, this preliminary study attempts to check, at least in the exploratory level, whether all the factors in one cluster are controlled to affect the decision model *in the same direction*. It assures that, when a cluster is set at the HIGH level (for example high *complexity*), all the individual factors in that cluster (such as *total number of processes* and *length of life cycle*) are set such that they increase the environmental complexity. If individual factors in a cluster are not synchronized, the result from the experimental study using the cluster concept can be misleading.

Based on this preliminary analysis, some individual factors may have to be excluded from the experimental design for the fuller analysis in Chapter VI. Only the factors that survive this winnow-out procedure will be carried forward to the complete experimental research. The goal of this preliminary analysis is, therefore, not to draw any conclusion, but to *explore* the behavior of the model and to *sharpen* the factor settings. Any conclusions will come out from the more complete experimental study conducted in Chapter VI.

5.1.2 Design of Preliminary Experiment

For each of the fifteen experimental factors suggested in Chapter IV (also see Table 5.1 for the summary), HIGH and LOW levels are selected with guidance from the field study. A *base case* is created for the environment where all factors are set at the LOW level. Then a total of fifteen different decision environments are generated, each of which has one particular factor set at the HIGH level. Table 5.2 shows the factor settings for the total 16 runs. Exceptions for this setting are the runs from 11 to 13, where the organizational learning factors are tested. When each of these learning factors is set at the HIGH level, the corresponding uncertainty factor is also set at the HIGH level to examine the impact of learning more clearly. The performance of the decision model under each environment setting is then compared with the base case to examine the impact of the particular factor.

For each environment, the *linked* model (IN) and *unlinked* model (PP) are simulated over 25 periods. The results of the first five periods are excluded from analysis in order to assure that the steady state is reached. Since the decision model is simulated at time *zero* without any product or technologies acquired, the model needs some *warm-up* periods (Kleijnen 1987). For all the runs, five periods seemed enough to reach the steady state. The performances of the two decision models over the next twenty periods are then

compared. The results are examined to see whether each factor contributes to *the difference between the two models* as suggested by the hypotheses presented in Chapter IV.

The performance of each decision model is measured by the *average net cash flow* over the twenty periods. At each decision period, the *cash inflow* is determined by multiplying the unit contribution margin ($p_{it} - m_{it}$ in Chapter III) by the realized demand volume. Then the *cash outflow* is determined as the sum of the product development investment, cost of technology acquisition (minus the salvage value of disposed technology), fixed cost of maintaining each process technology, variable cost of operating each process technology, and overtime penalty cost resulting from capacity shortage. The difference between cash inflow and outflow is the *net cash flow* of the particular decision period. The average net cash flow is then determined over the experimental period.

The results from the two models are then compared to find the ratio PP/IN , where the ratio PP/IN is defined as:

$$PP/IN = (\text{Average net cash flow of model PP}) / (\text{Average net cash flow of model IN})$$

This ratio from the base case is compared with the ratio from each of the fifteen different cases. As discussed in Chapter IV, the ratio PP/IN is expected to be less than 1 from the logical viewpoint. Particularly under the condition of perfect forecasts, the linked model should always outperform the unlinked model. The main concern in this preliminary analysis is, therefore, how the ratio PP/IN changes depending on the environmental setting.

The HIGH and LOW levels for each factor are set such that the experimental environment approximates what was found from the field study. However, necessary adjustments and assumptions were unavoidable due to the structure of the model and the computing capability. Table 5.3 summarizes the levels of each factor, along with the mechanism used to implement them. The next section explains this factor setting in more detail.

5.2 IMPLEMENTATION OF ENVIRONMENTAL FACTORS

The experiment brings in the environmental factors following a two-phase approach. First, a *global* environment is formulated that will remain the same throughout the simulation period. This data set contains the parameters that remain unchanged for the entire experimental period, regardless of the decisions made at each period. Then, at each period of decision making, a *local* environment is formed only for the planning-horizon periods included in the decision model. This local data set is limited to the current decision session, and is affected by the past decision. The parameters for the decision model are determined based on this local environment. Figure 5.1 describes this two-phase approach briefly.

Different decision models (such as the *linked* or the *unlinked* model, or the decision model with or without *flexibility* constraints) are simulated over the *same* global environment. However, since different models make different decisions (for example, the linked model may decide to introduce a particular product in a particular period, while the unlinked model decides not to), the local environment for each decision model at a particular period is also different. The following two sections describe the procedures used to formulate the global and local environments, showing how the environmental factors are reflected in the decision models.

5.2.1 Global Environment Formation

Complexity and *tightness* are the experimental clusters that form the global environment, under which different decision models are simulated over the *entire number of periods*. The global environment is determined based on the level of *complexity* and

tightness factors. Once determined, this global environment remains unchanged regardless the level of *uncertainty* and *learning* factors.

When a decision model is simulated, a section of the global environment (covering the planning-horizon period of the decision model) is taken out by the simulation model, and the parameters are updated to form the local environment on the basis of the decisions made in the previous periods. Therefore, for each of the parameters in the decision model, a corresponding global parameter is formed. For example, for the forecasted demand in the decision model d_{imt} , a global demand GD_{it} is formulated. Then at the decision period t' , the simulation model takes the portion of GD_{it} corresponding to the period $t = t', t'+1, t'+2, \dots, T$, and makes necessary adjustment based on the previous period's ($t'-1$) status (such as early or late entry to the market) to generate d_{imt} . Table 5.4 summarizes the linkages among all the global and local parameters.

Figure 5.2 describes how the global environment is generated. It is represented by the following matrices:

- a. Global demand matrix
- b. Global process requirement matrix
- c. Global technology efficiency matrix
- d. Global technology costs matrices
- e. Global contribution margin matrix

Each of these global matrices is explained further.

5.2.1.1 Global demand matrix : GD_{it}

The global *demand* is determined based on the factors in the *complexity* cluster. The number of product lines defines the *size* of the matrix, as does the number of products in each product line. The other two factors in the complexity cluster, namely the length of the product life cycle and the cyclical variability of demand over the product's life cycle,

determine the *content* of the matrix. A larger matrix with more products represents a more complex environment, as does more variation in its elements.

The global demand matrix consists of the stream of demand for product i in period t , GD_{it} . It is generated following four steps. First, a zero-one vector for each product is randomly generated for each period based on the factor *length of life cycle*. This vector represents whether a particular product i exists in the market in a particular period t . Second, the average demand for each product is generated from a uniform distribution of between 100 and 1000 units. Third, the demand for each period during its life cycle is then determined based on the factor *cyclical variability of demand*. When this factor is set at the HIGH level, the demand of a product fluctuates largely over its life cycle, starting at a very low demand during the introduction phase and peaking to a very large demand during the maturity phase (see Table 5.3 for the detailed information). Finally, the resulting demand for each period is multiplied by a random number from a uniform distribution between 0.8 to 1.2 so as to provide randomness to the experiment. At each decision period when the local environment is formulated, this global demand GD_{it} is converted into d_{imt} , which is the input parameter for the decision model.

5.2.1.2 Global process requirement matrix : GR_{ij}

The global *process requirement* matrix is formulated based on the factors in the *complexity* cluster. As the *total number of different processes* in the plant becomes larger, the similarity in process requirements between products decreases, thus implying higher environmental complexity. Also as a larger *number of different processes* are needed for *each product*, the complexity increases.

This setting is different from the conjectures by Van Dierdonck and Miller (1980), who view the environment for production planning and control to be more complex when more processes are shared by different products. The rationale for reversing the setting

here is that this study covers design issues rather than the short-term infrastructure issues of Van Dierdonck and Miller. When a firm covers a wide variety of processes, implying less similarity among products, its decisions regarding product and technology would seem to be more complex.

The global process requirement for each product is generated following three steps. First, a zero-one vector is created for each product i to represent whether a particular process j is required or not. The number of ones in the vector is controlled by the factor *number of processes per product*. Second, the average number of hours that is required for each product is determined from a uniform distribution between 3.0 and 5.0, and it is multiplied by the zero-one vector. Finally, the result is multiplied by a random number from a uniform distribution between 0.8 and 1.2 to provide randomness to the experiment.

For the higher quality products in each product line, additional processes are added and processing time requirements are increased. Similarly for the lower quality products, some processes are dropped and processing time is decreased. When the local environment is formulated at each decision period, this global requirement GR_{ij} is converted into r_{ij} based on the *uncertainty* and *learning* factors.

5.2.1.3 Global technology efficiency matrix : GS_{kj}

The *technology efficiency* s_{kj} in the decision model represents the efficiency of process technology k in performing process j . A value of s_{kj} close to 1 means that the technology k can handle the process j very efficiently. Several *classes* of technologies are presented to the decision model, ranging from a specialized technology to a general-purpose technology. For each technology class, both conventional and automated technologies are offered to the decision model. Two of the *complexity* factors affect the global efficiency matrix: 1) the total number of processes included in the model, and 2) the total number of different process technologies available.

The global technology efficiency matrix is generated following two steps. *First*, a zero-one vector is generated for each technology k , representing whether a process j can be performed by the technology. The number of different processes that can be performed by a technology varies from one to one-half of the total number of processes. For each technology which can perform only one process, each different process is assigned to be eligible. For a technology that can perform more than one process, different processes are randomly picked and designated as *performable* by the technology. *Second*, the average efficiency of the technology is multiplied by the zero-one vector. The average efficiency of a particular technology is determined depending on the number of processes it can perform. As the technology can perform more processes (i.e. for a more general-purpose technology), its average efficiency is reduced accordingly, suggesting the trade-off between the efficiency and scope of process technology (Krajewski and Ritzman 1987). In the experiment, for each additional process added, the average process efficiency is reduced by 10% on average, reflecting the executive survey results.

For each class of technology that can perform the same number of processes, two different technologies are offered in the model: conventional and automated. On the average, the automated technology is set to be twice more efficient than the conventional counterpart. As a result, the conventional technologies have efficiencies ranging from 0.4 to 0.6, while the automated technologies have GS_{kj} values ranging from 0.6 to 1.0. These ranges match reasonably close to the data collected by the field study. Later in the local environment formation phase, this GS_{kj} is converted to s_{kj} by reflecting the *uncertainty* in efficiency estimation and the organizational *learning* effect.

5.2.1.4 Global technology costs matrices: GA_{kt} , GF_{kt} , GU_{kt} , GB_{kt}

The acquisition cost (GA_{kt}), fixed cost (GF_{kt}), variable costs (GU_{kt}), and salvage value (GB_{kt}) of each process technology k in period t are generated based on the average

figures from the executive survey data. It was found that these cost factors are closely related with the efficiency and scope of the technology.

Reflecting the survey results, the acquisition cost of an automated technology is set, on the average, as three times higher than the cost of a conventional one. Also, a flexible automated technology that can perform multiple processes has, on the average, two times higher acquisition cost than a specialized automation technology. The acquisition cost matrix also provides information regarding the time when a new technology becomes available. When a particular technology k is not developed yet, the acquisition cost is set at a very large number. Also, as suggested by the literature (Monahan and Smunt 1989; Roth 1986), the acquisition cost for flexible automation technology is set to decrease as time proceeds and the technology develops further.

Fixed cost is assumed to be proportional to the acquisition cost of the technology. Thus fixed cost was set at 20% of acquisition cost, implying a *pay-back period* of five periods. Variable cost depends on the scope of processes to be performed and the degree of automation. The more processes the technology performs, the higher the variable cost. The literature in process design (Hayes and Wheelwright 1984) suggests that general-purpose equipment tends to require more skilled labor, thus resulting in a higher variable cost. Also, an automated technology has lower variable cost than a conventional technology, as suggested by the literature (Groover 1984).

Salvage value of a particular technology is assumed to be proportional to its acquisition cost. Guided by the executive survey, more specialized technology is set to have a lower salvage value (on the average, 30% of the acquisition cost) than does a more general-purpose one (on the average, 60%). Also, the automated technology is set to have a lower (about two-thirds) salvage value than does a conventional one. The decision model presented in Chapter III assumes that the salvage value of a process technology is not

explicitly the function of its age, but it is assumed to depend on the market price of the technology at a particular time.

5.2.1.5 Global contribution margin matrix : GC_{it}

The *contribution margin* for each product depends on the degree of competition in the market. This factor is included in the *tightness* cluster. The factor is set such that a highly competitive environment translates into a smaller contribution margin.

The global contribution margin of each product is generated following three steps. *First*, for each product, average fixed and variable cost are estimated using the process requirement information and the overall average technology cost. *Second*, the average cost estimate is multiplied by a *markup rate* to generate an overall average margin of the product. For the HIGH level of tightness, a smaller markup rate, two, is used, while for the LOW level of tightness, the margin ratio is three. *Finally*, the contribution margin is adjusted as the product goes through its life cycle. It starts at a low level during the introduction stage, increases during the growth stage, and then decreases during the maturity and decline stages (Wasson 1978).

5.2.2 Local Environment Formation

The global environment formulated above provides a general structure for the simulation over the entire length of the experiment. At each period t , the simulation model picks up a part of the global environment, and makes necessary adjustments to form a local environment for the next few periods to be covered by the planning horizon. Some of the parameters (such as demand level) are determined depending upon prior decisions, and the errors in estimating parameters are reflected in this phase. The additional factor clusters that affect this local environment formation thus include *uncertainty*, *learning*, and *tightness*. Figure 5.3 describes this phase of local environment generation.

The following matrices are determined and fed into the decision model:

- a. *Forecasted* demand for different product strategies in the next planning horizon
- b. *Forecasted* technology efficiency
- c. *Forecasted* process requirements
- d. Available capital for the next planning horizon

The detailed procedures to select these local parameters are now described.

5.2.2.1 Forecasted demand : d_{it}

The forecasted demand for each product is calculated based on the global level of demand (GD_{it}) and the degree of forecast error. At each decision period, the portion of the global demand matrix covering the next planning horizon is picked up by the simulation model. Then, the demand is forecasted with error. The magnitude of the error is determined based on three factors: 1) the level of uncertainty, 2) the degree of organizational learning in demand forecasting, and 3) the number of periods during which the particular product is offered to the market, which is a function of prior product decision. In general, the global demand is adjusted in period t by the following equation:

$$d_{it} = GD_{it} \cdot (1 + DERR_t \cdot (1 - DLER_{it})) \quad (5.1)$$

where GD_{it} = Global demand level for product i in period t

$DERR_t$ = Demand forecast error in period t

$DLER_{it}$ = Learning in demand forecast for product i in period t

Reflecting the executive survey result, the demand forecast error, $DERR_t$, is generated from a uniform distribution between +0.2 and -0.2 for a highly uncertain environment. For the case of low uncertainty, it varies between +0.05 and -0.05. Equation (5.1) also implies that the forecast error decreases (by the effect of $DLER_{it}$) as the firm gains more experience with the product. As shown in Table 5.3, $DLER_{it}$ is a linearly

increasing function of the age of the product, and the slope of the function is twice as steep with the HIGH learning factor level as the one with the LOW learning level.

Once the forecast error is reflected, the demand for an alternative *introduction strategy* m is generated. First, all possible product strategies (such as early entry, early exit, or late entry) are generated for each product, considering the prior periods' decisions. When a product is introduced late into the market, some portion of market share is assumed to be lost, thus resulting in the lower demand level. Reflecting the literature from the marketing area (Urban et al. 1986), the loss of market share due to late entry is set at 30% on the average. Thus, the demand level for each product is adjusted according to the timing of its market entry at each decision period. As a result, the forecasted demand for product i in period t for the strategy m , d_{imt} , is generated and fed into the decision model.

5.2.2.2 Forecasted process requirement : r_{ij}

At each decision period, the simulation model adjusts the global process requirement, GR_{ij} , on the basis of three factors: 1) the level of uncertainty, 2) the degree of learning, and 3) the number of periods during which the product is manufactured by the firm. Similar to the demand forecasting procedure, the forecasted requirement for process j per unit product i , r_{ij} , is generated as follows:

$$r_{ij} = GR_{ij} \cdot (1 + RERR_t \cdot (1 - RLER_{it})) \quad (5.2)$$

where GR_{ij} = Global process requirement for process j for product i

$RERR_t$ = Requirement estimation error in period t

$RLER_{it}$ = Learning in requirement estimation for product i in period t

On the basis of the field study data, the estimation error, $RERR_t$, is chosen randomly from a uniform distribution between +0.2 and -0.2 for the high uncertainty case. The range is reduced to +0.05 and -0.05 for the low uncertainty case. As the firm gains experience in producing a product, its capability of estimating process requirements

improves, thus making the forecasted value r_{ij} closer to the actual value GR_{ij} . The decrease in the estimation error is reflected through $RLER_{it}$, which is a linearly increasing function of the product's age. (See Table 5.3 for the detailed form of the function.) For the fast-learning environment, $RLER_{it}$ increases twice as fast as the slow-learning environment.

5.2.2.3 Forecasted technology efficiency : s_{kj}

The global technology efficiency, GS_{kj} , is also converted into s_{kj} , based on three factors: 1) the level of uncertainty, 2) the degree of learning, and 3) the number of periods during which the firm owns the technology. At each decision period, the global efficiency matrix is adjusted as follows:

$$s_{kj} = GS_{kj} \cdot (1 + SERR_t \cdot SLER_{kt}) \quad (5.3)$$

where GS_{kj} = Global efficiency of technology k in performing process j

$SERR_t$ = Efficiency estimation error in period t

$SLER_{kt}$ = Learning in efficiency estimation for technology k in period t ,

that is a decreasing function of time.

On the basis of the executive survey, the value of $SERR_t$ is randomly picked from a uniform distribution whose range is shown in Table 5.3. In general, the error is higher for a new type of technology (such as flexible automation) than a conventional technology. Also, as the firm accumulates experience in using a particular technology, the errors in estimation decrease. Thus, the value of $SLER_{kt}$ decreases over time from the initial acquisition of the particular technology. As shown in Table 5.3, the definition of $SLER_{kt}$ is similar to the traditional learning curve, except that the number of periods replaces the cumulative volume. For the faster learning environment, $SLER_{kt}$ is defined as an 80% learning curve, while the slower learning case uses a 90% learning curve.

5.2.2.4 Available capital for product and process investment : KT_t , KP_t , KR_t

The available capital for investment is generated on the basis of two factors: 1) the level of tightness, and 2) the performance of the model during the last period. In a tighter environment, the availability of capital is low, thus creating a more difficult decision situation for a firm. Also, when a firm earns a large profit in the previous period, it is assumed that the firm can invest more capital on its product and process development. The total available capital in period t , KT_t , is determined as follows:

$$KT_t = K_b + K_r \cdot \text{NETCASH}_{t-1} \quad (5.4)$$

where K_b = Base capital granted,

K_r = proportion of last period's net cash flow to be invested in t

NETCASH_{t-1} = net cash flow in period $t-1$.

For the low tightness case, K_b was set at \$10 million. This is a large amount which exceeds the total investment in all the experimental periods. Therefore, this represents the case when there is no limit on capital availability. For the high tightness case, K_b was set at \$1 million. According to the preliminary runs, this corresponds to the average level of investment. Since the investment amount varies widely, setting the investment limit around the average represents a very severe limitation on the investment decision. On the basis of the survey result, K_r is set at 0.4. This suggests that 40% of net cash flow can be invested for product development and technology acquisition.

Inclusion of the base capital K_b is necessary to allow for investment following the periods of zero cash flow. This could arise because, during some periods, the global demand matrix may not provide any product opportunity to the decision model due to randomness. That is, if the base capital is not provided, throughout the periods after this no-demand period, the model cannot generate any cash flow and cannot invest any capital on either product development or technology acquisition.

For the unlinked model (PP), the total available capital KT_t is divided into product investment capital KP_t and process investment capital KR_t . During the preliminary runs, it was observed that the average investment in product development was almost the same as the average investment for technology acquisition. Thus, as an approximation, the total capital KT_t was evenly divided into KP_t and KR_t .

5.3 RESULT OF PRELIMINARY ANALYSIS

The results of this preliminary experimentation are summarized in Table 5.5 and Figure 5.4. As shown in Table 5.5, the linked model IN always outperforms the unlinked model PP. However, the degree of difference between IN and PP (measured by the ratio PP/IN) differs among the environments. The preliminary analysis focuses on the direction of changes in the PP/IN ratio caused by the HIGH setting of each environmental factor. In the following sections, differences in this ratio are examined to investigate whether the clusterings of individual factors, as suggested in Chapter IV, are appropriate. The results set the stage for the complete experimental study in Chapter VI.

5.3.1 Sensitivity of PP/IN to Complexity Factors

The first seven runs (runs 1 to 7) are generated by setting *one* factor in the complexity cluster at the HIGH level. The relative performance of models IN and PP is graphically summarized in Figure 5.5. When a factor in the complexity cluster is set at the HIGH level, the ratio PP/IN is *smaller* than it is for the base case, in all cases but one.

Except for one case (the total number of processes in the model), all the factors in the original complexity cluster seem to affect the relative performance of the linked and unlinked models in the same direction. It suggests that the hypothesized effects of each

factor in this complexity cluster are similar. Thus they can be grouped into one factor – the *complexity cluster* – without any cancelling-out effects.

The only exception was run number 5, in which the total number of processes is set at the HIGH level. The result shows that, when more processes are involved in the decision environment, the ratio PP/IN increases from the base case. The difference between the unlinked model PP and the linked model IN becomes smaller when the total number of processes is increased. This result is opposite from the expectation suggested earlier when the complexity cluster was originally formed.

Two explanations are possible for this unexpected result. *First*, it may suggest that, when the total number of processes increases, the complexity of the decision problem actually becomes *smaller*, not larger, because the interrelationships among different products (centered around the common process) are reduced. This explanation suggests that the earlier conjecture could be in the wrong direction. In Chapter IV, it was hypothesized that when more processes are involved in the decision problem, the problem *size* increases, thus making the linkage between the two decisions more critical. Thus this contradictory result may imply that the complexity of the decision problem comes not from the mere size, but from the nature of interrelationships between decision components. The *second* explanation for the result can be the randomness of the sample. The total number of processes may not affect the model's performance significantly. Or the sampled values may not accurately depict the relationships between the total number of processes and the model's performance.

In order to explore the real reason, another set of runs was conducted. In this set, the number of processes in the model was set at 7 (between the HIGH setting of 8 processes and the LOW setting of 6 processes). The result of this extra run is summarized in Table 5.6 and Figure 5.6. As shown, the changes in PP/IN are not consistent over the three levels. The ratio PP/IN for the extra run (with 7 processes) was 0.9804. This is

higher than both 0.9688 (with 6 processes) and 0.9759 (with 8 processes). Therefore, the *first* explanation is not supported. Thus, the *randomness* explanation appears to be more appropriate in explaining this phenomenon. Accordingly, the factor *total number of processes* is not used as part of the experimental design in forming the complexity cluster.

This section observed the impact of individual factors in the original complexity cluster. The result, except for one factor, was consistent with the expectation. Therefore, when the complexity cluster is set at the HIGH level in Chapter VI, all the individual factors in the group will be set at the HIGH level as shown in Table 5.3. The factor *total number of processes* will not be included in the experimental design, but will be fixed at 6 processes.

5.3.2 Sensitivity of PP/IN to Uncertainty Factors

The next three runs (runs 8 to 10) are related to the factors in the uncertainty cluster. The results are summarized in Figure 5.7 graphically. It shows that as the factors in the uncertainty cluster are set at the HIGH level, the ratio PP/IN increases from the base case, again with one exception. In other words, as the uncertainties in estimating various parameters in the decision model increase, the difference between the linked model IN and unlinked model PP becomes smaller. The *same direction of changes* supports the original clustering of individual factors.

One exception occurs in the run number 9 where the uncertainty in process requirements is set at the HIGH level. The ratio PP/IN decreases from the base case, suggesting a larger difference between the two models. The exact reason for this unexpected result is not understood. However, the following explanation is speculated. In the unlinked decision model (PP), the process requirement parameters (r_{ij}) affects the product decision as well as the process decision. In model PP, the contribution margin for a product is approximated based on its process requirement (see equation 3.13 in Chapter

III). The incorrect estimation of process requirement in the model PP may cause a large error in estimating the profitability of a product, leading to much poorer product decisions than in the linked decision model IN, where no such approximation is necessary. This speculation, though, could not be verified. Accordingly, the factor *uncertainty in estimating process requirement* is excluded from the experimental design in forming the uncertainty cluster.

As observed above, the HIGH settings of two other uncertainty factors (demand uncertainty and technology efficiency uncertainty) affect the ratio PP/IN in the same direction. Thus in the experimental study of Chapter VI, when the uncertainty cluster is set at the HIGH level, the uncertainties in demand and technology efficiency estimation will be set at the HIGH level. The factor *uncertainty in process requirement* will be *fixed* in the experimental study.

5.3.3 Sensitivity of PP/IN to Learning Factors

The concept of learning in this experimental study is defined as the firm's capability to reduce the uncertainty in parameter estimation. In order to examine the impact of learning more clearly, when the learning factors are set at the HIGH level, the corresponding uncertainty factors were also set HIGH. Thus the results of runs 11 to 13 are compared with runs 8 to 10 respectively, not against the base case.

As shown in Figure 5.7, the results from runs 11 to 13 are almost identical to the runs 8 to 10, except the case involving the efficiency estimation. However, even for this case, the difference between runs 10 and 13 is almost negligible. It appears that the degree of learning, as implied by better estimation of parameters, hardly affects the decisions. One possible reason is that, since the decision model uses the *discounted* values of the parameters, the reduction in forecast errors for the future events may not seriously affect the current decision making. Thus the HIGH and LOW learning cases result in similar

decisions. A second reason could be attributed to the difference between the HIGH and LOW settings. The difference may not be large enough to generate different consequences.

Because the cause of this insignificant result is not identified, the experimental study in the following chapter will not include these learning factors. All the learning factors will be fixed at the LOW level, and the organizational learning cluster will be excluded from the environmental context.

5.3.4 Sensitivity of PP/IN to Tightness Factors

Runs 14 and 15 involve the tightness factors. As shown in Figure 5.8, these runs generate the most significant difference from the base case. When the contribution margin is set at the lower level (thus the tightness in contribution is HIGH in the run number 14), the relative performance of the unlinked model PP is much worse than the linked model IN. The difference in the ratio PP/IN is much more significant than other cases. It suggests that the decision model might be highly sensitive to the objective function coefficient.

Run number 15, in which the available capital for investment is limited to a smaller amount, shows the most significant difference between models IN and PP. When the available capital is severely limited, the integration of the product and process decisions seems to be much more critical to the firm. The linked model appeared to perform considerably better than the unlinked model.

One possible explanation for this large difference could be the arbitrary allocation of total capital into the two groups, that is forced in the unlinked model PP. In the model PP, the total capital is evenly allocated to product development and technology acquisition each decision period. (As described in Section 5.2, this allocation was determined on the basis of the average capital investment actually observed from the decisions made by the linked model.) However, in some periods more capital could be required for product development (or technology acquisition), while in other periods the requirement may be

evenly distributed. The periodic imbalance between these two investments might have caused the unlinked decision to result in a poor performance. This arbitrary allocation of the total capital *unfairly* forces the unlinked model to perform worse than the integrated model. This decrease in performance appears to be not because of its inherent inferiority but because of the ill-designed outside control.

The proposed mechanism to reflect the tightness of investment capital seems to be inappropriate. Thus, the experimental analysis of the next chapter will exclude this tightness factor of capital availability. The environmental tightness cluster is represented by the factor *tightness of contribution margin*.

5.4 CONCLUSION

In this chapter, a preliminary analysis was conducted to reinforce the original factor clusterings proposed in Chapter IV. The purpose of this chapter was *not* to draw any conclusion, *but* to check the soundness of the environmental clusterings. The main interests of this chapter center on whether an individual factor in one cluster, set at the HIGH and LOW levels, affects the performance of the decision model in unison with the other factors in the same cluster. If they do not affect the model in the same decision, including them into one cluster can cause the effects of individual factors to be cancelled out. Thus, the main objective of this preliminary analysis was to winnow out those factors that are not important, or that do not affect the decision model in unison with other factors.

The results presented in Section 5.3 show that most of the individual factors affect the decision model as suggested in Chapter IV. Two factors generated contradictory results, and possible reasons were presented. These factors will be excluded in the following experimental research. A future study may concentrate on the impact of the

individual factors rather than on *clusters* of factors. The interactions between factors within the same cluster may explain other important phenomena in manufacturing strategy.

However, this dissertation examines the impact of the environmental *clusters* rather than the individual factors. The factors that survived this preliminary analysis are carried forward to the complete experimental research in Chapter VI. Thus the experimental design in the next chapter includes three environmental clusters: complexity, uncertainty, and tightness. The individual factors, which will be included in each cluster, are summarized in Table 5.7.

Figure 5.1

Two-Phase Approach in Creating Environments

Figure 5.2

Global Environment Formation

Figure 5.3

Local Environment Formation

* For the definition of run number, see Table 5.2.

Figure 5.4

Ratio of Net Cash between Model IN and PP

* For the definition of run numbers, see Table 5.2.

Figure 5.5

Ratio of Net Cash between Model IN and PP :
Cases for High Complexity

Figure 5.6

Ratio of Net Cash between Model IN and PP:
Cases for Different Number of Processes

* For the definition of run numbers, see Table 5.2.

Figure 5.7

Ratio of Net Cash between Model IN and PP :
Cases for High Uncertainty and Learning

* For the definition of run numbers, see Table 5.2.

Figure 5.8
Ratio of Net Cash between Model IN and PP :
Cases for High Tightness

Table 5.1
Environmental Factors and Clusters : A Summary

1. Factors to define Environmental Complexity (C)

- C1. Number of product lines in global demand matrix
- C2. Number of products per product line in global demand matrix
- C3. Variability of demand over product life cycle
- C4. Length of product life cycle
- C5. Total number of different processes in global process matrix
- C6. Average number of different processes required for each product
- C7. Total number of different process technologies

2. Factors to define Environmental Uncertainty (U)

- U1. Percentage error in forecasting demand for each product
- U2. Percentage error of process requirement for each product
- U3. Percentage error of technology efficiency estimation

3. Factors to define Environmental Tightness (T)

- T1. Average contribution margin as a proportion of average process cost
- T2. Availability of capital for product and process investment

4. Factors to define Organizational Learning (L)

- L1. Learning in demand forecast
 - L2. Learning in process requirement estimation
 - L3. Learning in technology efficiency estimation
-

Table 5.2
Factor Setting for Preliminary Analysis

Cluster	Factor*	Run Number (Factor Level)**															
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Complexity	C1	L	H	L	L	L	L	L	L	L	L	L	L	L	L	L	L
	C2	L	L	H	L	L	L	L	L	L	L	L	L	L	L	L	L
	C3	L	L	L	H	L	L	L	L	L	L	L	L	L	L	L	L
	C4	L	L	L	L	H	L	L	L	L	L	L	L	L	L	L	L
	C5	L	L	L	L	L	H	L	L	L	L	L	L	L	L	L	L
	C6	L	L	L	L	L	L	H	L	L	L	L	L	L	L	L	L
	C7	L	L	L	L	L	L	L	H	L	L	L	L	L	L	L	L
Uncertainty	U1	L	L	L	L	L	L	L	L	H	L	L	H	L	L	L	L
	U2	L	L	L	L	L	L	L	L	L	H	L	L	H	L	L	L
	U3	L	L	L	L	L	L	L	L	L	L	H	L	L	H	L	L
Learning	L1	L	L	L	L	L	L	L	L	L	L	L	H	L	L	L	L
	L2	L	L	L	L	L	L	L	L	L	L	L	L	H	L	L	L
	L3	L	L	L	L	L	L	L	L	L	L	L	L	L	H	L	L
Tightness	T1	L	L	L	L	L	L	L	L	L	L	L	L	L	L	H	L
	T2	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	H

* See Table 5.1 for the definition of factors.

** H stands for HIGH level and L stands for LOW level of the factor.

Table 5.3
Preliminary Experiment : Individual Factor Settings

1. Factors to define *Environmental Complexity*

a. Number of product lines in global demand matrix

High : 10 product lines
Low : 5 product lines

b. Number of products per product line in global demand matrix

High : 5 products
(one standard, two high quality products, two low quality products)
Low : 3 products
(one standard, one high quality product, one low quality product)

c. Total number of different processes in global process matrix

High : 8 processes
Low : 6 processes

d. Average number of different processes required for each product

High : average 60% of all processes
Low : average 40% of all processes

f. Length of product life cycle

High : ranging 2 to 4 periods (average 3 periods)
Low : ranging 4 to 6 periods (average 5 periods)

g. Variability of demand over product life cycle

High : ranging 20% to 180% of average demand
Low : ranging 60% to 140% of average demand

h. Total number of different process technologies

High : increasing number of technologies for more general-purpose type
Low : same number of technologies for all types

Table 5.3 (Continued)

2. Factors to define *Environmental Uncertainty*

a. Percentage error in forecasting demand for each product

- High : uniformly distributed between +0.2 and -0.2
 Low : uniformly distributed between +0.05 and -0.05

b. Percentage error of process requirement for each product

- High : uniformly distributed between +0.2 and -0.2
 Low : uniformly distributed between +0.05 and -0.05

c. Percentage error of technology efficiency estimation

- High : for conventional technologies,
 uniformly distributed between +0.1 and -0.1
 for new technologies,
 uniformly distributed between +0.4 and -0.4
 Low : for conventional technologies,
 uniformly distributed between +0.05 and -0.05
 for new technologies,
 uniformly distributed between +0.2 and -0.2

3. Factors to define *Environmental Tightness*

a. Average contribution margin

- High : average margin equals two times the estimated fixed and variable costs
 Low : average margin equals three times the estimated fixed and variable costs

b. Availability of capital for product and process investment

- High : $K_b = 1,000,000$, $K_r = 0.4$ (limited capital)
 Low : $K_b = 10,000,000$, $K_r = 0.6$ (unlimited capital)
-

Table 5.3 (Continued)

4. Factors to define *Organizational Learning*

a. Learning in demand forecast

$$\begin{aligned} \text{High} &: \text{DLER}_{it} = \text{AGE}_{it} / \text{LIFE}_i \\ \text{Low} &: \text{DLER}_{it} = \text{AGE}_{it} / (2 \cdot \text{LIFE}_i) \end{aligned}$$

* AGE_{it} represents the number of periods since the introduction of the product i and LIFE_i is average length of life-cycle of the product i .

b. Learning in process requirement estimation

$$\begin{aligned} \text{High} &: \text{RLER}_{it} = \text{AGE}_{it} / \text{LIFE}_i \\ \text{Low} &: \text{RLER}_{it} = \text{AGE}_{it} / (2 \cdot \text{LIFE}_i) \end{aligned}$$

* AGE_{it} represents the number of periods since the introduction of the product i and LIFE_i is average length of life-cycle of the product i .

c. Learning in technology efficiency estimation

$$\begin{aligned} \text{High} &: \text{SLER}_{kt} = (\text{AGE}_{kt})^{**}(\log 0.8 / \log 2) \\ \text{Low} &: \text{SLER}_{kt} = (\text{AGE}_{kt})^{**}(\log 0.9 / \log 2) \end{aligned}$$

* AGE_{kt} represents the number of periods since the initial acquisition of the technology k .

Table 5.4
Global and Local Parameters

Parameters	Global Variables	Local Variables
1. Demand	GD_{it}	d_{imt}
2. Process requirement	GR_{ij}	r_{ij}
3. Technology efficiency	GS_{kj}	s_{kj}
4. Technology costs		
a. Acquisition cost	GA_{kt}	a_{kt}
b. Fixed cost	GF_{kt}	f_{kt}
c. Variable cost	GU_{kt}	u_{kt}
d. Salvage value	GB_{kt}	b_{kt}
5. Contribution Margin	GC_{it}	c_{it}
6. Investment capital		KT_t, KP_t, KR_t

Table 5.5
Summarized Results of Preliminary Study

Run	Factor set	Average net cash flow		Ratio
No.	at HIGH level	Model IN	Model PP	PP / IN
Base Case				
0	None	535172	517434	0.9668
High Complexity Cases				
1	Number of product lines	2273417	2180610	0.9592
2	Number of products per line	481822	445622	0.9578
3	Demand variability	344740	325378	0.9438
4	Length of product life cycle	222557	190620	0.8565
5	Total number of processes	776998	758240	0.9759
6	Number of processes per product	607550	572937	0.9430
7	Number of process technologies	588765	559763	0.9507
High Uncertainty Cases				
8	Demand uncertainty	508649	494164	0.9715
9	Process requirement uncertainty	534544	512205	0.9582
10	Technology efficiency uncertainty	519707	509866	0.9810
High Learning Cases				
11	Learning in demand forecasting	508649	494164	0.9715
12	Learning in requirement estimation	534544	512205	0.9582
13	Learning in efficiency estimation	520280	514585	0.9891
High Tightness Cases				
14	Tightness of contribution margin	317946	290167	0.9126
15	Tightness in available capital	438696	255035	0.5813

Table 5.6
Sensitivity of PP/IN to Number of Processes

Number of Processes	Net Cash Flow of Model IN	Net Cash Flow of Model PP	Ratio PP/IN
6	535172	517434	0.9668
7	839115	822683	0.9804
8	776998	758240	0.9759

Table 5.7

Environmental Clusters and Factors for Final Experiments

1. Environmental Complexity Cluster (C)

- C1. Number of product lines in global demand matrix
- C2. Number of products per product line in global demand matrix
- C3. Average number of different processes required for each product
- C4. Length of product life cycle
- C5. Variability of demand over product life cycle
- C6. Total number of different process technologies

2. Environmental Uncertainty Cluster (U)

- U1. Percentage error in forecasting demand for each product
- U2. Percentage error of technology efficiency estimation

3. Environmental Tightness Cluster (T)

- T1. Average contribution margin as a proportion of average process cost
-

CHAPTER VI

LINKAGE, FLEXIBILITY AND THE ENVIRONMENT: AN EXPERIMENTAL STUDY

In Chapter IV, it was hypothesized that the effect of a strategic policy depends on environmental conditions. Based on the literature in corporate and manufacturing strategy, the decision environment was structured using the concept of environmental clusters. Also, several conjectures were proposed on how the environment affects strategy formulation. In Chapter V, decision environments for the product planning and process design decisions were fully specified. A preliminary test evaluated each individual factor, which helped crystalize the environmental clusters.

In this chapter, an experimental study is conducted on how the different decision models perform under different environments. Two focal strategic policies – linkage between product and process decisions, and emphasis on manufacturing flexibility – are examined. By examining the performance differentials, the impact of different environments on the effectiveness of each strategic policy is assessed.

Section 6.1 presents a general description of the experimental research. Sections 6.2 and 6.3 compare the performance of the *linked* and *unlinked* models, and assess how important linkage is under different decision environments. Then Sections 6.4 and 6.5 explore the strategic value of manufacturing flexibility by comparing the performance of the decision models with and without *flexibility constraints*.

6.1 EXPERIMENTAL STUDY OVERVIEW

In this section, the overall experimental study is briefly described. First, the objectives of the study along with the research hypotheses are presented. Second, the design of study is presented, including the experimental factors, their factor settings, and the performance measures.

6.1.1 Objectives of Study

The objectives of this experimental study are twofold. *First*, the effectiveness of two strategic policies is evaluated. The study examines the importance of *linkage* by comparing the performance of the linked model and the unlinked model. The strategic value of manufacturing *flexibility* is explored by comparing the performance of the decision model *with* and *without* the additional flexibility constraints. (See Chapter III for the details of each decision model.)

Second, the impact of environmental conditions on the strategic policy is studied. The above comparisons are repeated under different environmental settings. The linked model and the unlinked model, with and without flexibility constraints, are simulated under different levels of environmental *complexity*, *uncertainty*, and *tightness*. This experimental research attempts to build a contingency theory regarding *when* integrating various decisions is most critical, and *when* emphasizing manufacturing flexibility is most critical.

6.1.2 Experimental Design

This section reviews three key aspects to the design of this experiment. First, the strategic policy factors to be tested are briefly reviewed. Second, the environmental factors and their treatment levels are described. Finally, performance measures are discussed.

6.1.2.1 Strategic Policy Factors

Two dimensions of manufacturing strategies are studied in the context of product and process decisions. The first factor is the *linkage* between these two decisions. This linkage factor is considered in this study by comparing the *unlinked* model and *linked* model, as described in Chapter III. The linked model makes the product and process decisions simultaneously, thus evaluating the interrelationship between the two decisions before the final choice is made. In the unlinked model, the product decision is made first without considering its process implications, and then the process decision is made on the basis of the product requirements. Reflected in these two decision models are the notions of *reactive* versus *proactive* roles of manufacturing (Wheelwright 1984), *ends-ways-means* versus *means-ways-ends* approaches of strategy formulation (Hayes 1985), and *top-down* versus *bottom-up* approaches (Sharma 1987).

The second strategic factor is the notion of manufacturing *flexibility*. This factor is implemented in this dissertation by adding (or not adding) an additional set of constraints that force the decision model to acquire *at least* a certain level of flexible process technology. This additional constraint forces the model to trade-off efficiency for flexibility. The experimental study thus considers the concepts of *efficiency* versus *flexibility* (De Meyer et al. 1989), and *economies of scale* versus *economies of scope* (Goldhar and Jelinek 1983).

6.1.2.2 Environmental Factors

Originally in Chapter IV, four clusters of environmental characteristics were proposed: complexity, uncertainty, tightness, and learning. Several individual factors were identified for each cluster (See Table 4.1). By evaluating the sensitivity of the decision model to the high and low levels of each factor in Chapter V, it was decided to include only the factors listed in Table 5.7 for the experimental study of this chapter. The factors in the

learning cluster (see Section 5.3) did not show much impact on the performance of the decision models. Therefore, as shown in Table 6.1, the learning cluster was eliminated from subsequent study, leaving *complexity*, *uncertainty*, and *tightness* for the final experiment.

Each environmental cluster has two treatment levels, HIGH and LOW. As a result, eight different environments are created. Table 6.2 identifies the factor settings for each environment. When an environmental cluster is set at a HIGH or LOW level, all of the individual factors in that cluster are set at their HIGH or LOW levels respectively. In the preliminary study conducted in Chapter V, each individual factor was tested to synchronize them within each cluster. The HIGH and LOW levels of each factor were determined such that their impact on the relative performances of the linked and unlinked models is in unison with other factors in the same cluster. Their specific values are based on prior research and the data collected during the field study (see Chapter V).

Table 6.3 shows that the environmental *complexity* cluster is defined by five individual factors: 1) number of product lines, 2) average number of different processes required for each product, 3) length of product life cycle, 4) variability of demand over the product life cycle, and 5) total number of different process technologies. The environmental *uncertainty* cluster is defined by two factors: 1) average percentage error in forecasting demand for each product, and 2) average percentage error of technology efficiency estimation. Finally, the environmental *tightness* cluster is defined by the level of average contribution margin.

The factor *number of products per product line*, which survived the winnow-out procedure in Chapter V, is not included in Table 6.3 for the experimental study. Even though the difference in this factor considerably influenced the relative performance of the linked and unlinked models (see Table 5.5), the factor was dropped from the experiment because of computational difficulties. When the number of product lines is set at HIGH

level creating ten product lines, the MILP software SCICONIC could not handle the problem size where there were five products per each product line. Thus the factor *number of products per product line* was fixed at three products per line.

6.1.2.3 Performance Measures

The comparison between different models is made on the basis of *average net cash flow* over the experimental periods. At each decision period, the cash inflow is determined by multiplying the unit contribution margin ($p_{it} - m_{it}$ in Chapter III) by the realized demand volume. Then the cash outflow is determined as the sum of the product development investment, cost of technology acquisition (minus the salvage value of disposed technology), fixed cost of maintaining each process technology, variable cost of operating each process technology, and overtime penalty cost resulting from capacity shortage. The difference between cash inflow and outflow is the *net cash flow* of the particular decision period. The average net cash flow is then determined over the experimental period. Each model is simulated for 20 periods with the planning horizon of 5 periods. The first 5 periods are excluded from the analysis to allow a sufficient warm-up period. For the most runs, the model appeared to reach the steady state within this period. The results during the remaining 15 periods are recorded to determine the average net cash flow.

It should be noted here that the size of cash flows largely depends upon the environmental factors. For example, the environment with a HIGH level of complexity has 10 product lines while there are only 5 product lines when the complexity is set at the LOW level. Consequently, the direct comparison of net cash flow between different environmental settings is less meaningful. Instead, the comparison between environments should be made based on the performance ratio of the different decision models. First, the average net cash flow from the unlinked model (PP) is compared with the one from the linked model (IN), generating a ratio variable PP/IN. This PP/IN ratio is used to evaluate

the impact of the different environments on the importance of decision linkage. Second, the average net cash flow of a model with the additional flexibility constraint (FF) is compared to the one without it (NF), generating a ratio variable FF/NF. This FF/NF ratio is used to examine how the environment affects the strategic value of manufacturing flexibility.

6.1.3 Results

The experiment includes a total of 128 runs. Three environmental factors generate 8 different environments, and four different models (IN.NF, IN.FF, PP.NF, and PP.FF) are evaluated for each environment. These 32 runs (8x4) are repeated for 4 replications, using different random number seeds. The average net cash flows from the 128 runs are shown in Appendix B.

6.2 LINKAGE AND PERFORMANCE

The performance of the linked and unlinked models are compared here to examine whether the linked model outperforms the unlinked model. Various aspects of the decisions made by the two models are analyzed to explain the differences. Then Section 6.3 examines the environmental impact to find out when the differences are largest.

6.2.1 Overall Impact

This section analyzes the overall performance of the two decision models with the intention of explaining why the linked model outperforms the unlinked model. Table 6.4 shows the ratio between the net cash flow generated by the two models (PP/IN) for all 32 comparisons.

Two points stand out from the overall comparison. First, as expected, the linked model performs better than the unlinked model. Overall, the average net cash flow of the unlinked model is 96.5% of that of the linked model. Moreover, in 24 out of the total 32 comparisons, the linked model outperformed the unlinked model.

This result should not be surprising. The linked model makes product and process decisions simultaneously. It also considers the implication of product decisions for process requirements, and the effect of particular process choice on the product profitability, prior to making the final choice. The unlinked model, in contrast, makes the product and process decisions sequentially. When a product decision is made, its impact on the process requirements is not considered. Similarly when a process decision is made, its impact on the profitability of the future product opportunities is ignored. The unlinked model has to *approximate* the processing cost of a product on the basis of the current technology mix, while the linked model evaluates the contribution margin and cost of a product more accurately. With all these conditions, the superior performance of the linked model is not unexpected.

What might be somewhat unexpected is that the superiority of the linked model is not so large. The average difference is only 3.5%, and in 8 cases out of the total 32 comparisons, the unlinked model actually outperformed the linked model. As described in Chapter III, the unlinked model results in a suboptimal solution, while the linked model seeks an optimal solution. Therefore, the linked model might be expected to always outperform the linked model. However, two conditions make the notion of optimality less meaningful. First, the decision model solves problems with *forecasted* parameters. Due to the uncertainty, the actual parameters differ from the forecasted ones, and the solution found by the model is not necessarily optimal for the actual problem. Second, the decision model solves the problem with a limited planning horizon following a rolling schedule scheme. The solution at a decision period is optimal only within the planning horizon. As

a new period is added to the horizon and new information becomes available, the current solution may not be the optimal solution. Consequently, the *optimal* solution generated by the linked model is not always superior to the *non-optimal* solution by the unlinked model.

6.2.2 Analysis of Decisions Made by Linked and Unlinked Models

The following subsections provide some explanations for the above performance differentials by analyzing in detail the product and process decisions made by the two decision models. The analysis focuses on four aspects: 1) overall profitability, 2) product decision, 3) process decision, and 4) pattern of decisions over time.

6.2.2.1 Overall Profitability

Within the context of the decision model, overall profitability is examined using two surrogate measures: 1) a *return-on-sales* measure, and 2) a *return-on-assets* measure. First, a *return-on-sales* measure is developed by dividing the net cash flow by the total cash inflow. The total cash inflow, as explained in Section 6.1, is similar to total *sales* as a general accounting concept. The net cash flow is determined by subtracting from this total cash inflow all of the cash outflows, such as product development investments, technology acquisition costs, and fixed and variable costs. Net cash flow corresponds to net *profit* in the accounting context. Therefore, the *return on sales* can be surrogated by the ratio of the net cash flow to the total cash inflow.

Figure 6.1 compares the total cash inflow and net cash flow generated by the two models during the second replication over all the environments. In all cases, the unlinked model generated a larger total cash inflow than the linked model. However, in most cases, the net cash flow generated by the unlinked model was smaller than the one generated by the linked model. This phenomenon was consistent over all replications. As a result, the overall *return-on-sales* measure of the unlinked model was consistently lower than the

linked model. Table 6.5 shows that the average *return on sales* of the linked model is 36.9% while the one for the unlinked model is 33.7%.

Second, a *return-on-assets* measure is developed by dividing the net cash flow by the dollar value of process technology. Within the context of the decision model, a firm's assets are represented by the dollar value of process technology maintained at a particular time. Therefore, the ratio between the net cash flow and the dollar value of process technology can be a surrogate measure for the return on assets. Table 6.5 shows that the average *return on assets* is 35% for the linked model, while the unlinked model results in a lower ratio, 33.8%. This comparison, combined with the *return-on-sales* measure, demonstrates the overall superior performance of the linked model. The following two subsections further examine the product and process decisions made by the two models, and provide some explanations for the above differences.

6.2.2.2 Product Decisions

Table 6.6 shows the average proportion of products actually offered. At each period, the proportion of products that are actually *offered* is calculated, by dividing the number of products actually offered by the total number of products that *can be* offered. Table 6.6 provides the overall averages. As shown, the unlinked model consistently offered a larger proportion of total products than does the linked model.

Two aspects of the decision model can explain this higher level of product offerings by the unlinked model. First, the linked model considers the changes in the process requirement mix before it decides to introduce a new product, while the unlinked model does not. Thus the linked model tends to *control* the offerings of different products more tightly than does the unlinked model. Second, the procedure of approximating the contribution margin used in the unlinked model (see the equation 3.13) *overestimates* the contribution margin of a product. The procedure estimates the cost of a product based on

fixed and variable costs, but does not include the technology acquisition cost that might be necessary for the new product. Thus, the unlinked model tends to offer more products, some of which the linked model decides not to offer.

This observation is consistent with the conjecture raised by several manufacturing strategy researchers. Hayes and Wheelwright (1984) and Wheelwright (1984) contend that a business strategy dominated by the marketing function tends to introduce more products into the market without considering the difficult tasks imposed on the manufacturing function. The experimental study seems to support their argument.

6.2.2.3 Process Decisions

The impact of offering various products by the unlinked model can be seen from the process decision. Table 6.7 compares the technology acquisition cost and disposed salvage value between the linked and unlinked models. These costs are expressed as a proportion of the total cash inflow. As shown, the unlinked model generates *both* a larger acquisition cost *and* a larger disposed salvage value. Compared to the linked model, the unlinked model acquires and disposes of more process technologies in each period. This result implies that the technology mix changes widely when the product and process decisions are not integrated. Since the unlinked model tends to introduce a larger portion of total available products, it creates a highly unstable process requirement mix on the process decision problem. The unlinked model, therefore, has to change its process technology mix more frequently, acquiring larger amounts of new technology each period, and at the same time, disposing of larger amounts of existing technology.

This inefficiency in the process decision can be attributed to the myopic decision making of the unlinked model. As described in Chapter III, when the unlinked model makes a product decision, the future status of process technology is a blind spot. When a

process decision is made, the future product plan is a blind spot. Thus the effectiveness of the whole decision is diminished.

This observation is reinforced by examining the types of technology acquired by each decision model. Table 6.8 shows the average process flexibility generated by each decision model. The process flexibility of a technology is measured by the ratio between the number of different processes it can perform and the total number of processes in the plant (see Chapter III). Then the average process flexibility is a weighted average of all technologies maintained in each period. As shown in Table 6.8, the linked model generated a higher level of process flexibility. This result explains what types of process technologies are acquired by each decision model. The linked model considers the future changes in product mix, thus future changes in the process requirements, before it decides to acquire a particular technology. Anticipating the changes in the process requirements, the linked model seems to acquire more general-purpose equipment. In contrast, the unlinked model does not consider the future product plan, and attempts to minimize the short-term cost. Thus the unlinked model tends to acquire more special-purpose equipment that can perform the given process requirements efficiently.

This comparison in process flexibility becomes more vivid when higher environmental uncertainty is introduced. Table 6.9 shows the reaction of the linked and unlinked models to the increased uncertainty. High uncertainty imposes on the process decision more *unstable* process requirements. The linked model increases the process flexibility significantly in response to the higher uncertainty. The process flexibility generated by the linked model increased from 0.18 to 0.23 as the uncertainty becomes higher. In contrast, the unlinked model barely changes its process flexibility.

Comparing the fixed and variable costs generated by the two models brings more insight to the linkage aspect of manufacturing strategy. Table 6.10 provides the fixed and variable costs generated by the two decision models, expressed as a proportion of the total

cash inflow. It shows that the linked model generates a larger fixed cost (21.1% compared to 19.9%) and a smaller variable cost (10.7% compared to 12.0%) than does the unlinked model. The experimental design assigned a higher fixed cost to more automated and more flexible technologies. Also, a lower variable cost was assigned to more automated and more special-purpose technologies. Therefore, Table 6.10 coupled with the previous observation of higher flexibility generated by the linked model, implies that the linked model acquires more automated technology than does the unlinked model. This result supports the argument of manufacturing strategy researchers that the myopic investment strategy of the U.S. manufacturers has resulted in the obsolete manufacturing technology (Buffa 1984). The experimental results show that the unlinked model, which represents a myopic decision, tends to acquire less automated and less flexible technology.

In summary, the product and process decisions made by the linked and unlinked models explain the difference in net cash flow. Table 6.11 summarizes the resulting cost structure of the linked and unlinked model. The unlinked model tends to generate higher acquisition and higher variable cost than does the linked model. Consequently, its profitability is significantly lower than the linked model.

6.2.2.4 Pattern of Decisions

It is interesting to compare the models over time. Figures 6.2 through 6.9 plot the performances of the two decision models for typical cases. The unlinked model seems to generate a more fluctuating pattern than does the linked model.

Figure 6.2 shows the changes in the net cash flow of the two models. It shows that the fluctuation in the net cash flows is somewhat larger in the unlinked model than the linked model, particularly in the low complexity case. This larger fluctuation in the net cash flow by the unlinked model can be explained by the following figures. Figure 6.3 shows that the unlinked model generates somewhat larger changes over time in the total

cash inflow. Since the unlinked model offers a wider range of products into the market (see Figure 6.9), the process requirements become more unstable, causing the larger acquisition cost and disposed salvage values shown in Figures 6.4 and 6.5. The myopic technology choice results in the higher fixed and variable costs (see Figures 6.6 and 6.7), and the lower process flexibility (see Figure 6.8).

Overall, the linked model is a more stable performer than the unlinked model. Particularly in an environment where capital availability is tight, the stable performance should be regarded as a critical factor in manufacturing strategy. This stability explains an earlier result in Chapter V. The unlinked model performs significantly worse with a tighter capital availability (see Section 5.3).

6.2.3 Summary

The linked model generated a higher net cash flow overall. In several cases, however, the unlinked model actually outperformed the linked model. Two reasons for this result were discussed: the uncertainty in the decision problem, and the impact of using a rolling time horizon.

The decisions made by the two models were analyzed in detail to explain the differences in performance. The analysis focused on the overall profitability, product decisions, process decisions, and stability in the pattern of decisions. Overall, the unlinked model, which does not consider the process aspects, tends to offer a wide variety of products. Consequently, the process requirements become less stable, and the unlinked model has to acquire and dispose of a large amount of process technology at the same time. Also, the unlinked model, which does not consider plans for the new products yet to be introduced, tends to acquire less flexible technology than does the linked model. As a result, the overall profitability of the unlinked model is much lower than the linked model.

6.3 LINKAGE AND THE ENVIRONMENT

In this section, the performance differentials between the two models are examined to explore the environmental impact on linkage. First, the result of a statistical test is presented. Then, the impact of each of the three environmental factors is discussed by examining the product and process decisions made by the two models.

6.3.1 A Statistical Test

The following three research hypotheses are evaluated next with regard to complexity, uncertainty, and tightness:

- H1: The linked model outperforms the unlinked model, particularly more when the environmental complexity is *higher*.
- H2: The linked model outperforms the unlinked model, particularly more when the environmental uncertainty is *lower*.
- H3: The linked model outperforms the unlinked model, particularly more when the environmental tightness is *higher*.

The relative performance of the linked and unlinked models is measured by the ratio (PP/IN) between the net cash flow of the unlinked model over the net cash flow of the linked model. The ratios for 32 observations (8 environments times 4 replications each) are provided in Table 6.12. They indicate that the PP/IN ratios change depending on the environmental factors.

A *completely randomized factorial design* with three factors and two-way interactions is applied to statistically test the impact of environment on the ratio PP/IN. The above research hypotheses are evaluated by testing the following *null hypotheses*:

- H1₀: The average PP/IN is indifferent to the degree of environmental *complexity*.
- H2₀: The average PP/IN is indifferent to the degree of environmental *uncertainty*.

H3₀: The average PP/IN is indifferent to the degree of environmental *tightness*.

The analysis of variance (ANOVA) table is provided in Table 6.13. As shown, the environmental complexity factor is significant at the 0.0001 level. The other two factors, uncertainty and complexity, are not found to be statistically significant. The experiment failed to show sufficiently strong evidence that the uncertainty and tightness factors significantly affect the relative performance of the linked and unlinked models. Also, no interactions between factors are significant.

6.3.2 Linkage and Environmental Complexity

The complexity factor is significant at the level of 0.0001 as shown in Table 6.13. The linked model outperforms the unlinked model, *particularly* when environmental complexity is higher. Table 6.14 shows the average PP/IN ratio over the four replications for both complexity levels. The PP/IN ratio is consistently smaller when complexity is higher. Its overall average is 0.9178 with high complexity, while it is 1.0130 with low complexity.

The high complexity setting represents an environment where the decision problem is bigger in size and more difficult to solve. There are more products to choose from, and the difference in process requirements between products is greater. Also, the product life cycle is shorter, the demand for each product fluctuates more widely over its life cycle, and there are more process technologies to choose from. There seem to be more opportunities to consider, and the penalty of not analyzing them carefully seems to be greater. This result is consistent with what Van Dierdonck and Miller (1980) contend. They suggest that more support from information processing systems is needed for production planning and control when the manufacturing tasks are more complex. Within the context of this study, "more need for information processing systems" translates into the linkage of the product and process decisions.

Figures 6.2 through 6.9 analyze the decisions made by each model in more detail. They portray the various decisions made by each model under different levels of complexity. First, it can be seen from Figure 6.9 that the difference in product offerings is much greater when the complexity is low. As discussed in earlier section, the unlinked model tends to introduce more products into the market. But this difference is considerably reduced when the complexity is high. Under a more complex environment, the linked model offered almost as many products as did the unlinked model.

Earlier in Section 6.2, it was observed that this wide variety of products reduces the stability in process requirements, and thus negatively affects the process decision. However, when there is more variety of process technologies available (see Table 6.3), the linked model can handle unstable process requirements more effectively by acquiring more flexible technologies. Figure 6.8 shows that the process flexibility of the linked model increases significantly with the high complexity. Thus the linked model does not have to give up many product opportunities, as it does when the complexity is low with limited variety of flexible technologies available. Consequently, high complexity enhances the superiority of the linked model.

Along the same line, it is interesting to note how often the unlinked model actually outperformed the linked model with low complexity. Table 6.12 shows that 8 cases out of 16 runs with low complexity generated the PP/IN ratio larger than 1. Also, the overall average PP/IN is 1.0130 when the complexity is low. The environment with low complexity includes such features as a smaller number of product opportunities, fewer processes required for each product, long product life cycles and low variability of demand over the life cycles, and a limited variety of process technologies. Under this type of environment, the benefit of integrating product and process decisions seems to decrease. The linked model seems to be *overly careful* in offering products, as suggested by Figures 6.3 and 6.9, thus losing opportunities which the unlinked model opts to take. This

reluctance in offering products is reinforced by the limited number of flexible technologies, which otherwise could help the linked model cope with new process requirements needed to introduce a new product.

6.3.3 Linkage and Environmental Uncertainty

It was earlier hypothesized that the difference between the linked model and the unlinked model would be smaller when the environment is more uncertain. The rationale is that the larger error in parameter estimation will reduce the value of integrated decisions. The ANOVA test shown in Table 6.13 does not strongly support this hypothesis. The test cannot find enough evidence to reject the null hypothesis H_{20} . However, the power of F-test was only 0.25, suggesting that the sample size was not large enough to draw any final conclusion. It means that there is 75% chance of committing the Type II error, not rejecting the null hypothesis when it is not true.

Even though the original hypothesis could not be statistically validated, the overall direction of differences was as hypothesized. Table 6.17 shows that the average value of PP/IN is 0.9742 with the high uncertainty, while it is 0.9566 with the low uncertainty. When the environmental uncertainty is higher, the unlinked model performed *closer* to the linked model. Also Table 6.12 shows that, in 10 out of total 16 comparisons between two levels of uncertainty (2 tightness levels x 2 complexity levels x 4 replications), the PP/IN ratio was higher with more uncertainty. Particularly, the trend is clearer when complexity is high: the PP/IN ratio was higher in 6 out of 8 cases with more uncertainty. Table 6.18 shows the result of an ANOVA test where the complexity is fixed at the HIGH level. The analysis based on the 16 observations in the left-hand column of Table 6.12 finds that the uncertainty factor is significant at the 0.10 level.

The overall result is consistent with the study by Swamidass and Newell (1987). They empirically find that, as the environmental uncertainty becomes higher, the role of

manufacturing managers in strategic planning is diminished. However, the results seem to suggest that the uncertainty factors have a weaker effect than do the complexity factors.

The product and process decisions made by two decision models under different uncertainty levels help explain these differentials. Table 6.19 shows that the difference in product offerings between the two models is smaller when the environment is more uncertain. Also Table 6.20 shows the overall profitability of the linked model decreases much more with the higher uncertainty, than does the unlinked model's profitability. Among various cost factors, the increase in acquisition cost stands out. As the uncertainty increases, the proportion of acquisition cost of the linked model jumps from 16.52% to 18.45% of the total contribution. For the unlinked model, the increase in acquisition cost is relatively modest, from 21.19% to 22.21%. It seems that the linked model adapts to the higher uncertainty by acquiring more flexible technology (see Table 6.19 for the increase in process flexibility), and the higher cost of the flexible technology might have contributed to the decrease in profitability.

6.3.4 Linkage and Environmental Tightness

It was hypothesized earlier that the difference between two decision models would increase as the environment is tighter. The statistical test was not able to provide sufficiently strong evidence to support the original hypothesis. Table 6.13 shows the null hypothesis H_{30} on the tightness factor could not be rejected. However, the power of the F-test was less than 0.20, suggesting that the statistical evidence is too weak to conclude that there is no impact.

Though the impact is not statistically significant, the results are in the hypothesized directions. Table 6.21 shows that the average PP/IN is lower, meaning the difference is larger, when the tightness is higher. Also, in 11 cases out of 16 direct comparisons shown in Table 6.12, the PP/IN ratio decreased with higher tightness. Particularly when the

complexity is set at the HIGH level, 7 out of 8 cases show the ratio decreased as the environment becomes tighter. Table 6.18 shows that the tightness is significant at the 0.05 level when the complexity factor is fixed at the HIGH level. This observation implies that the value of linkage can be greater when the environment is tighter with lower profit margins.

Tables 6.22 and 6.23 show that the high level of tightness affects the linked and unlinked model similarly. There is no apparent difference in the way two models adjust to the changes in the environmental tightness. It seems that the *more careful* decisions made by the linked model just help generate better results, and more so when profit margins are smaller.

6.3.5 Summary

In this section, the impact of the environmental factors on the linkage aspect of manufacturing strategy was discussed. The difference between the two decision models became larger when the environmental complexity increases. The impact was statistically significant. Thus we could conclude that more linkage is needed when the environment is more complex.

The other two other factors, uncertainty and tightness, also affected the decision models in the hypothesized direction. The difference between the linked and unlinked models becomes smaller with the higher uncertainty, and larger with the higher tightness. However, the results were not statistically significant. The low power of the test suggests that a larger sample size is needed to draw any further conclusion.

6.4 MANUFACTURING FLEXIBILITY AND PERFORMANCE

Earlier in Chapter III, additional constraints were suggested which force the decision model to develop more manufacturing flexibility than it might otherwise adopt. (See Section 3.2.4.) In the context of a mathematical programming problem, additional constraints are likely to worsen the objective function value. However, two aspects in the decision model might help the additional flexibility constraints to improve the performance. One is the rolling time horizon, and the other is the uncertainty in estimating the parameters.

The performance of the *linked* model with and without the flexibility constraints are now compared to examine 1) whether forcing more flexibility improves the performance, and 2) when the differences between the two models are greater. This section compares the overall performance of two models, analyzing the product and process decisions in detail. Then Section 6.5 examines the environmental impact on the value of manufacturing flexibility.

6.4.1 Overall Impact

The linked model with and without the flexibility constraints is simulated over eight different environments with four replications per each. Thus, a total of 32 comparisons are made between the net cash flow generated by the model with the flexibility constraints (FF) and the model without the constraints (NF).

Table 6.24 shows the FF/NF ratios for the total 32 comparisons. Overall, the model (NF) without the additional flexibility constraints outperformed the model (FF) with the constraints. The average net cash flow of the FF model is about 93% of the NF model. It also shows that in 31 cases, out of the total 32 comparisons, the NF model outperformed the FF model.

The above results did not meet the earlier expectation that forcing more flexibility than what the decision model (without the flexibility constraints) adopts might generate a better performance. The basic rationale for this original expectation comes from the characteristics of the model. If the decision problem is *static* (in that the problem is solved only once including the whole experimental periods) and *deterministic* (in that there are no uncertainties in estimating the parameters), the NF model without the additional constraints must always outperform the FF model with the additional constraints. However, the decision model presented in Chapter III is *dynamic* (in that the problem is solved with a limited planning horizon and a *rolling schedule*) and *probabilistic* (in that there are *uncertainties* in estimating the parameters). Therefore, the optimality in the *current* period's solution does not necessarily translate into optimality over all periods. Also, the solution made with the *false* parameters is not necessarily an optimal solution for the *actual* problem. These two reasons thus were expected to help the FF model cope with the additional constraints and generate better results.

Even though the NF model generally outperformed the FF model, it is interesting to note that the performance differentials are not so large considering the severity of the additional constraints. Table 6.27 shows that the FF model was forced to have 49.5% more flexibility that it wanted otherwise. But the difference in the net cash flow was 7% in average. Even in one occasion, the FF model indeed outperformed the NF model. (See the replication 3 with the environment 1.) This environment, as defined in Table 6.2, has the high tightness, high complexity, and high uncertainty. It might be therefore speculated that the FF model could outperform the NF model if the experimental settings were different. The next subsection compares the decisions made by two models in detail to assess the effect of the additional constraints that force the model to acquire more flexible technologies.

6.4.2 Impact on Decisions

In order to explain the difference in the performance, this subsection analyzes in detail the product and process decisions made by two models (FF and NF). The analysis focuses on three aspects: 1) overall profitability, 2) product decisions, and 3) process decisions.

6.4.2.1 Overall Profitability

As described in Section 6.2, the overall profitability is assessed by two measures: a *return-on-sales* measure and a *return-on-assets* measure. Table 6.25 summarizes the profitability of two models. As shown, the overall profitability of the FF model is lower than that of the NF model.

First, the average *return on sales* of the FF model is 34.7%, while the NF model shows a higher ratio of 36.9%. The reason for the low return on sales of the FF model is suggested in Figure 6.10. It presents the total cash inflow and net cash flow generated by two models over all environments. As shown, the FF model generates almost equal, or slightly smaller, total cash inflow than the NF model. The net cash flow generated by the FF model, meanwhile, is consistently smaller than the one by the NF model. As a result, the return on sales of the FF model is lower than the NF model. The additional flexibility constraints did not seem to affect the product decision significantly, since there is little difference between the total contributions generated by two models. Instead, the additional constraints seemed to change the process decision significantly. Earlier in Chapter II, the strategic value of manufacturing flexibility was suggested to come from the enhanced opportunities of offering diverse products. Figure 6.10 suggests that the model and the experimental environment did not generate this strategic changes in the product decision.

Second, the FF model generates a much lower *return on assets* (30.8%) than the NF model (35.0%). The difference is much larger than the difference in the *return-on-sales*

measure. It can be speculated that the mandated increase in flexibility did not generate the extra contribution that is large enough to compensate for the high acquisition cost of the flexible technology. The following subsections analyze the product and process decisions made by the two models, and provide some explanations for the differences in the overall profitability.

6.4.2.2 Product Decisions

The analysis of the product decisions made by two models reinforces the above interpretation. Table 6.26 shows the average proportion of total possible products that were actually offered by each model. There is no significant difference between the two models.

Two aspects of product decision may explain this lack of sensitivity. First, when a manufacturing system maintains more flexible technologies, it can handle unstable process requirements (that are caused by the introduction of different products) without acquiring new process technologies. This capability, that comes from the flexibility constraints, encourages the model to offer more products. On the other hand, the model with the additional flexibility constraints has to acquire, and maintain, more flexible technologies which tend to be less efficient. Thus the expected profitability of each possible product is reduced, and consequently fewer products are offered by the decision model. These two forces are in conflict with each other, and it seems that their effects have been cancelled out on most occasions.

In summary, the flexibility model did not provide enough leverage to change the product decisions. Originally it was expected that the model with the flexibility constraints would create more opportunities for a variety of products to be introduced profitably. However, the experimental environment did not support this expectation. The second

benefit of developing flexibility is the capability to handle the unstable process requirements, and it is examined next.

6.4.2.3 Process Decisions

The FF model was hypothesized earlier to adapt better to the frequent changes in process requirements that are created by dynamic changes in the product mix over time. By maintaining more general-purpose equipment, the FF model would not be forced to change its technology mix as much as done by the NF model.

The results presented in Table 6.28 support the above expectation. The table shows that the average acquisition cost (measured as a proportion of the total cash inflow) is almost same for both the FF and NF models. Since the unit acquisition cost for a more flexible technology was set at a higher value than the acquisition cost for a less flexible technology, it can be concluded that the amount of technology acquisition *in units* is smaller for the FF model than the NF model. It could be therefore speculated that the flexibility model changes the process technology mix less frequently than does the model without the flexibility constraints.

However, Table 6.29 shows that the FF model generates higher fixed and variable costs than the NF model. Thus as shown in Table 6.30, the profitability of the NF model was only 0.3477, lower than 0.3690 of the NF model. It implies that the savings from maintaining a stable process technology mix by the FF model was not enough to compensate for the increase in fixed and variable costs.

The above results show the trade-off between flexibility and efficiency. In order to satisfy the forced flexibility constraints, the FF model had to sacrifice the efficiency aspect and generated higher fixed and variable costs. The trade-off could have been changed in favor of the FF model, however, if the cost structure was set differently for the experiment.

6.4.3 Summary

This section compared the overall performance of the models with and without the additional flexibility constraints. The NF model consistently outperformed the FF model. However, the difference in performance was not so large considering the severity of the constraints. Also, the experiment showed that the FF model with additional constraints can actually outperform the NF model without them. The uncertainty in parameter estimation and the implementation of rolling schedule are two explanations for this possibility.

The strategic benefits of developing manufacturing flexibility were hypothesized earlier to come from two dimensions: the enhanced opportunities to offer various products, and the improved capability to handle unstable process requirements. The experiment could not show the first dimension since the lost efficiency negatively affected the product profitability. Overall, the trade-off between flexibility and efficiency affected the FF model negatively in this experiment.

6.5 FLEXIBILITY AND THE ENVIRONMENT

In this section, the performance difference between the two models is examined under various environments to explore the environmental impact on the flexibility aspect of manufacturing strategy. First, the statistical test results are presented. Then, the impact of each of the three environmental factors is discussed by examining the product and process decisions made by two models under different environments.

6.5.1 A Statistical Test

With regards to these three environmental factors defined in Chapters IV and V, the following three research hypotheses are evaluated in this experimental study:

- H4: The flexibility model FF performs better relative to the NF model when the environmental complexity is *higher*.
- H5: The flexibility model FF performs better relative to the NF model when the environmental uncertainty is *higher*.
- H6: The flexibility model FF performs better relative to the NF model when the environmental tightness is *lower*.

The relative performance of the FF and NF models is measured by the FF/NF ratio. The ratios of 32 observations (8 environments times 4 replications per each) are provided in Table 6.31. It shows that the FF/NF ratios change depending on the environmental factors.

A *completely randomized factorial design* with three factors and two-way interactions is applied to statistically test the impact of environment on the FF/NF ratio. The above research hypotheses are evaluated by testing the following *null hypotheses*:

- H4₀: The average FF/NF is indifferent to the degree of environmental *complexity*.
- H5₀: The average FF/NF is indifferent to the degree of environmental *uncertainty*.
- H6₀: The average FF/NF is indifferent to the degree of environmental *tightness*.

The analysis of variance (ANOVA) table is provided in Table 6.32. As shown, the environmental uncertainty factor is significant at the 0.01 level. Also the environmental tightness factor is significant at the 0.05 level. The complexity factor was found statistically insignificant. The experiment failed to show sufficiently strong evidence to support that the complexity factor affects the relative performance of the two models. Also, no interactions between factors are significant.

6.5.2 Flexibility and Environmental Complexity

The complexity factor is not statistically significant as shown in Table 6.32. Thus the earlier hypothesis, that the value of developing additional flexibility is more significant

when the environment is more complex, could not be confirmed. However, as shown in Table 6.32, the power of the F-test is less than 0.20, suggesting that the sample size was not large enough to draw any final conclusion. Table 6.33 presents the overall average value of the FF/NF ratio at both levels of complexity. The ratios change rather randomly between the two levels of complexity, and the overall averages are virtually the same.

Originally, the flexibility FF model was hypothesized to perform better relative to the NF model when the complexity is higher. There are more products to be considered, and large variety of flexible technologies are available with the high complexity level. Thus the FF model seemed to improve its performance, more so than the NF model. Various results presented in Tables 6.34 and 6.35 do not show any evidence to support this hypothesis. The effect on the product offerings from forcing more flexibility into the solution was not related to the degree of complexity (see Table 6.34). Nor do the cost structures shown in Table 6.35 show any significant difference between two complexity levels. In conclusion, the relative performance of the FF and NF models does not seem to be affected by the factors in the complexity cluster.

6.5.3 Flexibility and Environmental Uncertainty

The uncertainty factor is significant at the level of 0.01 as shown in Table 6.32. It can be concluded that the FF model with flexibility constraints performs better relative to the NF model when the environmental uncertainty is higher. Table 6.36 shows that the ratio FF/NF is much higher (0.9530) with the high uncertainty than the case of the low uncertainty (0.9082). This conclusion implies that the manufacturing strategy emphasizing flexibility is more effective when the decision environment is highly uncertain. This result is consistent with the finding of Swamidass and Newell (1987). They empirically found a strong correlations between the perceived environmental uncertainty and the emphasis given to manufacturing flexibility.

Tables 6.37 and 6.38 provide some explanations for the result. As shown in Table 6.37, the difference is smaller between two models on the proportion of products offered when uncertainty is higher. Earlier in Section 6.4, it was found that the flexibility constraints decrease the process efficiency and thus reduce the profitability of the possible products. With the high level of uncertainty, this negative impact is less severe to the FF model, since the NF model also has to raise its process flexibility. (See the change of process flexibility generated by the NF model from 0.1806 to 0.2263.) Also Table 6.38 shows that the difference between the two models in the fixed and variable costs decreases as the uncertainty becomes higher. Consequently, the difference between the two models on the overall profitability is reduced. These observations show that the negative impact of forcing flexibility – the loss of efficiency – become less severe when the environmental uncertainty is higher.

The results shown in Table 6.37 can be interpreted from a different perspective. It shows that the NF model, even without the flexibility constraints, increases its process flexibility when the environment becomes more uncertain (from 18.1% to 22.6%). This result suggests in a different way that developing more flexibility is an appropriate strategy to deal with the higher uncertainty in the environment.

6.5.4 Flexibility and Environmental Tightness

The tightness factor is significant at the 0.05 level (see Table 6.32). Table 6.39 shows that the FF/NF ratio is consistently higher when the tightness is lower. It can be concluded that the model with the flexibility constraints (FF) performs better relative to the model without them (NF) when profit margins are larger.

This conclusion is consistent with the general consensus in the operations management field. The trade-off relationship between flexibility and efficiency affects the FF model more severely when the environment is tight and profit margins are smaller.

Under this environment, higher efficiency, rather than flexibility, is required as a firm's competitive priority. Krajewski and Ritzman (1987) contend that a firm emphasizing top-notch efficiency has to maintain more efficient process technology.

The product decisions of the two models, summarized in Table 6.40, show the negative impact of emphasizing flexibility on the profitability of a product when profit margins are tighter. When the environment becomes tighter, the FF model has to reduce its product offerings (from 54.5% to 47.6%), much more so than the NF model has to (from 55.7% to 50.4%). Table 6.41 shows the changes in the impact of emphasizing flexibility on the cost structure with different levels of tightness. The difference between two models in fixed cost is much larger with the high tightness. The FF model generates a higher fixed cost, but the level of product offerings is much lower, resulting in the poor net cash flow, and *more so* when the environment is tighter.

6.5.5 Summary

In this section, the impact of the environmental factors on the flexibility aspect of manufacturing strategy was discussed. The difference between the models FF and NF becomes smaller when the environmental uncertainty is higher, suggesting that developing flexibility is more appropriate in the highly uncertain environment. The difference becomes greater when the environmental tightness is higher, implying that emphasizing flexibility is a less appropriate strategy when profit margins are tight. These effects were statistically significant. Therefore, we can conclude that the manufacturing strategy emphasizing flexibility performs better when the environment is highly uncertain and profit margins are larger. The other factor, environmental complexity, did not show any statistical significance. Also the overall data did not show any changes in the difference between two models at the two levels of complexity.

6.6 CONCLUSION

In this chapter, the result of an experimental study was discussed. The purpose of the experimental study was twofold: 1) to explore the effectiveness of two strategic policies – linkage and flexibility, and 2) to examine the environmental impact on the effectiveness.

The results were discussed in four sections. Section 6.2 discussed the overall impact of linking decisions. The superior performance of the linked model over the unlinked model was examined on the basis of the overall profitability, product decisions, process decisions, and the stability of performance over time. Section 6.3 discussed the impact of different environments on the relative performance of the linked and unlinked models. The difference seemed to be larger when the environment is more complex, less uncertain, and tighter.

Then Sections 6.4 and 6.5 discussed the flexibility aspect of the experiment. The model with the additional flexibility constraints performed worse than the model without them. However, there was one occasion where the FF model outperformed the NF model. From the mathematical programming viewpoint, this represents a significant finding. The model with additional constraints can indeed outperform the model without them due to the dynamic and uncertain nature of the decision problem. It was also found that the flexibility model improves its relative performance when the environment is more uncertain and profit margins are larger.

a. Total Cash Inflow

b. Net Cash Flow

* See Table 6.2 for the definition of the environment.

Figure 6.1
Comparison of Linked and Unlinked Models:
Total Cash Inflow and Net Cash Flow of Replication 2

a. Low Complexity Case

b. High Complexity Case

Figure 6.2

Pattern in Net Cash Flow by Linked and Unlinked Model
(High Tightness; Low Uncertainty; Replication 2)

a. Low Complexity Case

b. High Complexity Case

Figure 6.3

Pattern in Total Cash Inflow by Linked and Unlinked Model
(High Tightness; Low Uncertainty; Replication 2)

a. Low Complexity Case

b. High Complexity Case

Figure 6.4

Pattern in Technology Acquisition Cost by Linked and Unlinked Model
(High Tightness; Low Uncertainty; Replication 2)

a. Low Complexity Case

b. High Complexity Case

Figure 6.5

Pattern in Salvage Value of Disposed Technology by Linked and Unlinked Model
(High Tightness; Low Uncertainty; Replication 2)

a. Low Complexity Case

b. High Complexity Case

Figure 6.6

Pattern in Fixed Cost by Linked and Unlinked Model
(High Tightness; Low Uncertainty; Replication 2)

a. Low Complexity Case

b. High Complexity Case

Figure 6.7

Pattern in Variable Cost by Linked and Unlinked Model
(High Tightness; Low Uncertainty; Replication 2)

a. Low Complexity Case

b. High Complexity Case

Figure 6.8

Pattern in Process Flexibility by Linked and Unlinked Model
(High Tightness; Low Uncertainty; Replication 2)

a. Low Complexity Case

b. High Complexity Case

Figure 6.9

Products Offered as a Proportion of Total Possibilities
(High Tightness; Low Uncertainty; Replication 2)

a. Total Contribution

b. Net Cash Flow

*See Table 6.2 for the definition of the Environment

Figure 6.10

Comparison of the Models with and Without Flexibility Emphasis:
Total Contribution and Net Cash Flow of Replication 2

Table 6.1
Experimental Factors

Factor Groups	Factors	Treatment Levels	
a) Strategic Policy Factors	Linkage	Linked model	(IN)
		Unlinked model	(PP)
	Flexibility	Without flexibility constraint	(NF)
		With flexibility constraint	(FF)
b) Environmental Factors	Complexity	Highly complex	(HIGH)
		Less complex	(LOW)
	Uncertainty	Highly uncertain	(HIGH)
		Less uncertain	(LOW)
	Tightness	Very tight	(HIGH)
		Less tight	(LOW)

Table 6.2
Environment and Factors

Environment	Factors		
	Tightness	Complexity	Uncertainty
1	High	High	High
2	High	High	Low
3	High	Low	High
4	High	Low	Low
5	Low	High	High
6	Low	High	Low
7	Low	Low	High
8	Low	Low	Low

Table 6.3
Factor Levels for the Environment

1. *Environmental Complexity*

a. Number of product lines in global demand matrix

High : 10 product lines
Low : 5 product lines

b. Average number of different processes required for each product

High : ranging from 2 to 5 (average 3.6 processes)
Low : ranging from 1 to 4 (average 2.4 processes)

c. Length of product life cycle

High : ranging from 2 to 4 periods (average 3 periods)
Low : ranging from 4 to 6 periods (average 5 periods)

d. Variability of demand over product life cycle

High : ranging from 20% to 180% of average demand
Low : ranging from 60% to 140% of average demand

e. Total number of different process technologies

High : increasing number of technologies for more flexible types
(12 technologies capable to perform 1 process,
16 technologies capable to perform 2 processes, and
20 technologies capable to perform 3 processes)
Low : same number of technologies for all types
(12 technologies for each type)

Table 6.3 (Continued)

2. *Environmental Uncertainty*

a. Average percentage error in forecasting demand for each product

High : $\pm 20\%$
 Low : $\pm 5\%$

b. Average percentage error in estimating technology efficiency

High : $\pm 10\%$ for *conventional* technologies
 $\pm 40\%$ for *new* technologies
 Low : $\pm 5\%$ for *conventional* technologies
 $\pm 20\%$ for *new* technologies

3. *Environmental Tightness*

a. Level of average contribution margin

High : Average margin equals two times the estimated fixed and variable costs
 Low : Average margin equals three times the estimated fixed and variable costs

Table 6.4

Overall Performance of Linked and Unlinked Models:
Observed PP/IN Ratio of Net Cash Flow

Environment	Replication			
	1	2	3	4
1	0.9495	0.9194	0.9095	0.8695
2	0.8603	0.9384	0.8590	0.8576
3	1.0023	0.9549	1.0416	1.1217
4	0.9795	1.0807	1.0786	0.8967
5	0.9762	0.9217	0.9634	0.9407
6	0.9146	0.9190	0.9410	0.9456
7	0.9962	0.9948	1.0600	0.9659
8	1.0281	0.9860	1.0553	0.9652
Average	0.9633	0.9644	0.9885	0.9453
Overall Average	0.9654			

Table 6.5

Overall Profitability of Linked and Unlinked Models

Profitability Measure	Linked Model	Unlinked Model
Average Return On Sales*	0.3690	0.3373
Average Return On Assets**	0.3501	0.3383

*Return On Sales = (Net Cash Flow) / (Total Cash Inflow)

**Return On Assets = (Net Cash Flow) / (Total Dollar Value of Process Technology)

Table 6.6

Product Decisions of Linked and Unlinked Models:
Products Offered as a Proportion of Total Product Possibilities

Replication Number	Linked Model	Unlinked Model
1	0.5614	0.6722
2	0.4609	0.5872
3	0.5706	0.6583
4	0.4832	0.5500
Overall Average	0.5309	0.5970

Table 6.7

Process Decisions of Linked and Unlinked Models:
 Acquisition Cost and Disposed Salvage Value as a Proportion of Total Cash Inflow

Replication Number	Linked Model		Unlinked Model	
	Acquisition Cost	Salvage Value	Acquisition Cost	Salvage Value
1	0.1422	0.0699	0.1950	0.0970
2	0.1514	0.0511	0.1828	0.0677
3	0.1742	0.1154	0.2052	0.1348
4	0.2315	0.0693	0.2848	0.1005
Overall Average	0.1749	0.0765	0.2170	0.1000

Table 6.8
 Process Decisions of Linked and Unlinked Models:
 Process Flexibility

Replication Number	Linked Model	Unlinked Model
1	0.2046	0.1778
2	0.2062	0.1744
3	0.1984	0.1734
4	0.2043	0.1713
Overall Average	0.2034	0.1742

Table 6.9

Process Decisions of Linked and Unlinked Models:
Process Flexibility under Different Uncertainty Levels

Replication Number	Linked Model		Unlinked Model	
	High Uncertainty	Low Uncertainty	High Uncertainty	Low Uncertainty
1	0.2304	0.1791	0.1813	0.1747
2	0.2284	0.1841	0.1761	0.1729
3	0.2175	0.1792	0.1764	0.1706
4	0.2281	0.1798	0.1714	0.1711
Overall Average	0.2261	0.1806	0.1763	0.1723

Table 6.10

Process Decisions of Linked and Unlinked Models:
Fixed and Variable Costs as a Proportion of Total Cash Inflow

Replication Number	Linked Model		Unlinked Model	
	Fixed Cost	Variable Cost	Fixed Cost	Variable Cost
1	0.2197	0.1090	0.1851	0.1170
2	0.2088	0.1074	0.1992	0.1188
3	0.2054	0.1058	0.1965	0.1348
4	0.2083	0.1068	0.1962	0.1214
Overall Average	0.2108	0.1072	0.1994	0.1199

Table 6.11

Cost Structure of Linked and Unlinked Models:
Individual Cost as a Proportion of Total Cash Inflow

Cost Factor	Linked Model	Unlinked Model
Product Development Investment	0.2078	0.2211
Acquisition Cost of Technology	0.1749	0.2170
Fixed Cost	0.2108	0.1994
Variable Cost	0.1072	0.1199
Overtime Penalty	0.0069	0.0053
Salvage Value of Disposed Technology	0.0765	0.1000
Net Cash Flow	0.3690	0.3373

Table 6.12

Linkage and the Environment:
PP/IN Ratio of Net Cash Flow under Different Environments *

Tightness	Uncertainty	Complexity	
		High	Low
High	High	0.9495 0.9194 0.9095 0.8965 <i>0.9120</i>	1.0023 0.9549 1.0416 1.1217 <i>1.0301</i>
	Low	0.8603 0.9384 0.8590 0.8575 <i>0.8787</i>	0.9795 1.0807 1.0786 0.8966 <i>1.0089</i>
Low	High	0.9762 0.9217 0.9634 0.9407 <i>0.9505</i>	0.9962 0.9948 1.0600 0.9659 <i>1.0042</i>
	Low	0.9146 0.9190 0.9410 0.9456 <i>0.9300</i>	1.0281 0.9860 1.0553 0.9652 <i>1.0086</i>

* The first four numbers in each cell are results of four replications, and the last number (italicized) is the average of four replications.

Table 6.13

Analysis of Variance Result:
Dependent Variable : PP/IN

Source	Sum of Squares	d.f.	F Value	Level of Significance	Power of Test *
Complexity	0.07242095	1	30.86	0.0001	0.99
Uncertainty	0.00249085	1	1.06	0.3128	0.25
Tightness	0.00202872	1	0.86	0.3614	0.20**
C•U	0.00068121	1	0.29	0.5948	0.20**
C•T	0.00672122	1	2.86	0.1030	0.74
U•T	0.00073998	1	0.32	0.5795	0.20**
Within Cell	0.05867765	25			
Total	0.14376058	31			

* Power of test is the probability of rejecting the null hypothesis given that it is false. They were calculated using the approximation method suggested by Kirk (1982, pp.142-143).

** Less than 0.20. The actual value could not be found due to the limit of the table in Kirk (1982).

Table 6.14

Linkage and Complexity:
PP/IN Ratio of Net Cash Flow under Different Complexity Levels

Replication Number	High Complexity	Low Complexity
1	0.9251	1.0015
2	0.9246	1.0041
3	0.9182	1.0589
4	0.9033	0.9874
Overall Average	0.9178	1.0130

Table 6.15

Linkage and Complexity:
Average Proportion of Products Offered and Process Flexibility

	High Complexity		Low Complexity	
	Linked Model	Unlinked Model	Linked Model	Unlinked Model
Proportion of Products Offered	0.5050	0.5469	0.5568	0.6472
Process Flexibility	0.2078	0.1786	0.1991	0.1699

Table 6.16

Linkage and Complexity:
Cost Factors as a Proportion of Total Cash Inflow

Cost Factor	High Complexity		Low Complexity	
	Linked Model	Unlinked Model	Linked Model	Unlinked Model
Product Development Investment	0.2611	0.2750	0.1543	0.1671
Acquisition Cost of Technology	0.1599	0.2174	0.1898	0.2165
Fixed Cost	0.1971	0.1816	0.2245	0.2172
Variable Cost	0.0967	0.1203	0.1178	0.1195
Overtime Penalty	0.0072	0.0065	0.0066	0.0041
Salvage Value of Disposed Technology	0.0760	0.1093	0.0770	0.0908
Net Cash Flow	0.3540	0.3084	0.3840	0.3663

Table 6.17

Linkage and Uncertainty:
PP/IN Ratio of Net Cash Flow under Different Uncertainty Levels

Replication Number	High Uncertainty	Low Uncertainty
1	0.9811	0.9456
2	0.9477	0.9809
3	0.9936	0.9834
4	0.9744	0.9162
Overall Average	0.9742	0.9566

Table 6.18

Analysis of Variance Result with Complexity Fixed at HIGH Level:
Dependent Variable : PP/IN

Source	Sum of Squares	d.f.	F Value	Level of Significance
Uncertainty	0.00288864	1	3.30	0.0942
Tightness	0.00806759	1	9.23	0.0103
U•T	0.00016407	1	0.19	0.6726
Within Cell	0.01049224	12		
Total	0.02161254	15		

Table 6.19

Linkage and Uncertainty:
Average Proportion of Products Offered and Process Flexibility

	High Uncertainty		Low Uncertainty	
	Linked Model	Unlinked Model	Linked Model	Unlinked Model
Proportion of Products Offered	0.5222	0.5759	0.5396	0.6181
Process Flexibility	0.2262	0.1806	0.1762	0.1723

Table 6.20

Linkage and Uncertainty:
Cost Factors as a Proportion of Total Cash Inflow

Cost Factor	High Uncertainty		Low Uncertainty	
	Linked Model	Unlinked Model	Linked Model	Unlinked Model
Product Development Investment	0.2074	0.2179	0.2080	0.2242
Acquisition Cost of Technology	0.1845	0.2221	0.1652	0.2119
Fixed Cost	0.2134	0.2013	0.2082	0.1975
Variable Cost	0.1097	0.1237	0.1047	0.1161
Overtime Penalty	0.0108	0.0075	0.0030	0.0031
Salvage Value of Disposed Technology	0.0815	0.1031	0.0714	0.0969
Net Cash Flow	0.3356	0.3306	0.3823	0.3441

Table 6.21

Linkage and Tightness:
PP/IN Ratio of Net Cash Flow under Different Tightness Levels

Replication Number	High Tightness	Low Tightness
1	0.9478	0.9788
2	0.9733	0.9554
3	0.9722	1.0049
4	0.9364	0.9543
Overall Average	0.9574	0.9733

Table 6.22

Linkage and Tightness:
Average Proportion of Products Offered and Process Flexibility

	High Tightness		Low Tightness	
	Linked Model	Unlinked Model	Linked Model	Unlinked Model
Proportion of Products Offered	0.5042	0.5789	0.5576	0.6151
Process Flexibility	0.2039	0.2029	0.1741	0.1744

Table 6.23

Linkage and Tightness:
Cost Factors as a Proportion of Total Cash Inflow

Cost Factor	High Tightness		Low Tightness	
	Linked Model	Unlinked Model	Linked Model	Unlinked Model
Product Development Investment	0.2031	0.2175	0.2123	0.2246
Acquisition Cost of Technology	0.1999	0.2447	0.1499	0.1893
Fixed Cost	0.2361	0.2243	0.1855	0.1745
Variable Cost	0.1217	0.1342	0.0927	0.1506
Overtime Penalty	0.0080	0.0058	0.0058	0.0047
Salvage Value of Disposed Technology	0.0867	0.1113	0.0662	0.0887
Net Cash Flow	0.3180	0.2847	0.4200	0.3900

Table 6.24

Overall Performance of Models With and Without Flexibility Emphasis:
Observed FF/NF Ratio of Net Cash Flow

Environment	Replication			
	1	2	3	4
1	0.9366	0.9314	1.0083	0.8750
2	0.9044	0.8678	0.9309	0.8630
3	0.9093	0.9664	0.9667	0.9745
4	0.8999	0.9512	0.8146	0.7980
5	0.9916	0.9136	0.9749	0.9502
6	0.9517	0.9060	0.9828	0.9160
7	0.9678	0.9914	0.9418	0.9469
8	0.9371	0.9389	0.9572	0.9186
Average	0.9373	0.9333	0.9466	0.9030
Overall Average	0.9301			

Table 6.25

Overall Profitability of Models With and Without Flexibility Emphasis

Profitability Measure	With Flexibility	Without Flexibility
Average Return On Sales*	0.3477	0.3690
Average Return On Assets**	0.3080	0.3501

*Return On Sales = (Net Cash Flow) / (Total Cash Inflow)

**Return On Assets = (Net Cash Flow) / (Total Dollar Value of Process Technology)

Table 6.26

Product Decisions of Models With and Without Flexibility Emphasis:
Average Number of Products Offered as a Proportion of Total Product Possibility

Replication Number	With Flexibility	Without Flexibility
1	0.5521	0.5614
2	0.5214	0.4609
3	0.5340	0.5706
4	0.4761	0.4833
Overall Average	0.5209	0.5191

Table 6.27

Process Decisions of Models With and Without Flexibility Emphasis:
Process Flexibility

Replication Number	With Flexibility	Without Flexibility
1	0.3016	0.2047
2	0.3017	0.2063
3	0.3049	0.1984
4	0.3076	0.2043
Overall Average	0.3040	0.2034

Table 6.28

Process Decisions of Models With and Without Flexibility Emphasis:
Acquisition Cost and Disposed Salvage Value as a Portion of Total Cash Inflow

Replication Number	With Flexibility		Without Flexibility	
	Acquisition Cost	Salvage Value	Acquisition Cost	Salvage Value
1	0.1407	0.0729	0.1422	0.0699
2	0.1500	0.0505	0.1514	0.0511
3	0.1763	0.1207	0.1742	0.1154
4	0.2357	0.0702	0.2315	0.0693
Overall Average	0.1757	0.0786	0.1748	0.0764

Table 6.29

Process Decisions of Models With and Without Flexibility:
Fixed and Variable Costs as a Proportion of Total Cash Inflow

Replication Number	With Flexibility		Without Flexibility	
	Fixed Cost	Variable Cost	Fixed Cost	Variable Cost
1	0.2348	0.1177	0.2206	0.1089
2	0.2240	0.1112	0.2088	0.1074
3	0.2215	0.1064	0.2054	0.1058
4	0.2232	0.1110	0.2083	0.1068
Overall Average	0.2259	0.1116	0.2108	0.1072

Table 6.30

Cost Structure of Models With and Without Flexibility Emphasis:
Individual Cost as a Proportion of Total Cash Inflow

Cost Factor	With Flexibility	Without Flexibility
Product Development Investment	0.2067	0.2077
Acquisition Cost of Technology	0.1757	0.1748
Fixed Cost	0.2258	0.2108
Variable Cost	0.1116	0.1072
Overtime Penalty	0.0110	0.0069
Salvage Value of Disposed Technology	0.0786	0.0765
Net Cash Flow	0.3477	0.3690

Table 6.31

Manufacturing Flexibility and the Environment:
FF/NF Ratio of Net Cash Flow under Different Environments *

Tightness	Uncertainty	Complexity	
		High	Low
High	High	0.9366 0.9314 1.0083 0.8750 <i>0.9378</i>	0.9093 0.9664 0.9667 0.9745 <i>0.9545</i>
	Low	0.9044 0.8678 0.9309 0.8630 <i>0.8915</i>	0.8999 0.9512 0.8146 0.7979 <i>0.8659</i>
Low	High	0.9916 0.9136 0.9749 0.9502 <i>0.9576</i>	0.9678 0.9914 0.9418 0.9469 <i>0.9619</i>
	Low	0.9517 0.9060 0.9828 0.9160 <i>0.9392</i>	0.9371 0.9389 0.9572 0.9186 <i>0.9365</i>

* The first four numbers in each cell are results of four replications, and the last number (italicized) is the average of four replications.

Table 6.32

Analysis of Variance Result:
Dependent Variable : FF/NF

Source	Sum of Squares	d.f.	F Value	Level of Significance	Power of Test *
Complexity	0.00002662	1	0.02	0.8988	0.20**
Uncertainty	0.01598141	1	9.91	0.0042	0.99
Tightness	0.01056351	1	6.55	0.0169	0.99
C•U	0.00121359	1	0.75	0.3940	0.20**
C•T	0.00005580	1	0.03	0.8540	0.20**
U•T	0.00414007	1	2.57	0.1217	0.99
Within Cell	0.04032913	25			
Total	0.07231013	31			

* Power of test is the probability of rejecting the null hypothesis given that it is false. They were calculated using the approximation method suggested by Kirk (1982, pp.142-143).

** Less than 0.20. The actual value could not be found due to the limit of the table in Kirk (1982).

Table 6.33

Manufacturing Flexibility and Complexity:
FF/NF of Net Cash Flow under Different Complexity Levels

Replication Number	High Complexity	Low Complexity
1	0.9461	0.9284
2	0.9047	0.9619
3	0.9742	0.8939
4	0.9010	0.9095
Overall Average	0.9315	0.9297

Table 6.34

Manufacturing Flexibility and Complexity:
Average Proportion of Products Offered and Process Flexibility

	High Complexity		Low Complexity	
	With Flexibility	Without Flexibility	With Flexibility	Without Flexibility
Proportion of Products Offered	0.4904	0.5050	0.5307	0.5568
Process Flexibility	0.3021	0.2078	0.3058	0.1991

Table 6.35

Manufacturing Flexibility and Complexity:
Cost Factors as a Proportion of Total Cash Inflow

Cost Factor	High Complexity		Low Complexity	
	With Flexibility	Without Flexibility	With Flexibility	Without Flexibility
Product Development Investment	0.2600	0.2611	0.1534	0.1543
Acquisition Cost of Technology	0.1620	0.1599	0.1894	0.1898
Fixed Cost	0.2118	0.1971	0.2399	0.2245
Variable Cost	0.1009	0.0967	0.1223	0.1178
Overtime Penalty	0.0099	0.0072	0.0121	0.0066
Salvage Value of Disposed Technology	0.0786	0.0760	0.0767	0.0770
Net Cash Flow	0.3339	0.3540	0.3616	0.3840

Table 6.36

Manufacturing Flexibility and Uncertainty:
FF/NF Ratio of Net Cash Flow under Different Uncertainty Levels

Replication Number	High Uncertainty	Low Uncertainty
1	0.9513	0.9231
2	0.9506	0.9160
3	0.9732	0.9198
4	0.9366	0.8739
Overall Average	0.9530	0.9082

Table 6.37

Manufacturing Flexibility and Uncertainty:
Average Proportion of Products Offered and Process Flexibility

	High Uncertainty		Low Uncertainty	
	With Flexibility	Without Flexibility	With Flexibility	Without Flexibility
Proportion of Products Offered	0.5138	0.5222	0.5073	0.5396
Process Flexibility	0.3062	0.2263	0.3018	0.1806

Table 6.38

Manufacturing Flexibility and Uncertainty:
Cost Factors as a Proportion of Total Cash Inflow

Cost Factor	High Uncertainty		Low Uncertainty	
	With Flexibility	Without Flexibility	With Flexibility	Without Flexibility
Product Development Investment	0.2073	0.2074	0.2062	0.2079
Acquisition Cost of Technology	0.1863	0.1845	0.1652	0.1652
Fixed Cost	0.2238	0.2134	0.2279	0.2082
Variable Cost	0.1099	0.1097	0.1133	0.1047
Overtime Penalty	0.0149	0.0108	0.0071	0.0030
Salvage Value of Disposed Technology	0.0829	0.0815	0.0743	0.0714
Net Cash Flow	0.3407	0.3556	0.3547	0.3823

Table 6.39

Manufacturing Flexibility and Tightness:
FF/NF Ratio of Net Cash Flow under Different Tightness Levels

Replication Number	High Tightness	Low Tightness
1	0.9126	0.9619
2	0.9292	0.9374
3	0.9304	0.9626
4	0.8776	0.9329
Overall Average	0.9124	0.9488

Table 6.40

Manufacturing Flexibility and Tightness:
Average Proportion of Products Offered and Process Flexibility

	High Tightness		Low Tightness	
	With Flexibility	Without Flexibility	With Flexibility	Without Flexibility
Proportion of Products Offered	0.4762	0.5042	0.5449	0.5576
Process Flexibility	0.3041	0.2039	0.3038	0.2029

Table 6.41

Manufacturing Flexibility and Tightness:
Cost Factors as a Proportion of Total Cash Inflow

Cost Factor	High Tightness		Low Tightness	
	With Flexibility	Without Flexibility	With Flexibility	Without Flexibility
Product Development Investment	0.2022	0.2031	0.2113	0.2123
Acquisition Cost of Technology	0.2021	0.1998	0.1493	0.1499
Fixed Cost	0.2527	0.2361	0.1990	0.1895
Variable Cost	0.1256	0.1217	0.0976	0.0927
Overtime Penalty	0.0124	0.0080	0.0096	0.0058
Salvage Value of Disposed Technology	0.0891	0.0867	0.0681	0.0662
Net Cash Flow	0.2941	0.3180	0.4014	0.4199

CHAPTER VII

CONCLUSION

Since Wickham Skinner argued early in 1969 for a more strategic approach to the operations management, the concept of manufacturing strategy has gained increasing attention from both managers and researchers. During a relatively short period, the field experienced a considerable development in theory and practice. A conceptual framework of manufacturing strategy has been formulated by the leaders of the field, and recently several important variables have been defined and measured more precisely with empirical data. Now, some scholars suggest that manufacturing strategy research is entering a new stage. They propose that more implementable and transportable concepts and tools have to be developed at this point to fill the gap between the needs of practicing managers and the state of art in academia. Responding to this call, this research attempted to develop an analytical model to address various issues in manufacturing strategy.

Analytical research in manufacturing strategy is still in its infancy. The decision variables in models must be more precisely measured based on empirical data. The relationships among various variables also have to be statistically verified. The knowledge base of manufacturing strategy is not yet fully developed, limiting the full potential of analytical studies. However, it is the author's belief that both analytical and empirical studies must proceed in parallel. Analytical models can help managers and researchers alike to understand the structure of the decision problems. Also, analytical models provide a tool for a richer set of experiments. The descriptive and prescriptive findings from

analytical research can provide more insights on the phenomenon of manufacturing strategy. They can generate future research questions for more empirical studies.

This chapter summarizes the research conducted in this dissertation. Section 7.1 briefly overviews the content, focus, and findings of the study. Section 7.2 summarizes some contributions of this dissertation research for manufacturing strategy. Finally, Section 7.3 identifies some future research directions.

7.1 RESEARCH OVERVIEW

This section briefly describes the content and findings of the study. The scope and research questions are discussed first, followed by a discussion of the models, the environmental structure, and finally the experimental findings.

7.1.1 Research Scope and Questions

Manufacturing strategy includes numerous decision variables and issues. For a rigorous analytical study, the research scope has to be focused to a narrower range. Chapter II reviewed the knowledge base of manufacturing strategy research, and suggested that manufacturing strategy can be defined in terms of two key questions: 1) *What tasks* have to be achieved by the manufacturing function to support the business strategy, and 2) *How* these tasks should be achieved. Product planning and process design decisions are important parts of these two questions.

Two key strategic policy issues are associated with product and process decisions. The first issue is the pattern of linkage between product and process decisions. The nature of linkage between them reveals the role played by the manufacturing function in the process of business strategy formulation. The second issue is the value of manufacturing

flexibility, which has been suggested by researchers as a weapon enabling U.S. industries to better compete against foreign competitors.

Several research questions were established regarding these strategic issues. They center around the linkage, flexibility, and the environment: 1) Do integrated decisions perform better than non-integrated decisions? 2) Does a firm's performance improve if it has more flexibility in manufacturing process? 3) For which environments do these policies provide the most significant improvement? Reinforced with a literature review and a field study, these questions were translated into formal research hypotheses to be tested by the experimental study.

7.1.2 Models

Mathematical programming models were developed in Chapter III to represent the product planning and process design problems. An unlinked model was formulated to portray non-integrated decision making, in which the product and process decisions are made *sequentially*. A linked model was developed to make both decisions *simultaneously*, thus representing integrated decision making. Also, additional constraints were introduced into each model to represent a policy which emphasizes manufacturing flexibility.

Then a simulation model was developed to assess the consequences of different strategies under different environments. The simulation model generates various parameters for the decision problem, and solves the decision problem over several periods using a rolling schedule. The experimental research utilizes this simulation model to implement various experimental factors.

7.1.3 Environmental Structure

Chapter IV developed the environmental structure to be used in the experimental study. Guided by the organizational theory literature, four clusters of environmental

characteristics were proposed – complexity, uncertainty, tightness, and organizational learning. Also several individual factors were defined within the context of the decision model to form each cluster.

A field study examined managerial practices dealing with the environment-strategy connection. From the interviews of top manufacturing managers at three companies, it was found that companies operating under different environments developed different manufacturing strategies. The responses of the managers reinforced the cluster concept, and helped to set the factor levels for the experimental study.

7.1.4 Experimental Findings

Using the decision models, the experimental study assessed the impact of different policies under different environments. The major findings are summarized for the two key issues: linkage and flexibility.

7.1.4.1 Linkage, Environment, and Performance

The linked model generally outperforms the unlinked model. The unlinked model tends to introduce more products into the market, and thus generates unstable manufacturing requirements. Also the unlinked model tends to acquire more specialized equipment, thus resulting in a higher cost of changing the technology mix. However, several cases showed that the unlinked model can outperform the linked model. The optimality sought by the linked model has less value in an experimental environment which includes uncertainties in parameter estimation and a rolling schedule.

The experimental study also found that the environmental characteristics affect the relative performance of two decision models. The difference between two models were larger when the environment was more complex, less uncertain, and tighter. Thus it was concluded that more integration is needed among decisions under these conditions.

7.1.4.2 Manufacturing Flexibility, Environment, and Performance

The model with additional flexibility constraints is outperformed by the model without them. However, the performance difference is not large compared to the severeness of the constraints. Also the experiment showed that the model with additional constraints can indeed outperform the models without them. The uncertainty in the parameters and the rolling schedule are identified as possible reasons.

The experimental study also finds that flexibility is more beneficial when the manufacturing environment has high uncertainty and low tightness. The implication is that manufacturing flexibility is a viable alternative to cope with high environmental uncertainty when profit margins are larger.

7.2 RESEARCH CONTRIBUTIONS

The research contributions of this dissertation are discussed under two areas: methodology and experimental analyses.

7.2.1 Methodology

Analytical research in manufacturing strategy is needed as the field becomes more mature. Due to the abstractness of decisions in manufacturing strategy and the high uncertainty associated with them, analytical approaches have been used sparingly in manufacturing strategy research. However, recent developments and various empirical studies in this field provide a better basis for analytical research. Variables can now be defined and measured quantitatively, and the relationships among them are being verified. Analytical studies, in parallel with the empirical research, can help managers and researchers to better understand the problem structure of manufacturing strategy.

Descriptive and normative findings from a richer experimental study, enabled by the analytical model, add valuable insights on manufacturing strategy.

The decision model developed in Chapter III provides a tool for the analytical study of some aspects of manufacturing strategy. Multiple decisions are linked together into a mathematical programming problem, rather than focusing just on a single dimension of the problem. The model itself may not have a significant value as part of a decision support system, due to its abstractness and the uncertainty involved. Rather the model is valuable as a research *tool* to evaluate different strategic policies.

7.2.2 Experimental Analyses

The results of the experimental analyses can be helpful on two fronts: managerial practices and academic research. On the managerial practice front, the results can be helpful in formulating manufacturing strategy. Companies under a particular environmental setting can identify what to emphasize in developing its manufacturing strategy. For example, a company operating with a high level of uncertainty gains more benefit from manufacturing flexibility than from the integration of its product and process decisions.

On the academic research front, the experimental results help researchers to focus their study on more critical issues. The strong relationship between environmental complexity and the linkage aspect of manufacturing strategy implies that effective ways of linking decisions need to be found. Future research in this area can help managers integrate various decisions under a highly complex environment. Also the benefit of developing manufacturing flexibility is stronger under a highly uncertain environment. Thus researchers who study on the acquisition of flexible technology should give considerable attention to environmental uncertainty.

7.3 FUTURE RESEARCH DIRECTION

Manufacturing strategy research is still in its infancy. The findings of previous research, including this dissertation, cover only a small portion of the complex phenomenon of manufacturing flexibility. More decisions areas need to be covered, and more issues need to be addressed.

More research can be done within the context of the model developed in this dissertation. First, the planning horizon of the decision model can be controlled in the experimental study. Leaders in the field have suggested that the short-term orientation of the U.S. manufacturing managers has resulted in myopic decisions and poor performance (Hayes and Abernathy 1976; Buffa 1984). When the horizon is reduced, the effectiveness of the linked model would seem to decrease. Also the value of the additional flexibility constraints would seem to increase with a shorter planning horizon. An experimental research involving the length of planning horizon as a factor may generate valuable findings for the managers and researchers alike.

Second, the clustering of environmental factors need to be analyzed more rigorously. The results of the experimental study in Chapter VI might be sharpened by more careful definition of the environmental clusters. The preliminary study presented in Chapter V can be conducted more rigorously with a larger sample size. Testing on each individual factor may generate interesting results that can provide more insights to the environmental structure.

Also the model can be expanded to include other decision areas in manufacturing strategy that were not covered in this study. Researchers have suggested that the infrastructural decisions, such as production planning and control, can become a competitive weapon if managed properly (Hayes 1980; Wheelwright 1984). The impact of

product and process decisions on the product planning and control system can be studied by adding other modules to the model used in this dissertation.

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APPENDIX A
QUESTIONNAIRE FOR FIELD STUDY

QUESTIONNAIRE FOR EXECUTIVE SURVEY

* The following items are to be answered by top manufacturing managers. In the given space, please indicate your response following the five-scale measures: strongly disagree (1), disagree (2), neutral (3), agree (4), or strongly agree (5).

A. Business and Manufacturing Strategy

1. The current business strategy helps us compete effectively in the marketplace. ----- []
2. Manufacturing strategy is pursued with high consistency with business strategy. ----- []
3. Marketing strategy is pursued with high consistency with business strategy. ----- []
4. Marketing and manufacturing strategies are consistent to each other. ----- []
5. Manufacturing strategy follows from marketing strategy. ----- []
6. Marketing strategy follows from manufacturing strategy. ----- []

B. Product Planning

1. Product planning decisions are made mainly to respond to the market opportunity. ---- []
2. Product planning decisions are made mainly to exploit the manufacturing capability. -- []
3. We offer more standardized product at a lower price than our competitors. ----- []
4. We offer more customized product at a higher price than our competitors. ----- []

C. Process Design

1. Our manufacturing system is very efficient. ----- []
2. Our manufacturing system is very flexible. ----- []
3. Our manufacturing system can effectively handle the fluctuation in demand volume. --- []
4. Our manufacturing system can effectively handle the changes in products. ----- []
5. We purchase automated process technology because they are more labor-efficient. ----- []
6. We purchase automated process technology because they are more flexible. ----- []

D. Environmental Uncertainty

1. We operate our company in a very uncertain environment. ----- []
2. We have particular difficulty in forecasting future demand for the existing product. --- []
3. We have particular difficulty in forecasting future demand for the new product. ----- []
4. There exist high level of uncertainty regarding to the process capability of our manufacturing system. ----- []
5. The coordination between marketing and manufacturing is crucial to cope with the environmental uncertainty. ----- []

QUESTIONNAIRE FOR INDUSTRIAL CHARACTERISTICS

* The following items are answered by manufacturing managers. In the given space, please write your industry's high and low values for each item.

	LOW	HIGH
A. Demand Diversity Factors		
1. Number of product lines produced by the plant	_____	_____
2. Number of products per product line	_____	_____
3. Number of new product lines considered for introduction per year	_____	_____
4. Number of new product lines actually introduced per year	_____	_____
5. Number of new products per product line considered for introduction per year	_____	_____
6. Number of new products per product line actually introduced per year	_____	_____
 B. Demand Uncertainty Factors		
1. Average percentage error in forecasting next year's demand for the existing product	_____	_____
2. Average percentage error in forecasting next five year's demand for the existing product	_____	_____
3. Average percentage error in forecasting next year's demand for the new product	_____	_____
4. Average percentage error in forecasting next five year's demand for the new product	_____	_____
 C. Process Characteristics Factors		
1. Average number of different processes required for each product	_____	_____
2. Average machine hours required per unit product	_____	_____
3. Total number of different processes performed by the plant	_____	_____
 D. Technology Characteristics Factors		
1. Average number of different processes that can be performed by:		
a. conventional general-purpose technology	_____	_____
b. conventional special-purpose technology	_____	_____
c. automation technology	_____	_____
d. flexible automation technology	_____	_____
2. Compared to special-purpose technology, average relative efficiency of:		
a. conventional general-purpose technology	_____	_____
b. automation technology	_____	_____
c. flexible automation technology	_____	_____

3. Average unit acquisition cost of:

a.conventional general-purpose technology	_____	_____
b.conventional special-purpose technology	_____	_____
c.automation technology	_____	_____
d.flexible automation technology	_____	_____

4. Average unit salvage value (as a percentage of original value) of:

a.conventional general-purpose technology	_____	_____
b.conventional special-purpose technology	_____	_____
c.automation technology	_____	_____
d.flexible automation technology	_____	_____

5. Average annual fixed overhead cost per unit of :

a.conventional general-purpose technology	_____	_____
b.conventional special-purpose technology	_____	_____
c.automation technology	_____	_____
d.flexible automation technology	_____	_____

6. Average variable cost per machine hour for:

a.conventional general-purpose technology	_____	_____
b.conventional special-purpose technology	_____	_____
c.automation technology	_____	_____
d.flexible automation technology	_____	_____

7. Percentage of capacity in machine hours per year that is provided by:

a.conventional general-purpose technology	_____	_____
b.conventional special-purpose technology	_____	_____
c.automation technology	_____	_____
d.flexible automation technology	_____	_____

E. Process Uncertainty Factors

1. Errors in estimating process requirement per unit of existing product	_____	_____
2. Errors in estimating process requirement per unit of new product	_____	_____
3. Errors in estimating efficiency of existing technology in performing a particular process	_____	_____
4. Errors in estimating efficiency of new technology in performing a particular process ..	_____	_____

F. Investment Characteristics

- 1. Ratio between annual sales and total product development investment_____
- 2. Ratio between annual sales and total capital investment of technology acquisition_____
- 3. Average development investment per each new product line_____
- 4. Average development investment per each new product_____

G. Profitability and Market Competition Characteristics

- 1. Average unit profit margin as percentage of cost_____
- 2. Average length of product life cycle for a product line_____
- 3. Average length of product life cycle for a product_____

APPENDIX B
RESULTS OF EXPERIMENT:
AVERAGE NET CASH FLOW

Appendix B.1

Average Net Cash Flow : Replication 1

Environmental Factors			Model IN		Model PP	
Tightness	Complexity	Uncertainty	Without Flexibility Constraints	With Flexibility Constraints	Without Flexibility Constraints	With Flexibility Constraints
High	High	High	515019	482390	489025	425714
High	High	Low	589064	532728	506614	477759
High	Low	High	251712	228876	252287	225846
High	Low	Low	267644	240860	262168	236898
Low	High	High	892918	885463	871690	811493
Low	High	Low	971339	924489	888409	808655
Low	Low	High	428148	414372	426519	401799
Low	Low	Low	448759	420257	461355	408981

Appendix B.2

Average Net Cash Flow : Replication 2

Environmental Factors			Model IN		Model PP	
Tightness	Complexity	Uncertainty	Without Flexibility Constraints	With Flexibility Constraints	Without Flexibility Constraints	With Flexibility Constraints
High	High	High	563723	525028	518300	438152
High	High	Low	596949	518062	560152	465235
High	Low	High	322333	311515	307793	255486
High	Low	Low	361035	343421	390165	298590
Low	High	High	1035214	945809	954187	879097
Low	High	Low	1083454	981684	995663	884845
Low	Low	High	583740	578570	580732	499186
Low	Low	Low	661370	620958	652122	592126

Appendix B.3

Average Net Cash Flow : Replication 3

Environmental Factors			Model IN		Model PP	
Tightness	Complexity	Uncertainty	Without Flexibility Constraints	With Flexibility Constraints	Without Flexibility Constraints	With Flexibility Constraints
High	High	High	486350	490395	442359	467008
High	High	Low	560585	521819	481518	449796
High	Low	High	217147	210148	226176	195315
High	Low	Low	239311	194947	258116	214264
Low	High	High	838002	816953	807306	775308
Low	High	Low	879709	855722	819335	784908
Low	Low	High	382557	360295	405504	372305
Low	Low	Low	412430	392328	435225	390415

Appendix B.4

Average Net Cash Flow : Replication 4

Environmental Factors			Model IN		Model PP	
Tightness	Complexity	Uncertainty	Without Flexibility Constraints	With Flexibility Constraints	Without Flexibility Constraints	With Flexibility Constraints
High	High	High	358250	313461	311501	254338
High	High	Low	387348	334248	332171	266529
High	Low	High	105640	102947	118498	83599
High	Low	Low	150005	119689	134505	90671
Low	High	High	684084	650022	643520	571697
Low	High	Low	711557	651748	672822	585882
Low	Low	High	275671	261019	266265	231421
Low	Low	Low	297335	273137	286989	250311