UNDERSTANDING THE RELATIONSHIP BETWEEN MANUFACTURING STRATEGY AND COMPETITIVENESS: TOWARDS A DYNAMIC APPROACH

ESRC Centre for Business Research, University of Cambridge
Working Paper No.209

By

Dr. Shekhar Jayanthi
Division of Economics and Business
Colorado School of Mines
Golden CO 80401, U.S.A.
Phone: 1-303-273-3925
Fax: 1-303-273-3927
e-mail: sjayanth@mines.edu

September 2001

This Working Paper relates to the CBR Research Programme on Industrial Organisation, Competitive Strategy and Business Performance

Abstract
Manufacturing firms are facing a "competitive gridlock" despite implementing strategic organizational and technological changes. Building on the product-process matrix and developments in organizational learning, we develop a two-level model that focuses on balancing the decisions related to the short-term and long-term organizational activities at both the firm and manufacturing levels dynamically. The model indicates that the system behavior is *likely* to be dynamically robust as environmental uncertainty increases, suggesting that the set of drivers (practices and capabilities) of competitiveness *tends* to be bounded; the elements of this set are *likely* to be closely integrated across the two levels.

JEL Codes: L60, O31

Key words: Manufacturing strategy, competitiveness, manufacturing practices, competitive capabilities

Acknowledgements
An earlier version of this paper appeared as part of the proceedings of and was presented at the Manufacturing and Service Operations Management (MSOM) Conference held at the University of Michigan, Ann Arbor from June 25 – June 27 2000. I am thankful to Dr Andy Cosh, Professor Alan Hughes and Professor Mike Gregory of the Centre for Business Research at the University of Cambridge for their extensive comments on earlier versions of this paper.

Further information about the ESRC Centre for Business Research can be found on the World Wide Web at the following address:
http://www.cbr.cam.ac.uk

UNDERSTANDING THE RELATIONSHIP BETWEEN MANUFACTURING STRATEGY AND COMPETITIVENESS: TOWARDS A DYNAMIC APPROACH

1. Introduction

Manufacturing firms are facing a "competitive gridlock" despite implementing strategic organizational and technological changes (Skinner, 1996). In this paper, we consider a dynamic approach to understand the "missing link" between the firm and manufacturing strategies (Skinner, 1969) under environmental uncertainty resulting from changes in customer preferences, governmental regulations, technology, and competitors. Can this "missing link" be explained in terms of the practices and capabilities related to manufacturing that shape the competitive advantage of firms? As competition intensifies and the product and process life cycles become shorter and shorter – a trend observable in most manufacturing industries – there is an increasing emphasis on manufacturing operations to implement practices and develop capabilities that enhance competitiveness. In order to maintain this emphasis, the effective utilization of a firm's knowledge as new products and processes, and corresponding operational practices are implemented at an extremely fast pace, tends to be critical to the survival of manufacturing firms (Bohn, 1994). Recent studies in strategic management have also alluded to the knowledge and capabilities of firms as sources of manufacturing competitiveness.

Considering manufacturing strategy as a functional strategy within the hierarchy of a firm (Swamidass and Newell, 1987), this paper focuses on gaining an understanding of how the epistemic variables – manufacturing practices and competitive capabilities – can generate sustainable competitive advantage for a firm. The aim is to examine the critical link between strategic decisions related to manufacturing competitiveness at two levels – manufacturing operations and firm – in the face of changes in the external environment. Therefore, the *objectives* of this paper are threefold: first, to develop a framework for understanding the link between manufacturing strategy and competitiveness; second, to explore the strategic decision making processes at levels within the firm in the context of the changing external environment, and develop an analytical model that captures these processes and their interactions; and third, to understand the role of manufacturing in firm competitiveness and illustrate the nature of drivers of competitiveness.

The following section is an overview of the extant literature on competitiveness. The subsequent section outlines a conceptual foundation that describes decision-making processes at levels within the firm. The next section develops an analytical model that captures the processes at manufacturing business unit and firm levels and interactions between them. Later, we examine the implications of the model for linking manufacturing strategy to competitiveness. The subsequent section describes the nature of determinants of competitiveness. The paper concludes with remarks on implications of the model-based approach for theory and practice.

2. Theoretical Background

This section reviews the relevant literature on strategic decisions that a firm needs to make under different environmental conditions in order to be competitive, thereby providing a theoretical background for development of a conceptual framework in the following section. The rate and extent of change in a manufacturing firm's environment is reflected by the events, which characterize the processes in the environment. Some authors have also characterized the rate and extent of change in a firm's environment using the terms "clockspeed" (Mendelson and Pillai, 1998). These events determine the fitness landscape that the firm needs to adapt to. When the rate and extent of change in the environment is extremely high, this landscape tends to be "rugged." This is because the firm has to adapt to frequent and ongoing changes in the environment very rapidly. On the other hand, when the rate and extent of change is relatively low, the landscape is even with few "peaks."

The processes operating in a firm's environment are illustrated in the selection of, for example, technologies implemented and "best practices" developed by different firms in an industry. Usually, there are several technologies competing for implementation by manufacturing firms (Arthur, Ermilov, and Kaniovski, 1987). Increasing returns to implementation of technology may drive the industry to a single dominant technology. For example, a dominant technology could emerge as a result of implementation of flexible manufacturing systems by firms, thereby modifying the industry environment itself. As in the case of selection of a dominant technology, innovator firms in an industry seem to generate best practices by experimentation, while imitator firms tend to deploy these practices gradually at lower additional cost to them. The best practices of the innovator firms are selected in a Schumpeterian sense by "creative destruction", that is, using combinations of knowledge (and associated capabilities) that already exist (Nelson and Winter, 1982: 277).

The selection processes occur in a path-dependent manner with small changes in the events early on selecting the technology and "best practice" that eventually survives. It is difficult to say *a priori* which technology or practice will dominate the firm environment. The technology or "best practice" that becomes dominant, or the structure that emerges, need not be the best; events early on can "lock in" the system into an inferior technology or practice. Once a single structure emerges and becomes self-reinforcing, it is difficult to change it. Therefore, a firm's competitiveness depends on its ability to adapt to the "fitness" landscape or changes in the external environment. In other words, competitiveness is the ability of a manufacturing firm to not only be profitable in the short-run, but also be able to survive and prosper in the long run.

The adaptive activities of the firm – that result from the strategic organizational and technological changes – develop the knowledge and the associated capabilities to adapt to the fitness landscape in the firm's environment. The developments in the business strategy literature also referred to as the resource-based view focus on the formation of knowledge based on these activities and argue in favor of internal sources of a firm in obtaining a competitive advantage. More specifically, this view argues in favor of knowledge generated as a result of the activities related to the interaction between the organization and technology. The consensus of the resource-based view is that the seminal work of Penrose (1959) provides the appropriate vantage point to understand the firm activities that contribute to knowledge.

The manufacturing firm's adaptive activities, resulting from the strategic changes, exhibit two interdependent properties, which seem to be similar to the processes of selection in its environment. The first property is the path-dependent nature of these adaptive activities (Cyert and March, 1963). Since the knowledge and associated capabilities of firms developed in a path-dependent manner, this knowledge is unique and therefore its replication is a difficult and uncertain undertaking (Lippman and Rumelt, 1982: 420). The second property is the presence of a structure or the formation of "organizational routines" that emerge from engaging in activities over time. These routines embody a firm's knowledge and are sources of building capabilities, through constantly reconfiguring this knowledge, in a dynamic manner. As a firm's experience is unique, capabilities cannot be acquired but they must be built.

3. Conceptual Foundation

The external environment of manufacturing firms can be considered as the source of events and their associated selection processes that create opportunities and threats for individual firms, and hence trigger their strategic choices. There are two main characteristics of the firm environment – *resource dependency* and *informational complexity* – that contribute to the environmental uncertainty (Scott, 1992). The first characteristic focuses on the environment as stocks of resources, while the second concentrates on the availability of information. The external environment influences, and is influenced by, the manufacturing firm in two interdependent ways. First, the external environment leads to the implementation of those organizational and technological changes by firms, which could contribute to competitiveness. These changes seem to be guided by the processes of selection operating in the external environment. Second is the promotion of coordination of adaptive activities within the manufacturing firms that render effective decision-making and utilization of distributed knowledge within the firm. The capabilities that are necessary for survival are dependent on the selection environment. For example, in pharmaceutical manufacturing, firms need to be able to produce materials at extremely high purity levels, consistently.

From an operations standpoint, manufacturing strategy consists of two interdependent elements – manufacturing practices and competitive capabilities (Anderson, Cleveland, Schroeder, 1984; Hayes, Wheelwright, and Clark, 1988; Miller and Roth, 1994; Voss, 1992). Manufacturing practices refer to the technological and organizational changes that a firm makes to enhance its competitiveness through manufacturing. Understanding these practices and their impact on competitiveness is at the core of strategic management of manufacturing operations, and its overall contribution to firm competitiveness. The manufacturing practices can be classified into structural and infrastructural changes. Decisions related to structural changes form the "bricks and mortar" and are therefore considered to have long-term implications. Examples of these decisions are those related to size, capacity and equipment vintage of manufacturing operations. Decisions related to infrastructural changes are those that determine how the manufacturing operations are managed. Typically, these decisions are under the direct control of the manufacturing operations managers, and are easier to change because they do not require the large and costly modifications that structural changes do. Infrastructural changes are those related to equipment, quality, inventory, workforce and confusion-engendering activities (like, new product introductions and product variety) in manufacturing operations.

The *second* element of manufacturing strategy is competitive capabilities, which deals with what manufacturing operations must accomplish. This is achieved by the effective use of knowledge related to manufacturing and other functions in the firm in response to environmental uncertainty. New product development is an example of a critical competitive capability, which requires integration of different types of specialized knowledge in several areas. While development of some products is the result of the application of new knowledge, development of others results from reconfiguring existing knowledge to develop "architectural innovations." In order to adapt to changing environmental conditions, the competitive capabilities should have both a relatively short-term, and a long-term orientation. An important question is the critical balancing between short-term survival and the long-term development of capabilities. "Competitive advantage requires both, exploitation of existing internal and external firm-specific capabilities and exploration in developing new capabilities." (Kogut and Zander, 1987: 393).

4. Analytical Foundation

We conceptualize strategic decision-making processes at the firm and manufacturing levels as "streams" of organizational activities (Mintzberg, 1978; Spender, 1980) that contribute to firm's knowledge. Considering activities as "elements" of the decision-making processes aids not only in an understanding of the nature of strategic processes but also allows one to link the dynamics at the levels in a fundamental manner (Porter, 1991). Building on the product-process matrix (Hayes and Wheelwright, 1979) and organizational learning theory (March, 1991), adaptive activities within the manufacturing firm can be categorized into those that relate to the current demands of the environment and those related to the future demands of the environment. These two types of activities are focused on the short and long-term changes that also reflect the manufacturing firm's strategic position on the product-process matrix.

Activities related to future changes in the industry environment are *long-term activities*. The purpose of such adaptive activities is to ensure the survival and prosperity of a firm and its manufacturing operations in the future. At the firm level, the long-term activities could result from decisions related to changes in the external environment, such as those related to diversification, allocation of resources to development of technologies, and identification of new consumer markets can be included in this category. The long-term manufacturing activities, resulting from the strategic organizational and technological changes, could include experimentation with new process technology and equipment designs, or experimentation with new product designs, or both. A product structure that requires a low volume high standardization and a process structure that corresponds to a jumbled flow or job shop would concentrate on long-term adaptive activities. The unrestrained growth in long-term activities at each of the two levels can be represented as follows:

$$\Delta x_{it} = x_{it+1} - x_{it} = \kappa_i x_{it} \Delta t \quad (1)$$

The above equation represents the change in number of activities from x_{it+1} to x_{it} over a time Δt at the *i*th level. x_{it} denotes the number of long-term activities taking place at the *i*th level at time t – level 1 corresponds to the manufacturing operations and level 2 corresponds to the firm level. κ_i denotes the relative strength of long-term and short-term activities at the *i*th level. This parameter represents the intrinsic growth rate of activities at the *i*th level – that is, the rate at which long-term activities "grow" in the absence of "competition" from short-term activities.

Activities related to current changes in the external environment are *short-term activities*. At the firm level, these activities could be generated by self-reinforcing mechanisms described earlier. Similarly, at the manufacturing operations level, the short-term activities could include modification and refinement of existing products, equipment, process technologies and manufacturing practices aimed at high volume, reliable and replicable production. The purpose of such activities is to ensure the survival and prosperity of firm and its manufacturing operations in the present. A product structure that consists of high volume and a high degree of standardization and a process structure that is a continuous flow shop correspond to a focus on long-term activities. Analytically, the short-term activities at each of the two - levels (I=1,2), in absence of influence from the other level, can be represented by modifying Equation (1) using the feedback parameters α_{ii}:

$$\Delta x_{it} = \kappa_i x_{it} \Delta t - (\alpha_{ii}/\kappa_i)(\kappa_i x_{it} \Delta t) x_{it} \quad (2)$$

Engaging exclusively in either short or long-term activities is potentially self-destructive for an organization – firm or its manufacturing operations. The increasing returns to short-term adaptive activities could increase the opportunity cost of engaging in activities related to long-term changes. This is referred to as the success trap. A firm, whose manufacturing activities, focus only on high-volume production of its *existing* products is likely to find it extremely difficult to make an agile transition to high volume production of *new* line of products. On the other hand, firms and their operations engaged exclusively in long-term activities can be turned into frenzies of experimentation and change by a dynamic of failure – "the escalation of commitment to a course of action" (Staw, 1981). This is referred to as the failure trap. Concentrating purely on long-term activities can also be self-destructive because an organization is never likely to benefit from the returns of its knowledge gained from experimentation. Manufacturing operations that focus exclusively on experimenting with new product and process designs, and make no efforts toward attaining commercially reliable and replicable production volumes – to qualify for market orders (Hill, 1998) – are unlikely to survive for very long. A diagonal position in the product-process matrix corresponds to a proper match between product and process structures. An off-diagonal strategic position represents a mismatch that can result in unnecessarily high cost – for example, a firm operating its manufacturing as a job shop that produces only one product (resulting in opportunity cost), or a firm that uses continuous flow for its operations that undergo numerous equipment changeovers to several products demanded only in very low volume (resulting in cash costs).

Thus, the extent of focus on the short and long run can be used as a basis for understanding the interaction between the dynamics of firm and manufacturing activities. Given the streams of long-term and short-term activities, the effectiveness of these activities in gaining a competitive advantage (in a firm's external environment) is the result of strategic fit, that is, the consistency between the competitive advantage that a firm seeks and the competitive capabilities and manufacturing practices that it uses to achieve that advantage. Critical to understanding this interaction or the missing link is the extent to which the adaptive activities at the firm and manufacturing operations levels are *consistent* with one another (Hayes and Wheelwright, 1984). Too often top management overlooks manufacturing's potential to strengthen or weaken a company's competitive ability. For example, if top managers are unfamiliar with the process technology and leave the choice to technical managers, then the firm may end up with sophisticated, but inflexible, automated technology, while it may pursue a strategy of wide product variety and cost-efficiency that could be supported better with a relatively low-technology process equipment. Similarly, changes in engineering design specifications may not be consistent with the strategic decision-making processes at the firm level. This consistency can be included in the model by using a product term that represents the activities at the two levels by incorporating the consistency parameters α_{ij} $(i \neq j; j = 1,2)$:

$$\Delta x_{it} = \kappa_i x_{it} \Delta t - (\alpha_{ii}/\kappa_i)(\kappa_i x_{it} \Delta t) x_{it} - (\alpha_{ij}/\kappa_i)(\kappa_i x_{it} \Delta t) x_{jt} \quad (3)$$

x_{jt} is the unrestricted growth in the long-term activities at the *j*th level as in Equation (1).

Since we have already discounted the possibility of pure focus on either short or long-term activities, at the two levels, the strategic decisions should result in sufficient long-term activities at the firm level and short-term activities at the manufacturing operations level and *vice versa*, in order for the manufacturing firm to be competitive. In the former case, the long-term activities at the firm level could influence (measured with α_{12}) the manufacturing operations negatively, as short-term activities at this level would leave the manufacturing operations unprepared for any potential decisions taken at the firm level. However, the adaptive activities at the manufacturing operations level might contribute positively (measured with α_{21}) in the short-run towards high-volume production. For example, *Hewlett Packard* (HP) has focused primarily on the left hand quadrant of the product-process matrix (low volume and a job shop flow) in order to adapt to the environmental changes. The practices and capabilities of HP are directed mainly towards new product development and introduction. As a result, the decisions at the manufacturing operations level do not emphasize any changes to the processes unless required to do so by the firm level decisions related to, say, next generation of products. When this happens, new manufacturing processes are likely to be adapted, on an as-needed basis, from other industries where they are already well-developed, as in the use of postponement or delayed product differentiation (Feitzinger and Lee, 1997). Process and product transfer that are more important decisions at the firm level, not new process development or radical process innovation, become management's chief concerns when contemplating changes in manufacturing operations.

On the other hand, the firm level decisions could focus on short-term activities and the manufacturing operations level could engage in long-term activities. This situation means that there are two possible situations that relate to the consistency of the decision-making processes at the two levels. The first could have a positive impact on the strategic decisions at the manufacturing operations level, as the firm's operations would be able to cope with changes in the external environment. An example of a company that has followed this option is *Texas Instruments* (TI). TI often temporizes while other companies do much of the early product innovation (in the upper left-hand quadrant of the product-process matrix) until it identifies an appropriate entry point. After it enters, it uses its skills in process innovation through its manufacturing practices and capabilities to push rapidly down the product-process matrix diagonal, displacing some of the product's original developers, who neglected whether intentionally or unintentionally, to develop similar skills.

In the second situation in which the firm level decisions are focused on short-term activities, there could be a negative impact on strategic decisions at the manufacturing operations level because the benefits of the knowledge gained by exploration might not be rewarded at the firm level. Therefore, the adaptive activities resulting from the strategic decisions made at the two levels, manufacturing operations and firm, could have a positive or negative influence on each other. During the mid 1960s *RCA*, which had traditionally chosen to lead the industry was introducing newer more mechanized manufacturing such as transfer lines which automatically inserted electronic components into printed circuit boards. As the market evolved toward higher volumes and more standardized products this represented a move down the process dimension to a position below the diagonal. This strategy backfired when the introduction of integrated circuits and totally solid-state designs rendered much of this automated equipment obsolete.

In light of the above discussion, the dynamics of and the interactions among activities at the and firm and manufacturing operations levels, can be represented in *continuous* time using Equation (3) as $\Delta t \rightarrow 0$:

$$\frac{dx_i(t)}{dt} = f_i(x_i, x_j) = x_i(t)\left[\kappa_i - \sum_{j=1}^{2} \alpha_{ij} x_j(t)\right]; i = 1,2. \quad (4)$$

The above expression[1] is a variant of the Lotka-Volterra (LV) predator-prey system also used in the biological sciences. The left-hand side of the equation denotes the rate of change in the growth of activities at the *i*th level. The intuition behind using the above system of equations is that the growth rate of activities at one level occurs under the influence of those at the other level. In other words, the growth rate of the adaptive activities at each of the two levels cannot occur unconstrained, but is influenced by the strategic decisions made at the other level. The model represents the dynamic tension horizontally in terms of the short-term and long-term strategic decisions, and vertically in terms of consistency (strength and direction of interactions) among decisions made at the two levels.

The formulation in Equation (4) is sufficiently general to accommodate organizational diversity in a population with respect to size and structure as the focus is on the intensity with which the manufacturing firm utilizes its knowledge in making strategic decisions at the firm and manufacturing operations. Building on the resource-based view of the firm, a firm's survival and prosperity depends on the effectiveness with which it reconfigures its knowledge under environmental changes. In other words, knowledge serves as a resource for the manufacturing firm irrespective of the organizational form (size or structure). As in the case of biological sciences, we use this approach to indirectly address the problem of competitiveness, rather than using the exact equations in (4). As shown in Appendix B, a resource [knowledge] spectrum $K(z)$ is likely to exist for the diverse set of organizations within and across populations, so that competitiveness of an organization depends on the intensity of resource [knowledge] utilization at the two levels based on the knowledge utilization functions $h_i(z)$ for $i = 1,2$ under the presence of overlapping knowledge spectra.

In general, using a linearized approximation of the nonlinear dynamical system in Equation (4), the matrix represented by $\mathbf{A} = \begin{bmatrix} \partial f_1/\partial x_1 & \partial f_1/\partial x_2 \\ \partial f_2/\partial x_1 & \partial f_2/\partial x_2 \end{bmatrix}$ plays a critical role in the solution of the system of equations and hence in determining overall behavior of the manufacturing firm. The stability of the two-level system depends on the nature of eigenvalues $\lambda_j (j = 1,2)$ that can be decomposed into real and imaginary parts. The real part generates exponential growth at the respective level and the imaginary part is responsible for sinusoidal oscillations. The eigenvalues for the community matrix are given by (Boyce and DiPrima, 1992):

$$\mathbf{x}(t) = c_1 \xi^{(1)} e^{\lambda_1 t} + c_2 \xi^{(2)} e^{\lambda_2 t}. \quad (5)$$

The vector $\mathbf{x} = [x_1(t) \;\; x_2(t)]^T$ consists of the proportions of adaptive activities and the vectors represent the eigenvectors $\xi^{(1)}$ and $\xi^{(2)}$ corresponding to the two levels. c_1 and c_2 are constants.

The stability conditions of the dynamical system allow one to illustrate the four stages of the role of manufacturing in firm-level decisions (Hayes and Wheelwright, 1984). In the following cases, we will use the *relative* proportions of organizational activities with respect to their equilibrium $v_i(t) = (x_i(t) - x_i^*)/x_i^*$ for $i = 1,2$, to show the patterns of system dynamics in the phase plane (activities space) in the *neighborhood* of the equilibrium point.

Case 1 (unequal eigenvalues with the same signs). Depending on the magnitude and direction of the eigenvalues, the trajectories of the two-level system are directed inwards or outwards from the *improper node*, resulting in an unstable system behavior. When $\lambda_1 < \lambda_2 < 0$, the trajectory of the system moves towards the critical point. It is evident from the

Equation (5) that $\mathbf{x} \to \mathbf{0}$ as $t \to \infty$ regardless of the values of c_1 and c_2. In other words, all solutions approach the node at the origin as $t \to \infty$. When $0 < \lambda_1 < \lambda_2$, the trajectories have the same pattern as in the previous case, but the direction of motion is away from, rather than toward, the critical point at the origin. This situation is depicted in Figure 1A using an example in which the relative strength of influence of the firm-level activities on manufacturing is larger than the role of manufacturing in firm-level decision-making $\kappa_1 = \kappa_2 = 1$, $\alpha_{11} = 0.30$, $\alpha_{12} = 0.85$, $\alpha_{22} = 0.50$, and $\alpha_{21} = 0.30$. The pattern of dynamics around the equilibrium point probably reflects the case of Stage 1 companies that consider their manufacturing to be *internally neutral*, in that its role is simply to manufacture reactively. Depending on the focus of the manufacturing firm on purely short- or long-term activities, the strategic decision-making processes are either convergent or divergent at the improper node. This means that the manufacturing operations of the company merely react to the decision-making processes at the firm level. From a product-process matrix standpoint, this means that the manufacturing operations engage in the extremes of high-volume production (standardization), or in the processes employed to manufacture entirely customized products.

Case 2 (real eigenvalues with opposite signs). In this case, eigenvalues with real and opposite signs could lead to an unstable system with trajectories around a *saddle point.* All solutions starting along the positive eigenvector (say $\xi^{(1)}$) remain along this vector as t increases. Since $\lambda_1 > 0$, the Euclidean distance $\|\mathbf{x}\| \to \infty$ as $t \to \infty$. If the solution starts at an initial point on the line through $\xi^{(2)}$, then the situation is similar except $\|\mathbf{x}\| \to 0$ as $t \to \infty$. Figure 1B illustrates this case. The values of the parameters in Equation (4) in that the relative strength of the influence of firm-level decisions on manufacturing is higher compared to the feedback from its own activities. However, now the mutual interaction of one level on the other is relatively closer in magnitude ($\kappa_1 = \kappa_2 = 1$, $\alpha_{11} = 0.30$, $\alpha_{12} = 0.65$, $\alpha_{21} = 0.50$, and $\alpha_{22} = 0.25$). Firms operating in this stage are likely to focus outward and ask their manufacturing to be *externally neutral*, that is, be able to meet the industry standards and practices set by major competitors. Usually, the planning horizon for manufacturing investment decisions is extended to incorporate a single business cycle. The decision-making processes at the two levels are such that the manufacturing operations are not necessarily aligned with the strategic decisions at the firm level. This means that although manufacturing is doing its best to meet the industrial standards, firm's strategic decision-making processes are not consistent with the manufacturing activities.

Case 3 (equal eigenvalues). The presence of equal eigenvalues results in an asymptotically stable system that has trajectories about a *proper* or *improper node*. There are two sub cases, depending on whether the repeated eigenvalue has two independent eigenvectors or only one. When there are two independent eigenvectors, the trajectory of the system lies on a straight line through the origin, which is a proper node. When there is only one independent eigenvector ξ, each trajectory is asymptotic to a line parallel to the eigenvector. The critical point is called an improper node. The presence of the proper or improper node leads the system to be asymptotically stable. As an example, consider the situation shown in Figure 1C where $\kappa_1 = \kappa_2 = 1$, $\alpha_{11} = 0.50$, $\alpha_{12} = 0.75$, $\alpha_{21} = 0.75$, and $\alpha_{22} = 0.50$. In this situation, irrespective of the values of the interaction coefficients of the dynamical system in Equation (4), we have equal eigenvalues. The situation depicted in Figure 1C probably corresponds to Stage 3 companies which have manufacturing operations that are *internally supportive* of other parts of the company, with a coordinated set of manufacturing structural and infrastructural decisions tailored to their specific competitive strategy. The manufacturing operations are aligned with the firm level decisions, and maintain a mix of adaptive activities consistent with that at the firm level to a certain extent. The horizontal and vertical dynamic tension across the adaptive activities related to the overall firm and manufacturing is relatively difficult to manage because of the presence of both the short and long term activities at the two levels.

Case 4 (complex eigenvalues). If the eigenvalues are complex, the trajectories of the system are always *spirals* in the phase plane. They are directed inwards or outwards, respectively, depending on whether $\mathrm{Re}(\lambda_j)$ is negative or positive. More specifically, all the trajectories approach the critical point as $t \to \infty$. This is the case if eigenvalues are real and negative or complex with negative real part. At least one (possibly all) of the trajectories tends to infinity as $t \to \infty$. This is the case if at least one of the eigenvalues is positive or if the eigenvalues have positive real parts. When the eigenvalues are purely imaginary, the trajectories neither approach the critical point nor tend to infinity as $t \to \infty$. In this case, the presence of complex eigenvalues could enable the two-level system to be asymptotically stable in the neighborhood of an equilibrium (critical) point. This situation is shown in an example in Figure 1D where the influence of manufacturing activities on firm level activities is higher along with a decrease in the growth of activities at the firm level $\kappa_1 = -1$, $\kappa_2 = 1$ $\alpha_{11} = 0.50$, $\alpha_{12} = 0.50$, $\alpha_{21} = 0.85$, and $\alpha_{22} = 0.50$. This case is probably indicative of companies in Stage 4 that consider their manufacturing as *externally supportive*; that is, playing an essential and proactive role in helping the firm to achieve an edge over its competitors. The trajectories of the two-level system reflect the complexity involved in adapting to the changes in the external environment. The mix of adaptive activities at both the levels is such that manufacturing is centrally involved in major marketing or engineering decisions. Long-term activities are also pursued in order to acquire capabilities in advance of needs.

5. Linking Manufacturing Strategy to Competitiveness

The rate and extent of change in the external environment was identified in the section on theoretical background as being critical to competitiveness. This section considers environmental variability as a determining variable, in using the analytical model developed in previous section, to understand the relationship between manufacturing strategy and competitiveness. The development of the proposition is based on the question: *What is the impact of external environmental changes on decisions related to manufacturing that would enable it to be competitive in an environment?* In order to assess this impact we see how adaptive activities and their associated decision-making processes are influenced under changing environmental conditions. This section moves from relatively higher environmental variability to lower variability with the intent to take advantage of the time window over which the processes unfold (Brittain and Whooley, 1988).

5.1 High environmental uncertainty

The environments in which the uncertainty is *high* are referred to as "high-velocity" environments, "in which there is a rapid and discontinuous change in demand, competitors, technology and/or regulation" (Bourgeois III and Eisenhardt, 1988). In this environment the product and process life cycles are extremely short. Since the environment is extremely unpredictable, a manufacturing firm is more likely to engage in both short-term and long-term activities at a faster rate. The adaptive activities, which have a *dynamically robust* (May, 1981) character and therefore span a wider range of activities space, are more conducive to survival and prosperity of a firm in a highly variable environment. This follows from a relatively high value of the intrinsic growth rate parameters (κ_1 and κ_2) for both manufacturing operations and firm levels in Equation (4). This is because the selection processes in the firm environment are characterized by both mechanisms – those that are self-reinforcing and those related to rapid and ongoing changes in the environment. Also, when the environmental uncertainty is very high, there is an increase in the generation of activities at both levels. A high rate of growth in activities will tend to reduce the strength of interaction among levels, implying a greater overlap in the decision-making processes at manufacturing operations and firm levels. This, in turn, means a stronger "bottom-up" contribution of manufacturing strategy to the overall firm competitiveness. For example, in the context of semiconductor manufacturing – an industry operating under high uncertainty and thus suggestive of future manufacturing in other industries – Polley (1994: 452) notes "... internal variations in resource allocation helped *Intel* make the choice to exit the dynamic random access memory (DRAM) market. Individual managers allocated wafer production [manufacturing operations] between DRAMs, EPROMs [erasable programmable read only memory], and microprocessors, which resulted in the de facto changes in strategy even before senior managers formally made strategic changes at the corporate [firm] level."

This situation is reflected in the nature of the dynamics of the LV Equation (4), when the system behavior is asymptotically stable – that is, the system tends to reach the equilibrium point only as time $t \rightarrow \infty$ (see Figure 2A). This means that the manufacturing operations and firm level activities – short-term and long-term – keep taking place without converging to the equilibrium point. Even small changes in the initial conditions, which are "sufficiently close" (within a circle with radius δ), could lead the system to follow entirely different paths. In other words, the proportion of adaptive activities over time could be entirely different for small changes in initial environmental conditions (Tyre and Orlikowski, 1994). The trajectory of the system tends to be within an *attractor*2 (the subset of activities space) given by the circle, around the equilibrium point, with a radius ε– that is, the nature of activities tends to be *bounded* (Eisenhardt and Tabrizi, 1994). The system behavior is said to be chaotic – that is, although the behavior appears to be completely random and unpredictable, there is an underlying order – and is in the domain of nonlinear dynamical systems.

The short-term and long-term activities contribute to the knowledge gained by this search behavior, which is reflected in the manufacturing firm's ability to rapidly innovate product and process technologies, and implement organizational and technological changes, which are the capabilities and practices associated with the manufacturing strategy to improve competitiveness. The knowledge tends to be weakly path-dependent because the firms in this type of environment are repeatedly dealing with rapid and ongoing changes.

5.2 Low environmental uncertainty

When the environmental uncertainty is *low*, the rate and extent of change can take place in two ways. The *first* is concerned with regular and predictable changes. The system behavior that could emerge from the dynamics of the LV Equation (1) in this type of environment related to predictable changes is periodic (Figure 2B). The system oscillates in a predictable manner around the equilibrium point. A system will assume a periodic orbit "close" to the equilibrium point, even if initial conditions vary but are "sufficiently close" (within the circle with radius δ). In other words, the short-term and long-term activities vary in a fixed proportion and periodically over time for small environmental changes. A consequence of the predictable nature of the environment is that the interaction at the two levels is still preserved. As a result, the extent of overlap between activities at intra-firm levels is maintained, varying only in a systematic and predictable manner over time. The adaptive activities of firms operating under this kind of environment are more likely to exhibit *dynamic fragility* to some extent. As the growth rate of activities at the firm and manufacturing levels, in this case, varies in a predictable manner, there tends to be an interaction between the two levels to some degree. This means that there is an overlap between the strategic decision-making processes at the two levels.

Depending on the proportion of adaptive activities and the strength of interaction between levels, the manufacturing operations can significantly contribute to the firm competitiveness. Because of the predictable nature of the external environment, there tends to be a greater emphasis on competitive capabilities, like quality improvement and efficiency. As a result of engaging in sufficient exploration, if not more, the firm is able to implement manufacturing practices, because of the availability of relevant knowledge. The knowledge generated as a result of the adaptive activities is more likely to be path-dependent to some extent.

The *second* is related to minimal or no changes in the external environment. The system behavior that could emerge from the dynamics of the LV system related to stable environmental conditions is constant over time (Figure 2B). Unlike the condition of asymptotic stability, the system behavior remains relatively insensitive to changes in the initial conditions. The trajectory of the system, which starts sufficiently close (within a radius δ of the equilibrium point), stays "close" (within the circle with radius ε). This means that the proportion of short-term and long-term activities does not change over time. The adaptive activities, which have a *dynamically fragile* character and therefore span a narrow range of activities space, are more suitable for survival and prosperity of the firm in this environment. As the growth rate of activities is very slow, there tends to be an increase in the strength of interaction between the manufacturing operations and firm levels. The relationships between activities at levels within the firm are more clearly defined. However, this means that there is not enough overlap between the strategic decision-making processes at the two levels. This would leave manufacturing unprepared and hurt the overall firm competitiveness when there are sudden and abrupt environmental disturbances.

The adaptive activities hardly contribute to the knowledge gained by the firm and its manufacturing operations, because of the restricted search behavior in activities space. That is, the firm does not engage in sufficient exploration, but concentrates on exploitation. The focus shifts to efficient performance and implementation of existing technologies to be competitive. As a consequence, an organization operating in this environment tends to be highly focused in market scope, customer requirements, or product and process technologies (Skinner, 1974). Decisions like facilities location (proximity to customers), and capacity utilization are more appropriate for gaining a competitive advantage under this environment. As a result of engaging in predominantly exploitative activities the manufacturing operations emphasize capabilities, like cost, that are based on repetitive learning. These capabilities are generated in a path-dependent manner through self-reinforcing mechanisms. Given the historical stability and routinized behavior of the firms and their manufacturing operations in this environment, the adaptability to changes in the external environment, or the "fitness" landscape, is likely to be difficult.

6. Nature of Determinants of Competitiveness

In order to illustrate the description in the Section 5, we use the Fokker-Planck (FP) equation derived from the analytical model, to capture the interactive dynamics of the strategic decision-making processes at the two levels. The reason for using an equation that assumes the firm environment to be stochastic is that it provides a benchmark for comparison with the three modes of behavior mentioned in the previous section. That is, the random distribution from which the fluctuations are drawn is the same at all times, with a constant variance, and there is no correlation between the fluctuations at successive instants. The Fokker-Planck equation (May, 1973) is given by:

$$\frac{\partial f}{\partial t} = -\sum_{i=1}^{2}\frac{\partial}{\partial v_i}(\mu_i f) + \frac{1}{2}\sum_{i=1}^{2}\frac{\partial^2}{\partial v_i \partial v_j}(\sigma_{ij} f) \qquad (6)$$

Here, f is the joint probability density function of the organizational activities relative to the equilibrium $v_i(t) = (x_i(t) - x_i^*)/x_i^*$ for $i = 1,2$. μ_i and σ_{ij} denote the mean and covariance of the joint probability density function f of v_i's. The first term on the right hand side of Equation (6) is the drift or friction term. It represents the interaction dynamics among the levels. If the system is stable, this term prevents the probability cloud in the activities space from dispersing. On the other hand, the second term in the above equation derives from the environmental stochasticity and acts to disperse the probability cloud in activities space. In order to understand the impact of environmental uncertainty, the random fluctuations in Equation (4) were considered to be part of the growth rate parameters so that they each consisted of a deterministic component κ_0 and a stochastic component with a mean 0 and variance σ^2:

$$\kappa_i = \kappa_0 + \gamma_i(t); i = 1,2 . \quad (7)$$

κ_0 is a constant and $\gamma_i(t)$ is "white noise" distributed normally with mean 0 and variance σ^2 under the assumption that there is no covariance between $\gamma_i(t)$ and $\gamma_j(t)$ for $i,j = 1,2$ and $i \neq j$. For the reduced model with the decision-making process at an individual level, the function f at equilibrium in Equation (6), solved by setting $\partial f / \partial t$ equal to zero, is the standard Pearson Type III Gamma distribution and is given by:

$$f^*(v_i) = C'[v_i]^{2(\kappa_0/\sigma^2)-2} \exp\left[-2v_i/\sigma^2\right] \quad (8)$$

provided that $\kappa_0 > 1/2\sigma^2$.

The exact nonlinear behavior of the combined two-level model specification with its random fluctuations can be investigated by conducting a simulation[3]. We simulated the system for three different values of the interaction coefficient after setting $\alpha_{ii} = 1$ and $\alpha_{ij} = \alpha \, (i \neq j)$, such that $\alpha = 0.00$, 0.50, and 0.85 (κ_0 and σ^2 being held constant) for 200 time periods. The plots in Figure 3 correspond to $\sigma^2 = 0.05$ and $\kappa_0 = 1$. All the simulations were carried out using a software code in *MATHEMATICA* (Wolfram, 1999). The nonlinear stochastic differential equations were solved numerically, and a point, which is plotted at successive interval time units, represents the three "populations". If we were to plot the actual phase trajectory as a continuous line, rather than the points at particular times, then we would have obtained a cluttered plot. The plots represent a particular realization of the dynamics for the schematic illustration. The relative fluctuations become more pronounced as the coefficient α increases towards unity (Figure 3).

Although a full analytical solution of the Fokker-Planck equation is not feasible, if the probability cloud is not too diffuse, an approximation may be obtained. We first define quantities ν_1 and ν_2 that measure the relative fluctuations of the three "populations" about the deterministic mean values. The contours of equal probability described by setting the left hand side of Equation (6) $\partial f/\partial t$ equal to zero, as also in Equation (A4) in Appendix A, are ellipses in the population space of the activities. The ellipsoids in Figure 3 are the contour surfaces such that in this approximation it is 90% probable that the "populations" of activities lie inside them. Figure 3 indicates that the analytic approximation accords well with the exact numerically derived results – that is, the exact probability distribution has contour surfaces that are probably somewhat banana-shaped rather than ellipsoids.

6.1 Manufacturing practices

In order to identify the drivers of competitiveness in terms of manufacturing practices, we incorporate a stochastic component into the growth parameter of the model. The growth rate parameter, which determines the mix of activities and the trajectory of the two-level system, and thus corresponds to *manufacturing practices*, can be modified for the "benchmark" case – with no path-dependence or structure – when environmental uncertainty is completely random as in Equation (7). The approximate equilibrium joint probability distribution in activities space is given by the following expression derived in Appendix A:

$$g^*(\nu_1,\nu_2)=C\exp\left[-\frac{x^*}{\sigma^2}\left(\nu_1^2+2\alpha\nu_1\nu_2+\nu_2^2\right)\right] \quad (9)$$

Here, ν_1 and ν_2 are the centered proportions $\left(x_i-x_i^*\right)/x_i^*; i=1,2.$ of adaptive activities at the manufacturing and firm levels. This approximate equilibrium distribution in Equation (9) indicates that the two-level system behavior in activities space consists of elliptical contours, with the greatest probability density near the equilibrium point and a gradually decreasing density away from the equilibrium point.

The presence of path-dependence of adaptive activities resulting from the strategic organizational and technological changes, as mentioned earlier, draws the activities close together in the activities (phase) space. The path-dependent nature of these adaptive activities defines the trajectories of the two-level system, which in turn reflects the nature of manufacturing practices over time. This can be readily illustrated mathematically by modifying the "white noise" stochastic component in the Equation (7) to reflect the temporal nature of the property of path-dependence. More specifically, using mathematical notation, the chaotic, periodic, or deterministic cases described qualitatively in the previous section can be represented using the following set of differential equations after incorporating the changes in Equation (7) using the result (A2) in Appendix A:

$$\frac{dx_i(t)}{dt} = -\mu[x_i(t),t] + \sigma[x_i(t),t]W[x_i(t),t]; i = 1,2 \qquad (10)$$

In the above set of equations[4], $\mu[x_i(t),t]$ denotes the mean equilibrium point and $\sigma[x_i(t),t]$ denotes the variance around the equilibrium point that is guided by the function $W[x_i(t),t]$. Thus, the presence of the function W that characterizes "chaotic" behavior, constrains the trajectory of the two-level system in the activities space, which in turn means that the variance around the mean (equilibrium point) is guided by the "chaotic" analog of the differential equations system in Equation (4). Since the behavior of chaotic systems is bounded in phase space, the two-level system behavior is restricted to a subset of the phase space, implying that the nature of manufacturing practices is also bounded. This analysis also holds for the two cases corresponding to low environmental uncertainty, when the function W assumes a *periodic* or *deterministic* form.

This approximate consideration for the "benchmark" case in Equation (7) scales the variance associated with the trajectories (of adaptive activities) by the appropriate eigenvalues. The stability requirement from this analysis reveals that the variance estimate (mean square magnitude) of the modified approximate bivariate joint equilibrium distribution is equal to the ratio of the actual variance to the minimum eigenvalue.

$$s^2 \sim \frac{\sigma^2}{\kappa_0(1-\alpha)} \sim \frac{\sigma^2}{\lambda_{\min}} \quad (11)$$

This stability condition shows that when the environmental uncertainty is high, manifest as a relatively large variance, the minimum eigenvalue should be as large, if not greater to compensate for the variance. This is equivalent to a relatively weaker mutual interaction coefficient α and a higher growth rate κ_0 for the two-level system. In other words, as the value of the interaction coefficient increases, the interaction dynamics prove an ever-weaker stabilizing influence to offset the randomizing environmental fluctuations. Therefore, the findings from this analysis concur with the qualitative explanations in the previous section on linking manufacturing strategy to competitiveness.

6.2 Competitive capabilities

A similar analysis relates *competitive capabilities* to the extent of interaction between the two levels. If we consider the "benchmark" case – with no path-dependence or structure – of a stochastic environment, the "optimal knowledge utilization" associated with the adaptive activities can be represented as follows using the constants c_{ij}'s (Equation (B3) in Appendix B):

$$\alpha_{ij} = c_{ij}\, exp\left[-d_{ij}^2/2\left(w_i^2 + w_j^2\right)\right]. \quad (12)$$

The eigenvalues for this case are a function of the ratio of extent of overlap between the two levels (d_{ij}) to the breadth of knowledge $(w_i \text{ and } w_j)$ that exists at these two levels (Figure 4). A greater overlap fosters a greater "knowledge utilization" across the two levels. Assuming that breadth of knowledge at the two levels to be equal $w_1 = w_2 = w$ and extent of overlap is given by $d_{12} = d_{21} = d$, the minimum eigenvalue that determines system stability can be determined to be as follows:

$$\lambda_{\min} = 4\sqrt{\pi}(w/d)\exp\left[-\pi^2 w^2/d^2\right] \quad (13)$$

This expression suggests again that a relatively greater variance associated with high environmental uncertainty would correspond to a greater overlap between the two levels in order for the two-level system to be stable (or for the manufacturing firm to be competitive).

Building on the modification of the set of differential equations in Equation (10), we now examine the nature of drivers of competitiveness in terms of competitive capabilities. The presence of path-dependence represented by the function W, as described earlier in the case of high and low environmental uncertainty, induces the formation of invariant sets[5] of regions in the activities (phase) space, which could potentially contribute to the exploitation of existing competitive capabilities or the development of entirely "new" competitive capabilities. The simplest case of an invariant set is the collection of points forming a *periodic* orbit. However, these sets could assume more complex forms, such as strange invariant sets, which are candidates for *chaotic* attractors. The invariant sets provide one with a means of decomposing the activities space. The intuition behind using the notion of invariant sets is that if we can observe a collection of invariant sets, then we can restrict our attention to the dynamics on each invariant set and then try to assemble a global solution from the invariant pieces. Invariant sets also act as boundaries in phase space, restricting trajectories to a subset of the activities (phase) space. Therefore, as in the case of manufacturing practices, since chaotic systems are restricted to "functional" variance in the phase space, the set of competitive capabilities also tends to be bounded. In the case of *periodic* and *deterministic* cases when the environmental uncertainty is low, the presence of a stronger path-dependence could result in the development of simpler bounded sets.

The preceding sections, and particularly Equations (11) and (12) suggest that the set of determinants (practices and capabilities) contributing to competitiveness, *tends* to be bounded; the elements of this set are *likely* to be closely integrated across the two levels. Conversely, the system behavior is *likely* to be dynamically fragile under low uncertainty, as the system would persist only for tightly circumscribed values of changes in environmental parameters; the drivers of competitiveness are *probably* more clearly defined at the two levels.

7. Conclusions

7.1 Theoretical implications

This paper investigated the relationship between the strategic decision-making processes related to manufacturing of a firm, and the firm's sustainability of competitiveness based on its manufacturing operations. We proposed a conceptual framework that captures the dynamics of processes at the manufacturing operations and firm levels, under changes in a firm's external environment. The analytical model, derived from the conceptual foundation, associated the endogenous organizational activities that reflect the strategic decision-making processes with the uncertainty related to exogenous environmental events. The analytical model provides interesting insights into the role of manufacturing strategy in enhancing firm competitiveness, and illustrating the nature of drivers of competitiveness.

We observed that the role of manufacturing strategy becomes more prominent in enhancing a firm's competitiveness as the level of a firm's environmental uncertainty increases. The two analyses based on the analytical model presented in this paper also provided important insights into the type of system behavior and the nature of determinants of competitiveness, under different environmental conditions. As we saw in the previous section, the set of drivers (practices and capabilities) contributing to competitiveness is likely to be bounded; the elements of this set are likely to be closely integrated across the two levels. Conversely, the system behavior tends to be dynamically fragile under low uncertainty, as the system would persist only for tightly circumscribed values of changes in environmental parameters; the drivers of competitiveness are likely to be more clearly defined at the two levels.

Of particular interest in this line of research is the interplay or "reciprocal relationship" between formation of practices and capabilities, and competitiveness (Henderson and Mitchell, 1997). Building upon various strands of research, such as organizational learning, business strategy, manufacturing strategy and economics, this paper explores these associations and their implications for manufacturing strategy and competitiveness. Synthesizing concepts across levels from prior work can contribute significantly to the development of manufacturing strategy research. In this paper, we have argued in favor of the endogenous nature of an operations-based competitive advantage. The framework presented here paves the way for developing a fusion of cross-level concepts of interest and highlights the importance of manufacturing strategy in shaping the context of the external environment and also in understanding the influence of environment on manufacturing strategy. In doing so, the paper is a step towards development of a *meso* theory of manufacturing strategy that links manufacturing and firm decision-making processes.

There are two important aspects in selecting the appropriate research setting: the first is associated with the rate of growth of adaptive activities and the second is associated with the extent of interaction between the firm and operations levels. The preceding analysis favors the selection of those manufacturing firms that are operating in rapidly changing environments and those in which there is a greater proximity between the decisions related to manufacturing and those at the firm level. These two requirements point towards the selection of small to medium-sized high-technology manufacturing firms as the appropriate research context, as in the case of biological experiments, where *Drosophilla* are studied because of their short life cycle (Fine, 1996; Oakey, 1984).

7.2 Practical implications

From a practical standpoint, the dynamic approach developed in this paper can be used to identify the nature of important determinants of competitiveness in terms of manufacturing practices and capabilities. What are the manufacturing practices and competitive capabilities that lead to a sustained competitive advantage? Should a firm place more emphasis on strategic decisions related to structural or infrastructural changes over time? How should a firm invest in its competitive capabilities in the short and long run? What is the nature of the knowledge that is critical in gaining competitive advantage? Are there trade-offs among competitive capabilities? Are there trade-offs among changes related to structure and infrastructure?

Capturing the strategic decision-making processes using an analytical model and estimating the parameters of this model empirically could provide the opportunity to conduct sensitivity analysis along the two dimensions. The first dimension is related to the parameter that deals with the growth rate at levels within the manufacturing firm. This parameter measures the right mix of proportions of adaptive activities that a firm and its manufacturing operations should engage in order to cope with changes in the environment and remain competitive. The second dimension is related to the strength of interactions among different levels. The estimation of interaction coefficients can allow decision-makers to adjust these interactions to reflect a proactive manufacturing strategy in given environmental conditions.

A practical implication of the framework presented in this paper is that it has the potential to aid in the development of the appropriate model – deterministic, nonlinear dynamical systems or stochastic – to answer "what-if" questions from a managerial standpoint. A simulation of the two-level system of strategic decisions using nonlinear system dynamics models can provide insights into behavior of the entities at individual levels and the overall system. These simulations could help managers in understanding manufacturing's responsiveness to changes internal and external to the firm.

From a managerial standpoint, the paper provides an analytical approach that could be used in understanding the extent of role of manufacturing operations in firm level decision-making. This in turn would determine the right mix of adaptive activities at the two levels that determine system stability, and thus the competitiveness of the manufacturing firm operating in the context of the environment. Also, the framework presented in this paper could be used to understand the *nature* of determinants of competitiveness over time. Contingent upon the environment in which the manufacturing operations and firm are operating, the drivers of competitiveness could be delineated that reflect the extent of environmental uncertainty. The set of determinants could then be used to develop the appropriate models – deterministic, nonlinear, or stochastic – to enhance the competitive position of manufacturing firms. The set of drivers of competitiveness in each of the three cases would reflect the strength of association of the types of the manufacturing and firm organizational activities.

Notes

1. From a mathematical standpoint, the set of equations in (1) also resemble the product and process innovation curves first put forth by Abernathy and Utterback (1975). If we consider the product innovation as primarily related to decisions at the firm level and process innovation as corresponding to the manufacturing operations level, then using the appropriate substitutions, we can arrive at the distributions for process and product innovations. In contrast to these innovation curves of Abernathy and Utterback, the LV system also incorporates the interaction between them.

2. Mathematically, an *attractor* or attracting set A in a trapping region D (for example, a sphere with radius ε in Figure 1) is defined as a nonempty closed set formed from some open neighborhood, $A = \bigcap_{n \geq 0} u^n(D)$. u is an n-recursive function that relates the state of the system represented by $\mathrm{x}(t) = [x_1(t) \quad x_2(t),]^T$ at time t to that at a lagged interval, ususally a single period (t+1). For example, the transformation function u for Equation (1) in discrete time can be identified from the following relationship: $x_i(t+1) = x_i(t)\left[\kappa_i - \sum_j \alpha_{ij} x_j(t)\right] + x_i(t); i = 1,2.$

3. We also conducted the simulations for the reduced models consisting of one and two levels. The simulation for one-level model consisted of altering σ^2 in the region of system stability. On the other hand, the simulations for the two-level model used various values of interaction coefficient α=0.00, 0.50, and 0.85 (κ_0 and σ^2 being held constant) in the region of system stability. Our simulations for both the models indicated that the normal distribution provides a valid approximation to the distribution specified in Equation (4) for the single and two level systems.

---

4. An example of modifying the variance in environmental fluctuations with the function $W_i[x_i(t),t]$ is setting it equal to $\sum_{n=0}^{\infty} b_n g\left(T^n(x_i(t)\exp(t))\right)$ for the chaotic case or $\sum_{n=0}^{\infty} b_n g\left(T^n(\sin(2\pi(x_i(t)+t)))\right)$ for the periodic case. Here, b is a constant, g denotes a function, and T is a recursive transformation applied n times to the respective functions.

5. Formally, a set S is an *invariant set* of a process (as in Equations (1) and (6)) if for any n-recursive transformation $u^n(P)=P$, some $\phi(\mathrm{x}(0),t)\in S$ for all n, where $\mathrm{x}(0)$ describes the initial state at time t=0, and $\mathrm{x}(t)=[x_1(t) \quad x_2(t),]^T$. S is an invariant set (of a process) if for any $u^n(P)=P$ we have $u^l(P)\neq P$ for all $\mathrm{x}(0)\in S$. We also speak of a *positively invariant set* when we restrict the definition to positive times, $t\in\mathbf{R}$ for $n\geq 0$. See Tufillaro, Abott, and Reily (1992) for more details.

FIGURES

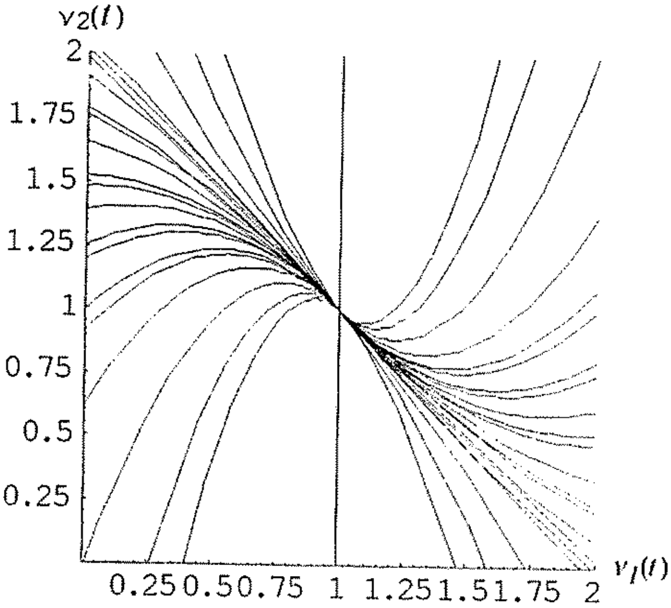

Figure 1A. Illustration of manufacturing activities being internally neutral ($\kappa_1 = \kappa_2 =,1$ $\alpha_{11} = 0.30$, $\alpha_{12} = 0.85$, $\alpha_{21} = 0.30$, and $\alpha_{22} = 0.50$).

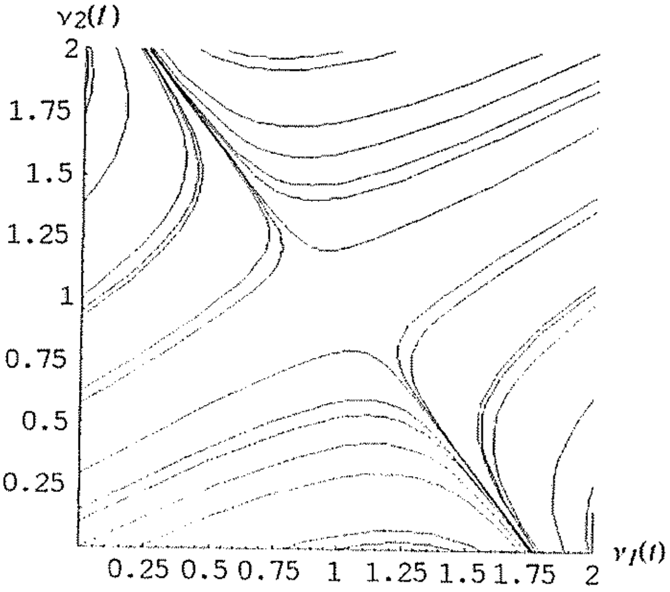

Figure 1B. Illustration of manufacturing activities being externally supportive ($\kappa_1 = \kappa_2 = 1$, $\alpha_{11} = 0.30$, $\alpha_{12} = 0.65$, $\alpha_{21} = 0.50$, and $\alpha_{22} = 0.25$).

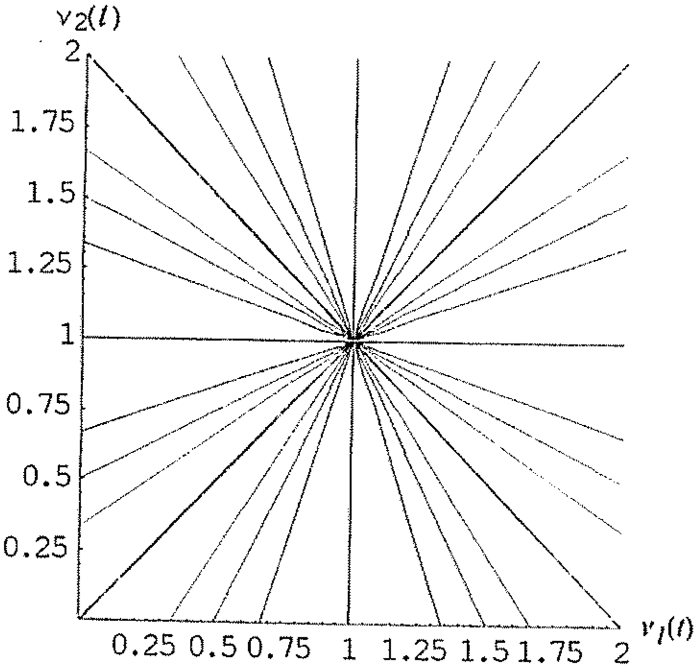

Figure 1C. Illustration of manufacturing activities being internally supportive ($\kappa_1 = \kappa_2 = 1$, $\alpha_{11} = 0.50$, $\alpha_{12} = 0.75$, $\alpha_{21} = 0.75$, and $\alpha_{22} = 0.50$).

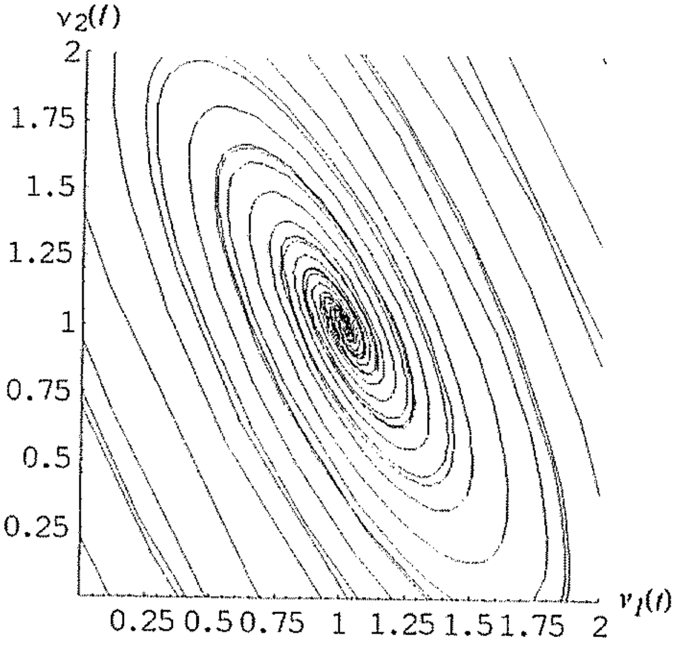

Figure 1D. Illustration of manufacturing activities being externally supportive ($\kappa_1 = -1$, $\kappa_2 = 1$, $\alpha_{11} = 0.50$, $\alpha_{12} = 0.50$, $\alpha_{21} = 0.85$, and $\alpha_{22} = 0.50$).

Figure 1. Patterns of dynamics in the neighborhood of the equilibrium point for relative proportions of organizational activities at the firm and manufacturing operations levels.

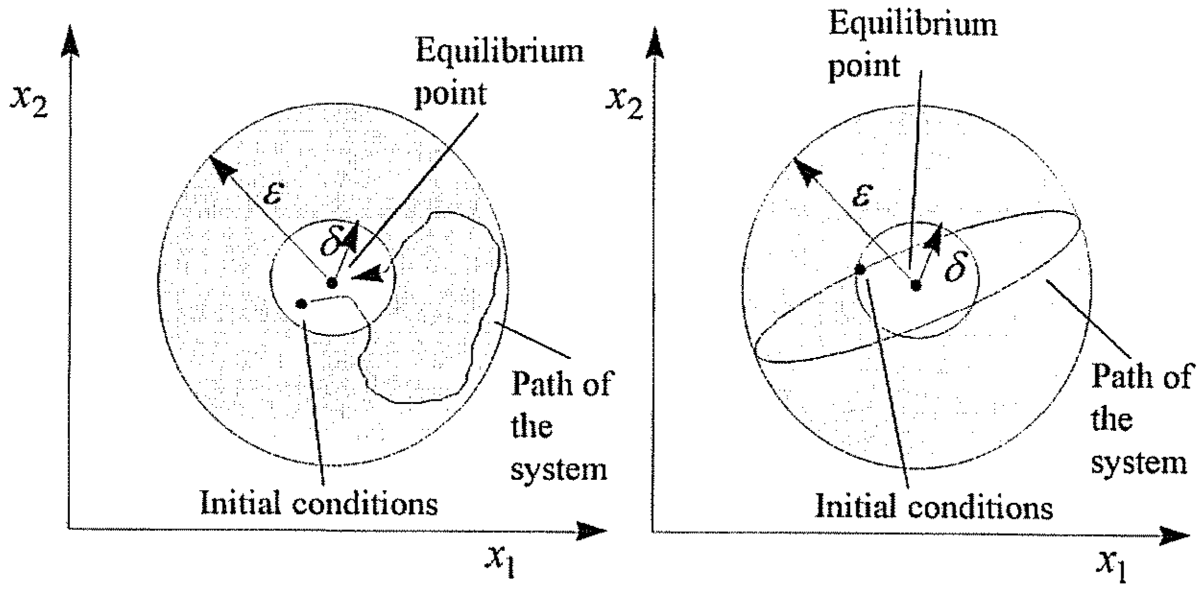

Figure 2A. Asymptotic stability

Figure 2B. Stability

Figure 2. Stability conditions for the Lotka-Volterra system

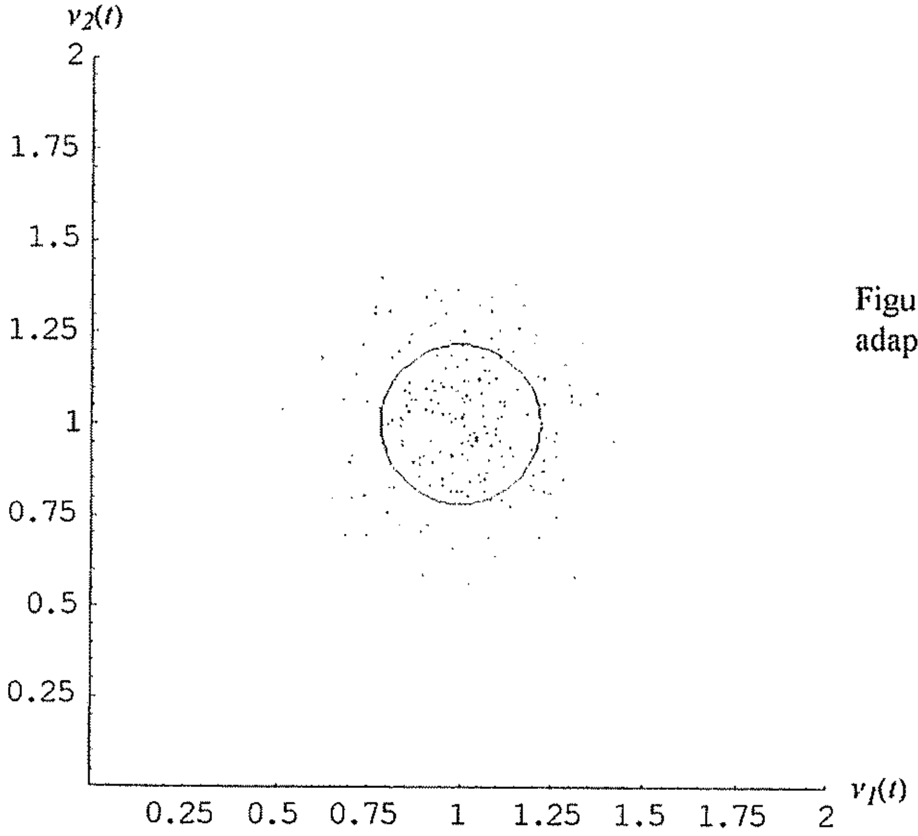

Figure 3A. Scatter plot of adaptive activities in phase space.

Figure 3. Illustration of the dynamics of the two-level system. The solid ellipse represents the 90% confidence interval of the bivariate normal approximation ($\kappa_0 = 1$ and $\sigma^2 = 0.05$).

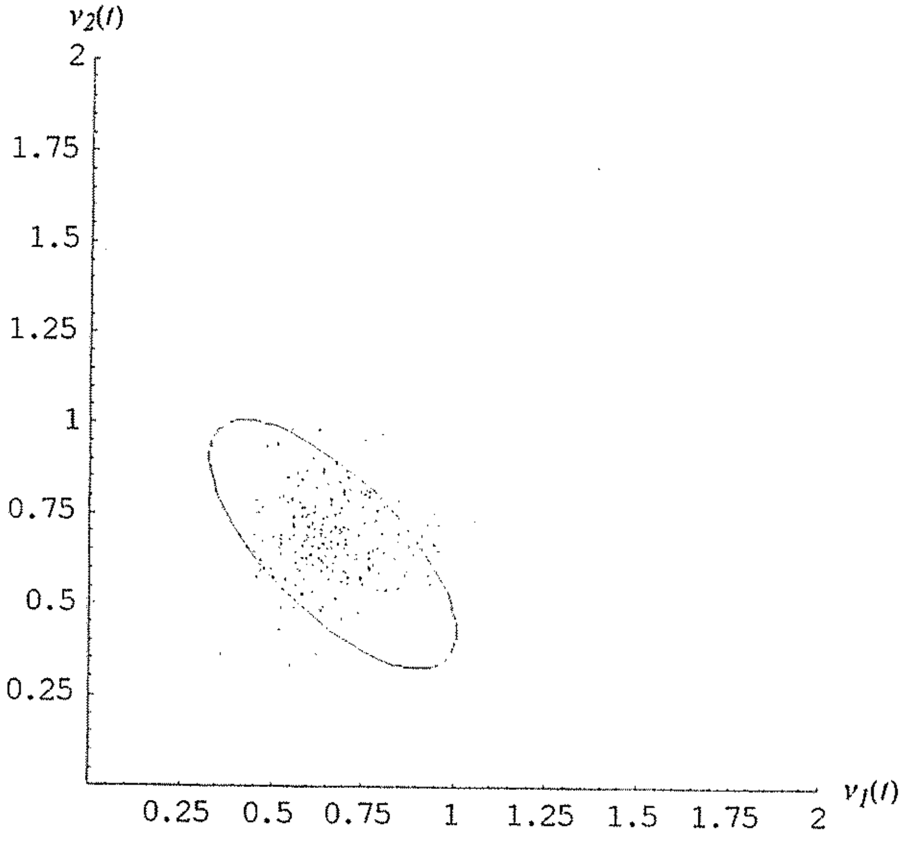

Figure 3B. Scatter plot of adaptive activities in phase space.

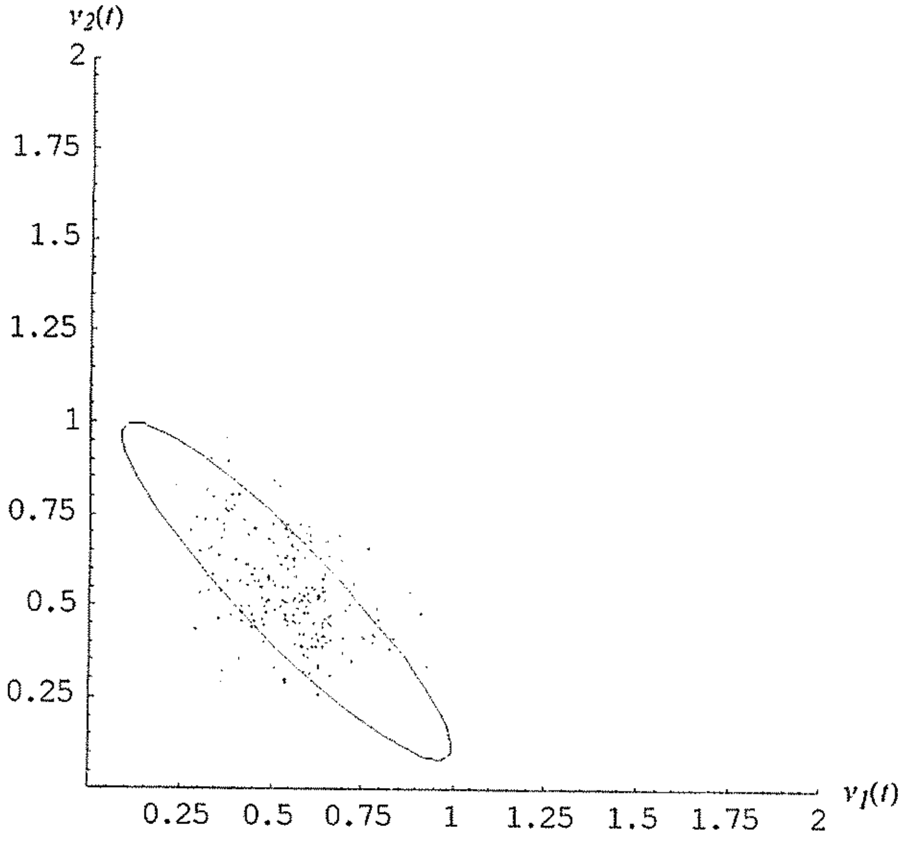

Figure 3C. Scatter plot of adaptive activities in phase space.

Figure 3. Illustration of the dynamics of the two-level system. The solid ellipse represents the 90% confidence interval of the bivariate normal approximation ($\kappa_0 = 1$ and $\sigma^2 = 0.05$).

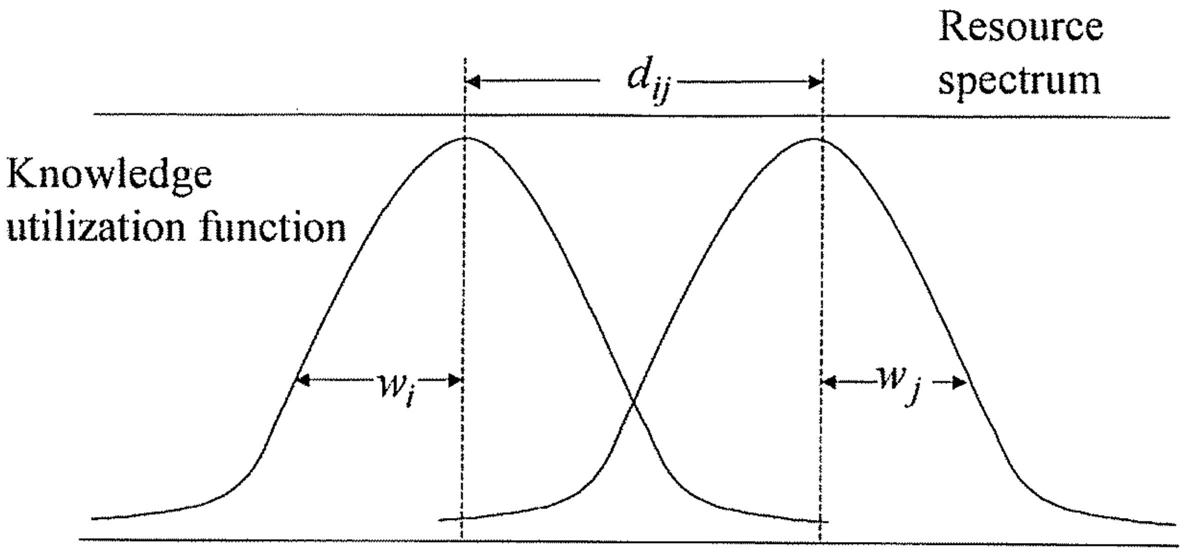

Figure 4. The knowledge resource spectrum showing the "utilization" function for the firm and manufacturing adaptive activities.

References

Abernathy, W. J., and J. Utterback (1975) Dynamic Model of Product and Process Innovation, *Omega*, 6, 639-657.

Anderson, J. C., G. Cleveland and R. G. Schroeder (1989) Operations Strategy: A Literature Review, *Journal of Operations Management*, 8(1), 133-158.

Arthur, W. B., Y. M. Ermoliev and Y. M. Kaniovski (1987) Path-dependent Processes and the Emergence of Macro-structure, *European Journal of Operational Research*, 30, 294-303.

Bohn, R. (1994) Measuring and Managing Technological Knowledge, *Sloan Management Review*. Fall, 61-73

Bourgeois Iii, L. G. and K. Eisenhardt (1988) Strategic Decision Processes in High-Velocity Environments: Four Cases in the Microcomputer Industry, *Management Science*, 34(7), 816-835.

Boyce W. E. and R. C. Diprima (1992) *Elementary Differential Equations and Boundary Value Problems*, John Wiley & Sons, Inc., New York.

Brittain, J. and D. R. Whooley (1988) Competition and Coexistence in Organizational Communities: Population Dynamics in Electronic Component Manufacturing, in Carroll, G. R. (ed.), *Ecological Models of Organizations*, Ballinger, Cambridge, MA.

Brown, R. and L. O. Chua (1999) Clarifying Chaos III. Chaotic and Stochastic Processes, Chaotic Resonance, and Number Theory, *International Journal of Bifurcation and Chaos*, 9 (5), 785-803

Cyert, R. M. and J. G. March (1963) *A Behavioral Theory of the Firm*, Blackwell Publishers, Cambridge, MA.

Eisenhardt, K. M. and B. N. Tabrizi (1995) Accelerating Adaptive Processes: Product Innovation in the Global Computer System Industry, *Administrative Science Quarterly*, 40, 84-110.

Fine, C. H. (1996) Industry clockspeed and competency chain design: an introductory essay, *Proceedings of the 1996 MSOM Conference*, Dartmouth College, Hanover, NH, June 24-25.

Feitzinger, E. and H. L. Lee (1997) Mass Customization at Hewlett-Packard: The Power of Postponement, *Harvard Business Review*, January-February, 116-121.

Hayes, R. H. and S. C. Wheelwright (1979) Linking Manufacturing Process and Product Life Cycles, *Harvard Business Review*, 133-140.

Hayes, R. H. and S. C. Wheelwright (1984) *Restoring Our Competitive Edge: Competing Through Manufacturing*, The Free Press, New York.

Hayes, R. H., S. C. Wheelwright and K. B. Clark (1988) *Dynamic Manufacturing*, The Free Press, New York.

Henderson, R. and W. Mitchell (1997) The Interactions of Organizational and Competitive Influences on Strategy and Performance, *Strategic Management Journal*, 8, 5-14.

Hill, T. (2000). *Manufacturing Strategy: Text and Cases*, Third Edition, McGraw-Hill Inc., NY.

Kogut, B. and U. Zander (1992) Knowledge of the Firm, Combinative Capabilities, and the Replication of Technology, *Organization Science*, 3(3), 383-397.

Lippman, S. A. and R. P. Rumelt (1982) Uncertain Imitability: An Analysis of Interfirm Differences in Efficiency Under Competition. *The Bell Journal of Economics*, 13,418-438.

March, J. G., (1991) Exploration and Exploitation in Organizational Learning, *Organization Science*, 2(1), 71-87.

May, R. M. (1974) *Stability and Complexity in Model Ecosystems*, Princeton University Press.

Mintzberg, H, 1978. Patterns in Strategy Formulation, *Management Science*, 9,5, 934-948.

Mendelson, H. and E. R. Pillai (1998) Industry Clockspeed: Measurement and Operational Implications, *MSOM Journal*, 1(1), 1-20.

Miller, J. G. and A. V. Roth (1994) A Taxonomy of Manufacturing Strategies, *Management Science*, 40(3), 285-304.

Nelson, R., and S. Winter (1982) *An Evolutionary Theory of Economic Change*, The Belknap Press, Cambridge, MA.

Oakey, R. (1984). *High-technology Small Firms: Regional Development in Britain and the United States*, Frances Pinter, London.

Penrose, E. (1959) *The Theory of the Growth of a Firm*, Oxford University Press, Oxford.

Porter M. E. (1991) Towards a Dynamic Theory of Strategy, *Strategic Management Journal* (Special Issue), 12, 95-118.

Scott, R. W. (1992) *Organizations: Rational, Natural, and Open Systems*, Prentice-Hall, Englewood Cliffs, NJ.

Skinner, W. (1969) Manufacturing – Missing Link in Corporate Strategy, *Harvard Business Review*, 3, 136-144.

Skinner, W. (1996) Three Yards and a Cloud of Dust: Industrial Management at Century End, *Production and Operations Management Journal*, 5(1), 15-24.

Spender, J. C., 1996. Making Knowledge the Basis of a Dynamic Theory of the Firm, *Strategic Management Journal*, 17, Special Issue, Winter, 45-62.

Staw, B. M. (1981) The Escalation of Commitment to a Course of Action, *Academy of Management Review*, 6(4), 577-587.

Swamidass, P. M. and W. T. Newell (1987) Manufacturing Strategy, Environmental Uncertainty, and Performance: A Path-Analytical Model, *Management Science*, 33,4, 509-524.

Teece, D. J., G. Pisano and A. Shuen (1997) Dynamic Capabilities and Strategic Management. *Strategic Management Journal*, 18(7), 509-533.

Tufillaro, N. B., T. Abbott and J. Reily (1992) *An Experimental Approach to Nonlinear Dynamics and Chaos*, Addison-Wesley Publishing Company.

Tyre, M. J. and W. J. Orlikowski (1994) Windows of Opportunities – Temporal Patterns of Technological Adaptation, *Organization Science*, 5, 98-118.

Voss, C. A. (1992) *Manufacturing Strategy: Content and Process*, Chatham and Hall, London.

Wolfram, S., 1999. *The Mathematica Book*, Cambridge University Press, Fourth Edition.

APPENDIX

Appendix A

Approximate probability distribution for the analysis of manufacturing practices

Allowing for random fluctuations in the parameters of the LV model, the stochastic generalization of the system with m levels of hierarchy may be written as follows (May, 1974):

$$\text{(A1)}\ \frac{dx_i(t)}{dt} = F_i\left(x_1(t), x_2(t), \ldots\ldots\ldots\ldots, x_m(t); \{\kappa_i(t)\}\right),$$

where, each of the set of growth parameters has the form $\kappa_i(t) = \kappa_0 + \gamma_i(t)$. Here, κ_0 is the constant average (across the m levels) value of the parameter, and $\gamma_i(t)$ is the "white-noise" with the covariance between the *i*th and *j*th environmental fluctuations being measured by some σ_{ij}^2. The mean proportion of adaptive activities is given by the solutions of the following time-independent equations $F_i\left(x_1^*, x_2^*, \ldots\ldots\ldots, x_m^*\right) = 0$, using the mean values of κ_0 for the growth parameters. The actual fluctuating levels of proportions of adaptive activities can be expanded about these constant mean values as follows: $x_i(t) = x_i^* + y_i(t)$. The *relative* fluctuations can then be represented as $Y_i(t) = y_i[t]/x_i^*$. For relatively small environmental fluctuations, the covariance across levels σ_{ij} is relatively small, the equations may be expanded using Taylor's series about this mean point keeping only the first-order terms in $Y_i(t)$ and in the parameter fluctuations $\gamma_i(t)$. This leads to the following set of linear stochastic differential equations:

$$\text{(A2)}\ \frac{dY_i(t)}{dt} = \sum_{j=1}^{m}\left(\left(x_j^*\right)^{-1}\alpha_{ij}x_j^*\right)Y_j(t) + \sum_k \mu_{ik}\gamma_k(t).$$

Here α_{ij} are calculated for the deterministic problem, using the average growth rate parameters and average interaction coefficients. The overall coefficients $\bar{a}_{ij} = \left(x_i^*\right)^{-1}\alpha_{ij}x_j^*$ form the matrix $\bar{A}$. In a similar vein, the constant coefficients μ_{ij} involve the average parameter values. The above approximate Equation (A2) containing the "white noise" stochastic term can be transformed into a Fokker-Planck diffusion equation. The approximate equilibrium distribution $g^*(v_1, v_2, \ldots\ldots\ldots\ldots, v_m)$, if it exists, gives the probability to observe the relative fluctuations having the values $Y_i(t) = v_i$. It is determined by the following expression:

$$\text{(A3)}\ 0 = -\sum_{i,j} \frac{\partial}{\partial v_i}\left(\overline{\alpha}_{ij} v_j \hat{f}^*\right) + \sum_{i,j} D_{ij} \frac{\partial^2 \left(f^*\right)}{\partial v_i v_j}.$$

Here D_{ij} represents the overall covariance between the "white noise" fluctuations in the stochastic differential equations for the *i*th and *j*th levels. As can be seen by direct substitution, the above Equation (A3) satisfies the multivariate normal distribution: so that

$$\text{(A4)}\ \hat{g}^*(v_1, v_2, \ldots\ldots\ldots\ldots\ldots, v_m) = C \exp\left[\sum_{i,j} v_i B_{ij}^{-1} v_j\right],$$

where the elements of the symmetric covariance matrix B_{ij} must satisfy the following:

$$\text{(A5)}\ \sum_k \left(B_{ik}^{-1} \overline{a}_{kj} + a_{ik}^T B_{kj}^{-1}\right) = 2 \sum_{k,l} B_{ik}^{-1} D_{kl} B_{lj}^{-1}.$$

In the specific case of the two level system, $\overline{A} = \begin{pmatrix} -x_1^* & -\alpha x_2^* \\ -\alpha x_1^* & -x_2^* \end{pmatrix}$. Assuming that the proportions of activities at equilibrium are equal, that is, $x_1^* = x_2^* = x^*$. The covariance matrix *D* has σ^2 along its diagonal and 0 elsewhere and $B^{-1} = D^{-1}\overline{A}$. Substituting the components of this matrix into Equation (A4), we arrive at the Equation (9) – a bivariate distribution of the relative proportions of adaptive activities.

Appendix B

Calculation of the interaction coefficients in the analysis of competitive capabilities

In a separate analysis, we capture the knowledge generated as the difference between the actual and available "production" of adaptive activities as follows (May, 1974):

$$\text{(B1)}\quad Q(t)=\int\left[K(z)-\sum_{i} h_i(z)x_i(t)\right]^2 dz,$$

where the quantities κ_i and α_{ij} are defined by $\kappa_i=\int K(z)h_i(z)dz$ and $\alpha_{ij}=\int h_i(z)h_j(z)dz$. The resource spectrum $K(z)$ can be conceptualized as the breadth of knowledge available as a function of the extent of environmental uncertainty (z) – that is, the ruggedness of the external environment. It is (approximately) synthesized from the addition of the m generalized Fourier components $h_i(z)$ with the proportion of adaptive activities being the Fourier coefficients. The function $h_i(z)$ is the knowledge utilization function in response to the environmental changes at each of the levels i. The choice of the equation ensures that the equilibrium proportions of activities give the best least squares fit and that any other choice of the proportions of activities will tend to this equilibrium as optimal. That is, $dQ/dt \le 0$ with the equality pertaining to only if $x_i=x_i^*$. With this definition, Q can be rewritten as follows using a constant minimum value Q_0:

$$\text{(B2)}\quad Q(t)=Q_0+\sum_{i,j}\left(x_i(t)-x_i^*\right)\alpha_{ij}\left(x_j(t)-x_j^*\right)$$

Assuming that the function $h_i(z)$ is normal, $h_i(z)=E\exp\left[-z^2/\left(2w_i^2\right)\right]$ Here, E is a constant, and w_i is the width of the utilization functions (Figure 3). The interaction coefficients are therefore:

$$\text{(B3)}\quad \alpha_{ij}=\left(\pi w_i w_j\right)^{-1/2}\int_{-\infty}^{\infty}\exp\left[-\left\{z^2/2w_i^2\right\}-\left\{\left(z-d_{ij}\right)^2/2w_j^2\right\}\right]dz=c_{ij}\exp\left[-d_{ij}^2/2\left(w_i^2+w_j^2\right)\right]$$