MODELLING THE INNOVATION IMPLEMENTATION PROCESS IN THE CONTEXT OF HIGH-TECHNOLOGY MANUFACTURING: AN INNOVATION DIFFUSION PERSPECTIVE

ESRC Centre for Business Research, University of Cambridge
Working Paper No. 112

Shekhar Jayanthi
ESRC Centre for Business Research
University of Cambridge
Sidgwick Avenue
Cambridge
CB3 9DE

Phone: 01223 766403
Fax: 01223 338076
Email: sj215@eng.cam.ac.uk

December 1998

Abstract

High-technology manufacturing operations are characterized by rapid and ongoing innovation implementations. The transfer of knowledge from one innovation implementation to the other is critical to survival of the manufacturing firm. This paper identifies a model-based approach to capture successive innovation implementations in high-technology manufacturing operations. The paper tests the validity of the approach on successive innovation implementations in a high-technology manufacturing plant – a wafer fabrication plant of a semiconductor manufacturing company. The empirical data for a two and a half year period suggests that the model-based approach provides an excellent fit. Although the empirical analysis conducted in this paper is preliminary, the model-based approach has the potential to be extended to a larger scale investigation. The concluding section of the paper consists of implications for theory, practice, and public policy, and directions for future research.

Acknowledgements

I would like to thank Dr Andy Cosh, Professor Mike Gregory, and Mr Alan Hughes for their support in preparing this manuscript. This paper was presented at the INFORMS National Meeting in Seattle, WA (October 25-28, 1998).

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1. Introduction

Adapting to a rapidly changing external environment through innovation is critical to the survival of manufacturing firms, which cannot afford to miss "the beats of the industry." Synchronizing organizational and technological changes to the accelerated industrial "clockspeed" is absolutely critical to managing modern manufacturing operations (Fine, 1996; Mendelson & Pillai, 1998). As life cycles of products are becoming shorter and shorter – a trend that is observable in most manufacturing industries (von Braun, 1990:50) – new product introductions are becoming increasingly commonplace in manufacturing plants. These introductions are accompanied by changes and modifications of process technologies, replacement with new and advanced process technologies, or both; operational and organizational practices are modified or changes. In other words, rapid and repeated innovation implementation is central to any high-technology manufacturing operations (Jelinek & Schoonhoven, 1990).

The transfer of knowledge from previous implementations is vital for making a smooth transition, as innovation implementations are made in manufacturing plants. Metaphorically, "executing transitions in rapidly changing markets is like running the 4×100 relay – the laps are so short that the baton passes often determine the outcome of the race" (Eisenhardt & Brown, 1998: 63). Previous studies have indicated the importance of implementation and also the transfer of knowledge across implementations. However, there is a dearth of studies aimed at *how* this transfer can be attained. This paper is a step towards understanding the *critical connections* transcending innovation implementations.

This paper focuses on successive innovation implementations taking place in high-technology manufacturing, because (1) it is a natural setting for multiple and ongoing innovation implementations – where the transition can be distinctly observed, and (2) the operations are prototypical of future manufacturing in other industries. Because of the rapid pace of change in this industry, the research context provides a testbed for undertaking this study. The *objectives* of the paper are threefold: first, to conceptualize consecutive implementations using developments in the innovation diffusion theory; second, to identify and empirically investigate a model-based approach for capturing the transition across innovation implementations; and, third, to describe implications of the model-based approach for theory and practice.

The rest of the paper is organized as follows. The next section deals with the development of the theoretical background of the problem. The following section on analytical background explores how the process can be modelled. The section on empirical evidence suggests some evidence for the specified model-based approach. The following section provides some concluding remarks with implications for theory and practice.

2. Theoretical Foundation

To appreciate how the transition across innovation implementations in manufacturing operations occurs, first one needs to understand the theoretical background of the innovation process. Specifically, this section depicts the distinction between innovation diffusion and implementation phases of innovation. This is followed by considering the appropriateness of studying the innovation implementation process in the context of manufacturing operations, and explaining the temporal patterns of the process.

2.1 Stages of the innovation process

The purpose of this subsection is to delineate the stages of the innovation process, thereby identifying the place of innovation diffusion and implementation. The locus of innovation in this paper is the organization (manufacturing plant). Consistent with Van de Ven (1986: 592), we consider innovation as an "idea" that is "perceived" to be "new" by the organization although it may appear "to be an imitation of something that exists elsewhere." This definition purposefully makes no distinction between "technical innovations" (for example. new products and process technologies) and "administrative innovations" (for example, new operational and organizational practices) because such "distinction often results in a fragmented classification of the innovation process."

Rogers and his associates were among the first to categorize the overall process of innovation as a sequence of three stages: *invention* of new ideas, followed by their *development* and *adoption* (Rogers, 1983; Rogers and Shoemaker, 1971). In a recent review of the innovation literature, Van de Ven (1993: 271) has observed that "specialized fields of study and research have emerged for each of these three innovation stages." The *idea invention* stage has been examined both by psychologists (for example, Cummings, 1965; Amabile, 1983; Angle, 1989) and economists (for example, Rosenberg, 1982; Thirtle and Ruttan, 1987). The *development* stage has been studied by several management scholars (for example, Utterback and Abernathy, 1975; Burgelman, 1983; Kanter, 1983; Tushman and Romanelli, 1985; Van de Ven, Angle & Poole, 1989). The *adoption* stage has been widely investigated by social scientists, in general. However, research on the adoption stage has been primarily focused on *innovation diffusion* – that is, marketing, dissemination, and transfer of an innovation to the end users (cf. Rogers, 1983; Mahajan, Muller and Bass, 1990). The *implementation phase* of the adoption stage, that determines the eventual success or failure of the innovation, has not received much attention (Rice and

Rogers, 1980; Van de Ven, 1993). Consistent with Gerwin and Kolodny (1992: 233), we define the implementation phase as the period of time from the "initial tryout" of the innovation until its "full scale operation is attained."

Based on the studies of the Minnesota Innovation Research Program[1], Van de Ven (1993: 280) identified the following two issues as being critical to advancing our understanding of the innovation process: (i) the need for extending the conceptualization of the innovation process to include re-definition of the innovation by the organizational participants in order to *implement* the innovation, and (ii) the need for broadening the focus of users within the organization as developing or implementing only a single innovation; in fact, many users *simultaneously* engage in innovative activity in many different areas, such as products, processes and practices. The following subsection elaborates on both these ideas with specific relevance to manufacturing operations.

2.2 Innovation implementation in manufacturing

This subsection discusses the suitability of manufacturing operations as a context for studying innovation implementation, and focuses on temporal patterns of the innovation implementation process. The few studies which have focused on the implementation phase of the innovation process have taken place where manufacturing operations have been used as the context of research (cf. Kazanjian & Drazin, 1986; Ettlie, 1988; Leonard-Barton, 1988, 1990; Schroeder, Scudder & Elm, 1989; Tyre, 1991; Tyre and Hauptman, 1992; Georgantzas and Shapiro, 1993; von Hippel & Tyre, 1995; Tyre and Orlikowski, 1994). The simultaneous implementation of diverse sets of innovations can be readily observed in manufacturing operations. For example, Ettlie (1988), and Georgantzas and Shapiro (1993) have noted that the general trend in manufacturing plants is toward the implementation of "synchronous innovations" – that is, the simultaneous implementation of technological and administrative innovations. In the same vein, Gerwin and Kolodny (1992: 264) have noted that implementation of new manufacturing technologies often occurs simultaneously with implementation of new operational practices that are aimed at supporting the new technologies. It is also a proper setting for studying the *re-definition* (as explained earlier) of innovations as they are implemented in an organization, because the re-definition of innovation embodies the temporal patterns associated with the implementation process.

The re-definition of innovation implementation has been considered to be a source of uncertainty in manufacturing operations (Hayes & Clark, 1985; Gerwin & Kolodny 1992). For instance, Van de Ven & Polley (1992: 106) have alluded to unexpected "critical problems" that "were encountered in the scale-up production" of therapeutic apheresis – a biomedical product. More generally, Chew et al. (1991: 5) have associated implementation of manufacturing innovations with "Murphy's Law" – that is, "whatever can go wrong, will." With increasing complexity of operations – due to the interactions between the introduction of new products, changes and upgrades in process technologies, and the ongoing efforts to automate and integrate the operations – the uncertainties associated with innovation implementation have been exacerbated to such an extent that they are now considered to be a "permanent" rather than a "transient" feature of the modern manufacturing plant (Weick, 1990: 8). As a result of these uncertainties, "learning occurs slowly and wastefully if at all" (Gerwin & Kolodny, 1992: 272), and as Weick (1990: 1) observes, modern manufacturing operations "creates unusual problems of sensemaking for managers and operators." It is the extent to which the people's arousal, attention, and motivation to engage in effortful problem-solving during innovation implementation that determines the smooth transition to later innovation implementations (Tyre & Orlikowski, 1994: 100). This study is a step in that direction.

3. Analytical Foundation: Successive Innovation Implementations

This section builds on the analytical background of the innovation diffusion theory to specify a model-based approach to understand the innovation implementation processes in terms of manufacturing. The model specification is guided by the "conjunction of diffusion and substitution" dynamics of sales behavior of subsequent generations of products in a population of potential adopters of innovation. This means that there is a continued existence of demand for earlier innovations despite the presence of recent innovations. Norton & Bass (1987) introduced a model that can be applied to a number of product generations simultaneously. As the number of generations increases, the sales of the earlier generations of products approach zero as a result of substitution of earlier products with newer products. The earlier generations lose in sales to the current product generation, which gains from the earlier generation. The present generation, however, loses to the later generations of products, including the actual and potential gains from earlier generations.

The implementation of innovation in an organization is characterised by "nonlinear cycles of mutual adaptation" (Leonard-Barton, 1988). As innovations are implemented in a manufacturing plant, the process of adaptation of previous implementations is in conflict with that of the newer innovation implementations. Gradually, as in the case of sales from generations of products, the earlier implementations give way to the newer innovation implementations. The knowledge gained by engaging in the adaptive process during earlier implementations is useful in the implementation of the present innovation. However, as the number of implementations increase, the process of "mutual adaptation" of organization and innovation from earlier implementations tends to cease. The later innovation implementations tend to make the earlier implementations obsolete. Therefore, there is an ongoing selection of adaptive processes associated with the innovation implementation process in a manufacturing plant (Tyre & Orlikowski, 1994; Bohn, 1994).

The process of "mutual adaptation" in the context of high-technology firms is based on an "experiential strategy" involving "accelerated learning through iteration and testing combined with motivation and focus of leadership and frequent milestone" (Eisenhardt & Tabrizi, 1995: 107). High-technology firms operate in high-velocity environments, in which there is "rapid and discontinuous change in demand, competitors, technologies, and/or regulation" (Bourgeois III & Eisenhardt 1988: 570). This is an environment in which "if you do not innovate, someone else will" (Eisenhardt, 1989:570). Therefore, manufacturing operations where the end-game is played out is the focus of a dynamic tension between current and future demands of the marketplace (Jelinek & Schoonhoven, 1990). The dynamic tension is a result of manufacturing operations having to simultaneously respond to short and long term competitive pressures – striving for higher quality, flexibility, and productivity amidst ever changing product characteristics and increasingly complex process technologies. It is this dynamic tension of the adaptation process associated with an implementation, focusing on both future and current demands of the marketplace, which is at the heart of conceptualizing the innovation implementation process.

If we visualize the process of adaptation associated with an implementation as composed of several adaptive activities[2] (Tyre & von Hipple, 1997), then following Norton & Bass (1987), we can represent the number of cumulative adaptive activities at time t as a result of a single innovation implementation by:

$$A(t) = mF(t) \tag{1}$$

Since the adaptive activities represent the knowledge gained during the innovation implementation process, the above equation can be thought of as a measure of knowledge. Thus, this equation forms the basis for studying the transfer of knowledge across implementations. The adaptive activities[3] are proportional to the S-shaped cumulative distribution function $F(t)$ of the rate of extent of integration of the innovation in the manufacturing plant – a mathematical representation of the temporal pattern of the implementation process. Thus, the distribution function captures the characteristics of the process – "initial burst of innovative activity" followed by a gradual emergence of routinized behavior over time (Tyre & Orlikowski, 1994; Cheng & Van de Ven, 1996).

Following the specification of the distribution function, we consider successive innovation implementations. As in the case of diffusion-substitution, each successive innovation implementation results in (1) the expansion of knowledge gained by engaging in entirely new adaptive activities associated with that implementation, and (2) a shift in the focus away from those adaptive activities that could have been associated with previous innovation implementations. Equation (1) can be modified by including these two aspects.

If we use the index i to denote the sequence of innovation implementations, then we can denote the adaptive activities at time t associated with the ith innovation implementation by $A_i(t)$. For the case of two consecutive innovation implementations, the adaptive activities of the first implementation can be written in terms of their interaction with the subsequent implementation in the plant (Figure 1):

$$A_1(t) = F_1(t)m_1 - F(t-\tau_2)F_1(t)m_1 = F_1(t)m_1\left[1 - F(t-\tau_2)\right] \qquad \text{for } t > 0 \qquad (2)$$

and for the second implementation,

$$A_2(t) = F_2(t-\tau_2)\left[m_2 + F_1(t)m_1\right] \qquad \text{for } t > \tau_2 \qquad (3)$$

The cumulative distribution function $F_i(t)$ for the ith innovation implementation is defined by the Bass model:

$$F_i(t) = \frac{1 - e^{-(p_i+q_i)t}}{1 + \frac{q_i}{p_i}e^{-(p_i+q_i)t}} \qquad (4)$$

Here, m_1 denotes the "potential" for the first innovation implementation – that is, the adaptive activities triggered as the innovation is integrated into the manufacturing plant. Similarly, m_2 refers to the "potential" served uniquely by the second innovation implementation. τ_2 is the time at which the second innovation implementation is introduced and $F(t-\tau_2)=0$ for $t<\tau_2$.

In the above set of equations, p_i denotes the "coefficient of innovation" and q_i denotes the "coefficient of imitation" for the ith innovation implementation. The coefficient of innovation can be interpreted as being associated with those adaptive activities that are responsible for future demands of the marketplace. These activities ensure the survival and prosperity of the manufacturing plant in the long run. Examples of such activities could include experimentation with new process technology and equipment designs, or experimentation with new product designs, or both. Similarly, the coefficient of imitation q can be viewed as related to those adaptive activities that are responsible for high-volume reliable replicable production. Examples of adaptive activities associated with the coefficient of imitation include modification and refinement of existing products, equipment, process technologies and manufacturing practices aimed at high volume production. These adaptive activities are responsible for the survival of the manufacturing plant in the short run.

Consistent with the theory on dynamics of innovation diffusion-substitution, the above model-based approach assumes (1) the existence of a series of decisions related to ongoing innovation implementations, each of which has the same or possibly greater potential than its earlier counterparts, (2) a density function of time to implementation for each innovation implementation applying against a time-varying potential, and (3) the rendering of actual and potential adaptive activities from earlier to later innovation implementations as obsolete. From expression (4), a simplification of the model-based approach can be achieved by relaxing the assumption that the coefficients of innovation and imitation, p_i and q_i, are not the same across implementations. This relaxation is plausible when dealing with innovations that are highly similar, so that the knowledge can be transferred from one innovation to the other almost completely (Norton & Bass, 1987).

4. Research Setting

A wafer fabrication plant of a U.S. merchant semiconductor manufacturing firm is the high technology manufacturing plant that served as the research site for this study over a two and a half year period. In a wafer fabrication plant, "the equipment changes frequently; new manufacturing processes are introduced frequently; existing technologies are improved through process development; and new products are introduced on new and continuously improving technologies" (Schoonhoven & Jelinek 1990: 106). We considered the wafer fabrication plant to be an *ideal* research site for this study because it is a natural setting for multiple and ongoing innovation implementation.

The operations of a wafer fabrication plant represent probably the "most complex" manufacturing process in the world today (Chen et al. 1988: 203). The changes in equipment, processes and products, just alluded to, and the interactions between these changes contribute toward the increasing complexity of wafer fabrication operations (Cooper et al., 1992). In addition, there are two other sources of complexity. First, there is the extremely broad spectrum of the knowledge base underlying the production technologies. Specialists in crystallography, metallurgy, ceramics, physics, chemistry, electronic engineering, mechanical engineering, and other areas all contribute to the semiconductor knowledge base. The second additional source of complexity is the rapidity with which new discoveries are quickly channeled into products and manufacturing processes. There are armies of ingenious physicists, engineers, designers, and manufacturing specialists who regularly conspire to find ways to push the technology, and expand the envelope of the possible (Jelinek and Schoonhoven, 1990).

At our research site, the raw material that served as the input to the plant were wafers. A wafer is a slice of polished silicon disc; the diameter of wafers used in the plant was 6 inches. The output of the plant was a broad array of memory dice (potential integrated circuits; *die* is singular, and *dice* is plural) with changing designs. During the two and a half year study period in 1988-90, the two major process technologies used in the plant to produce dice from wafers were NMOS (Negative Metal Oxide Semiconductor) and CMOS (Complementary Metal Oxide Semiconductor) technologies. Common to the devices produced by the MOS (Metal Oxide Semiconductor) technologies are three electrodes – a *source* which emits electrical carriers; a *drain* which collects the carriers emitted by the source; and a *gate* which controls the amount of carriers flowing from the source to the drain. NMOS technology produces devices in which the active carriers are electrons flowing between an N(negative)-type source and an N-type drain in an electrostatically formed N-channel in a P(positive)-type silicon substrate. CMOS technology produces devices that incorporate both P-channel and N-channel structures within the same silicon substrate.

As shown in Figure 2, the two and a half year study period represented a time-window during which there was a transition going on from the NMOS technologies to the CMOS technologies. There were also upgrades within each of these two process technologies – 5 upgrades for the NMOS, and 2 upgrades for the CMOS – during this period. The transition from the NMOS to CMOS technologies was consistent with the general technology trend in the semiconductor industry. CMOS was becoming the dominant technology of choice across all products by the late 1980s. The relative complexity (measured by the number of processing steps) of CMOS technology was higher than the NMOS technology. However, its "popularity" was growing because of (i) the inherent low power capability of CMOS devices, (ii) their simple circuit design, and (iii) the availability of special features on CMOS technology (El-Mansy and Siu, 1988: 238-239).

Due to the ongoing transition from NMOS to CMOS technologies, and the ongoing upgrades within the two process technologies, the two and a half year study period was an *ideal time-window* for examining the innovation implementation process in a natural setting. Throughout the study period we noticed a constant pressure to improve manufacturing productivity – that is, to efficiently manufacture high volumes of continuously changing set of dice with changing process technologies. Our review of the weekly production reports[4] of the plant suggested ongoing activities in the plant related to the coefficient of innovation and imitation.

Adaptive activities associated with the "coefficient of imitation" included de-bugging of new equipment and processes, and modification of equipment to reduce machine downtime, unit processing times, contaminants, wafer handling, wafer breakage or scratches. "Corrective action teams" were formed. These teams comprised of operators, engineers and vendor representatives who were empowered to address operational problems in the plant. A "stretch goal program" was implemented that set ambitious goals for quality improvement and production volumes, and in turn forced extensive planning and coordination across different functional areas in the plant.

Adaptive activities associated with the "coefficient of innovation" included experimentation with process technologies aimed at achieving superior functional performance from new die designs introduced in the plant, and also reducing the variability in the quality of the dice manufactured in the plant. A "paperless fab project" was initiated that aimed at eliminating several hundred pieces of paper involved in the production processes and allow the operators to use touch screen interfaces and bar code readers to collect data for computer input. A "cell project" was implemented allowing computers and equipment to interface without the need for operator intervention.

5. Empirical Analysis

5.1 The data

The unit of analysis for conducting the empirical analysis is the manufacturing plant. From a methodological viewpoint, the objective of the empirical analysis is to validate the model-based approach presented in the earlier section, Thus, the empirical analysis procedure consisted of three steps: identifying the variable(s) that could serve as proxy for adaptive activities representing the innovation implementation process, specifying an appropriate model for the research setting, and estimating the parameters in the model.

The implementation phase represents the "first opportunity to regulate an innovation"; hence, the data on plant performance collected during innovation implementation are monitored carefully by the managers (Gerwin & Kolodny, 1992: 261). Problems in the innovation implementation process – for example, "failure to integrate advanced equipment and systems fully into production" – directly affect the output of a plant (Tyre, 1991: 59). Therefore, the output from the wafer fabrication plant, for the two process technologies, was chosen as a proxy for adaptive activities as in Equation (1) because of the correspondence with the examination of total shipments in the innovation diffusion-substitution literature. The output from a manufacturing plant is also a common variable used in the literature on organizational learning (Argote & Epple, 1990).

At the wafer fabrication plant managers routinely analyzed performance data to gain insights into the process of innovation implementation. Our examination of the plant's weekly production reports revealed the data on plant output from the two process technologies. The production reports provided additional information on other performance metrics, which were of interest to managers and reported regularly, related to quality, flexibility, and productivity. The following subsection addresses the next two steps in conducting the empirical analysis.

5.2 Model estimation and fitting

The specification of the model for the research setting over the time window of study requires the inclusion of two innovation implementations – NMOS and CMOS process technologies. The adaptive activities pertinent to the NMOS technology seem to have reached their full "potential." As the CMOS technology is implemented, the previous implementation is phased out gradually. The implementation of CMOS technology in the manufacturing plant shows the adaptive activities corresponding to the coefficient of innovation. There is some degree of adaptive activity associated with the implementation of CMOS technology.

Since the two types of process technologies are closely related, there is a great deal of transfer of knowledge that can occur across implementations, which in turn allows one to relax the assumption of distinct diffusion parameters across implementations. Assuming that the parameters p and q are constant across the two innovation implementations described above, the model-based approach can be specified in the following manner for the series of two innovation implementations:

$$\begin{aligned} A_1(t) &= m_1 F(t)\left[1 - F(t-\tau_2)\right] \\ A_2(t) &= F(t-\tau_2)\left[m_2 + F(t)m_1\right] \end{aligned} \qquad (5)$$

where, $F(t) = \dfrac{1 - e^{-(p+q)t}}{1 + \dfrac{q}{p} e^{-(p+q)t}}$.

From Figure 2, $\tau_2 = 1$. Since the time-window of the study period did not include the actual time of implementation of the NMOS technology, a corrective parameter ϕ was subtracted from time t in the cummulative distribution function for the first implementation. The model consisting of the simultaneous equations was estimated using the Statistical Analysis System (SAS, 1988). The PROC MODEL procedure – a nonlinear system of equations routine – was used to estimate the parameters in the model using the maximum likelihood estimation (MLE) method. Table 1 shows estimates of the parameters in the simultaneous equations. As the table shows, the directions and magnitudes of the parameters are as expected and consistent with and comparable to the estimates of the parameters determined by Norton & Bass (1987). All the parameter estimates in the model consisting of the simultaneous equations are highly significant with extremely low p-values. Figure 2 shows the original and fitted values for both the innovation implementations.

The empirical analysis was guided by the following question: *What is the extent of influence that the previous innovation implementation have on subsequent implementations?* Thus, the testing of the model-based approach was conducted in order to investigate whether the knowledge from the implementation of the earlier process technology was transferred completely to the next implementation. In other words, was the process of adaptation entirely useful in the implementation of the newer process technology?

The results of the estimated model using time-series data on the number of wafers output from the two process technologies are shown in Tables 1 and 2. The value of the estimate of the parameter m_1 is very large compared to that of the parameter m_2. This is because the NMOS process technology in the manufacturing plant is in the ramp-up stage, while the full "potential" of the CMOS technology is yet to be exploited. The magnitude of the estimate of the coefficient of innovation p is smaller than that of the estimate of the coefficient of imitation q. This is consistent with the assumption of constant parameter values across implementations. If we consider the two innovation implementations together, it can be readily seen that the CMOS process technology needs to be fully integrated yet into the manufacturing plant. The sign of the estimate of the corrective parameter ϕ is in the expected direction. However, the exact magnitude of the parameter can only be determined when we know the magnitude of the actual cumulative output since implementation.

The extent to which the simultaneous equations approach provides a good fit to the empirical data from the wafer fabrication plant is indicated by extremely high values of R-square and adjusted R-square for both the trajectories of the two process technologies – NMOS and CMOS. The very high degree of fit indicates that the parameters p and q representing the coefficient of innovation and imitation used in the model are similar for both the process technologies. Any test of the hypothesis that the parameters p and q are equal across implementations would reject the hypothesis only if the fit of the model to the data without the constraint that $p_i = p$ and $q_i = q$ is markedly superior to the fit with the constraint. Since the empirical data and the fitted values are extremely close, we can say that the data do not reject the idea that the assumption of constant p and q for the innovation implementations is reasonable (Norton & Bass, 1987).

Thus, the empirical analysis suggests that the innovation implementation process in the context of high-technology manufacturing operations can be modelled using the theory of innovation diffusion. In other words, the model-based approach specified here has the potential to be used for modelling the successive implementations of innovation in the context of high-technology manufacturing operations.

6. Concluding Remarks

This paper explores the process of innovation implementation with reference to innovation diffusion theory – that is, it borrows from the dynamics of diffusion to identify a relevant model for the innovation implementation process. The paper explains a theoretical rationale for using the proposed model-based approach, and also presents empirical support for the use of the analytical model. This concluding section discusses implications for theory and practice, and directions for future research.

6.1 Theoretical implications

The theoretical contribution of this paper is in relating the two stages of the innovation process – diffusion and implementation. The distinction between the two stages is often obscured, as prior studies have focused primarily on implementation as an integral part of the diffusion process. The use of dynamics of innovation diffusion-substitution in understanding the implementation process shows the potential for a synthesis. Norton and Bass (1987) applied the model at the level of population of potential adopters of innovation to the dynamic sales behavior of successive generations of high-technology products. The same model-based approach is also applicable to the dynamics within an individual manufacturing plant. Thus, diffusion, which is a "group" level phenomenon, could be integrated with "individual" level phenomenon of innovation implementation.

Previous studies, for example, in the area of management of innovation have called for the use of "nonlinear models of learning" (Cheng & Van de Ven 1997; Koput 1996) in the context of the invention stage. If we consider the innovation implementation process as essentially a process of "reinvention" by the organization, the applicability of nonlinear models seems plausible. This paper illustrates the use of a system of nonlinear simultaneous equations to capture successive innovation implementations. Thus, it adds to the potential for a synthesis across stages of the innovation process.

Prior studies have characterised the properties of the implementation process in manufacturing operations qualitatively. For example, they have stressed the dependence of successful implementation on initial conditions, and the presence of temporal patterns in the process. This paper builds on this earlier theoretical background to identify an approach for modelling the process of implementation using available quantitative techniques. In doing so, it advances the frontier of our understanding by augmenting the rich tradition of anecdotal and case-based research in this area (Mohrman & Von Glinow, 1990).

6.2 Practical implications

This paper shows an approach that can be used when implementing organizational and technological changes in manufacturing plants. This model-based approach provides a continuity in the manufacturing operations over time. The transfer of knowledge from one generation to the other, of product technologies, process technologies, and/or both, is clearly of great importance to practitioners. In this sense, the proposed model-based approach can be thought of as making a connection with the much studied models for organizational learning. So far, the models used to study learning in manufacturing have focused primarily on the improvements in output mainly as a result of repetitive engagement (related to q). However, the approach used in this paper indicates that there is also another component to learning – the experimental (related to p) part observed during early stages of the implementation process. The proposed model-based approach, which includes both types of learning, provides a comprehensive approach that ensures connectivity of manufacturing operations temporally across different product and process technologies.

The significant implication is that it can be used in obtaining forecasts for how an innovation implementation process will unfold over time. These forecasts can be used either to alter the organizational and technological changes made during the current implementation process, or guide the trajectory of future innovation implementations in a manufacturing plant. In other words, the model-based approach can be used to identifying the best course of action during the innovation implementation process.

Identifying the trajectories of the innovation implementation process can enable one to determine the optimal time window for implementation (for example, Bayus, 1995). This is the time during which there is a surge in adaptive activities during the implementation. As the degree of experimentation is determined by both earlier and later innovations, identifying the optimal time before which high-volume reliable replicable production should be carried out is very critical. Similarly, describing the temporal path of innovation implementation can enable a manufacturing plant to ensure its long-term survival. Managers can determine when a new product should be introduced, or when the process technology should be operational for ramp-up production. Several successful companies already use "vintage" charts, which show percentage sales from "new" products, to ensure the survival of their manufacturing operations (Mendelson & Pillai, 1998).

6.3 Implications for public policy

While innovation is fundamental to the competitive success of economies, rapid and discontinuous innovations pose a complex problem for the policy-makers. As the implementation of innovations determines the "end game," the policy issues are critical in shaping the competitiveness of the manufacturing operations in an industry. Thus, a policy of innovation implementation should focus on "transfer sciences" – that is, how can the transfer of knowledge be encouraged across implementations with the "optimal" amount of experiential learning (Dodgson & Bessant, 1996). This perspective of an innovation policy reveals three important issues.

The *first* issue is concerned with the extent to which the policies facilitate the implementation of newer innovations *vis-à-vis* implementation of previous or existing innovations. Understanding the dynamics at the manufacturing plant level, by considering the influence of previous innovation implementations, and relating the dynamics to those at the industry level can benefit firms in developing effective strategies. A policy designed using the parameters of the trajectories of implementations can be very useful in enhancing the competitiveness of manufacturing operations. If the dynamics at the industry and plant level are guided by similar mechanisms, the policy makers have a tremendous advantage in using the parameters from the "best" plants in the industry to design and develop policies to facilitate "catching up" of manufacturing operations of other firms in the industry.

The *second* issue should address the duration of time of facilitation, in relation to prior implementations, as newer innovations are implemented. This is a critical issue since the competitive success of the innovation depends on expeditious and effective manufacturing, else imitators should concentrate the market. The time period of exploration when implementing an innovation can provide imitators with a "window of opportunity" to proliferate. This means that the smoother and quicker the implementation of the innovation, the greater the probability that the innovation is likely to appropriate rents (Teece, 1986). Thus, knowing the "optimal" trajectory of an innovation implementation can enable policy-makers to develop mechanisms to foster the profitability of innovators, while keeping imitators at bay.

The *third* issue is related to the connectivity across innovation implementations. If newer innovations are radically or incrementally different from previous ones, the policy-makers need to facilitate those mechanisms which are critical to the survival and prosperity of manufacturing firms. Knowing the "best" paths of both development and high-volume production activities in manufacturing plants can provide clues to the direction and extent of changes that could occur in the industry. The innovation policy can then focus on dealing with such shifts in the innovations to improve manufacturing competitiveness.

6.4 Directions for future research

This paper tested the validity of the model-based approach on successive technological innovation implementations in a single high-technology manufacturing plant. As it is, this paper presented preliminary work that can be used as a basis for conducting a larger scale investigation. Hence, there are several directions for future research that could follow. Future research should examine the validity of the model-based approach over multiple implementations of innovation, in several manufacturing plants. These implementations could be either technological or organizational (for example, work teams, reward systems, quality programs, and workforce training). This would not only reinforce the validity of the model over successive innovation implementations, but would also test its robustness in dealing with "incremental" or "radical" implementations – that is, the extent of connectivity of successive implementations over time.

An obvious direction for future research is to examine the validity of the model-based approach in other industries. Manufacturing plants in different industries are subject to different rates and magnitudes of change in their external environment. A critical question of interest is whether the approach consisting of the system of simultaneous equations is valid in different types of industries. Alternatively, are there any modifications that need to be made to the current set of equations? In this case, do these modifications vary in a systematic manner across several external environments in which the manufacturing plants operate?

Notes

1. A multi-year, multi-organizational and multi-investigator research program. See Van de Ven et al. (1989) for more details on the studies that were a part of the program.

2. See Jayanthi and Sinha (1998) for more details on adaptive activities.

3. From this point onwards, we use the phrase adaptive activities as synonymous with knowledge generated from implementation.

4. These were 1-page reports which summarized the plant's production status in a given week. Besides quantitative production data, the reports contained qualitative comments on the state of operations in the plant.

TABLES AND FIGURES

Table 1. Parameter estimates of the simultaneous equations

Parameter	*Estimate*	*Standard error*	*t ratio*	*Probability* $>\|t\|$ *(p-value)*
m_1	378613.70	3239.00	116.89	0.0001
m_2	91510.27	4980.00	18.38	0.0001
p	0.0034	0.00007	47.10	0.0001
q	0.0139	0.000258	53.99	0.0001
ϕ	-3.5024	0.5961	-5.88	0.0001

Table 2. Model fit to data

Equation	*R-square*	*Adjusted R-square*
NMOS process technology	0.9828	0.9827
CMOS process technology	0.9984	0.9984

Figure 1. Successive innovation implementations (Norton and Bass, 1987)

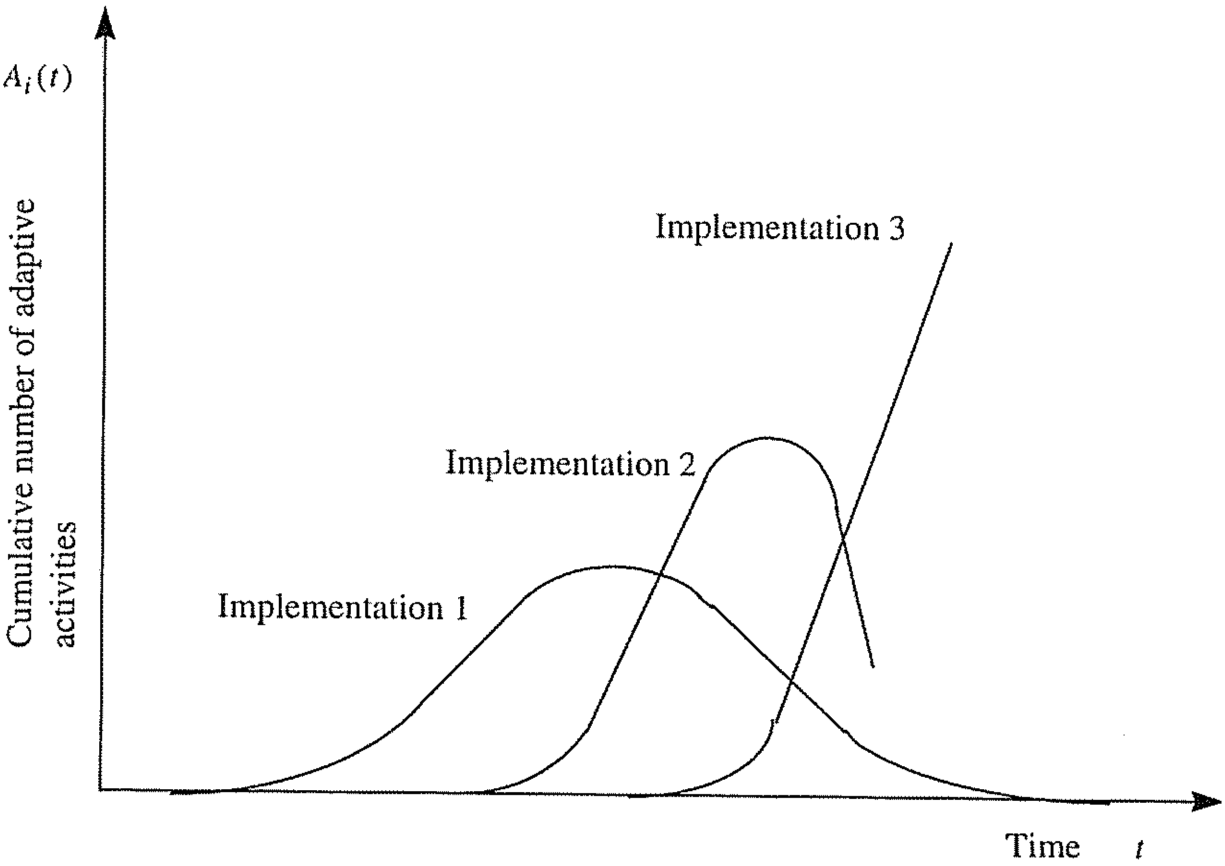
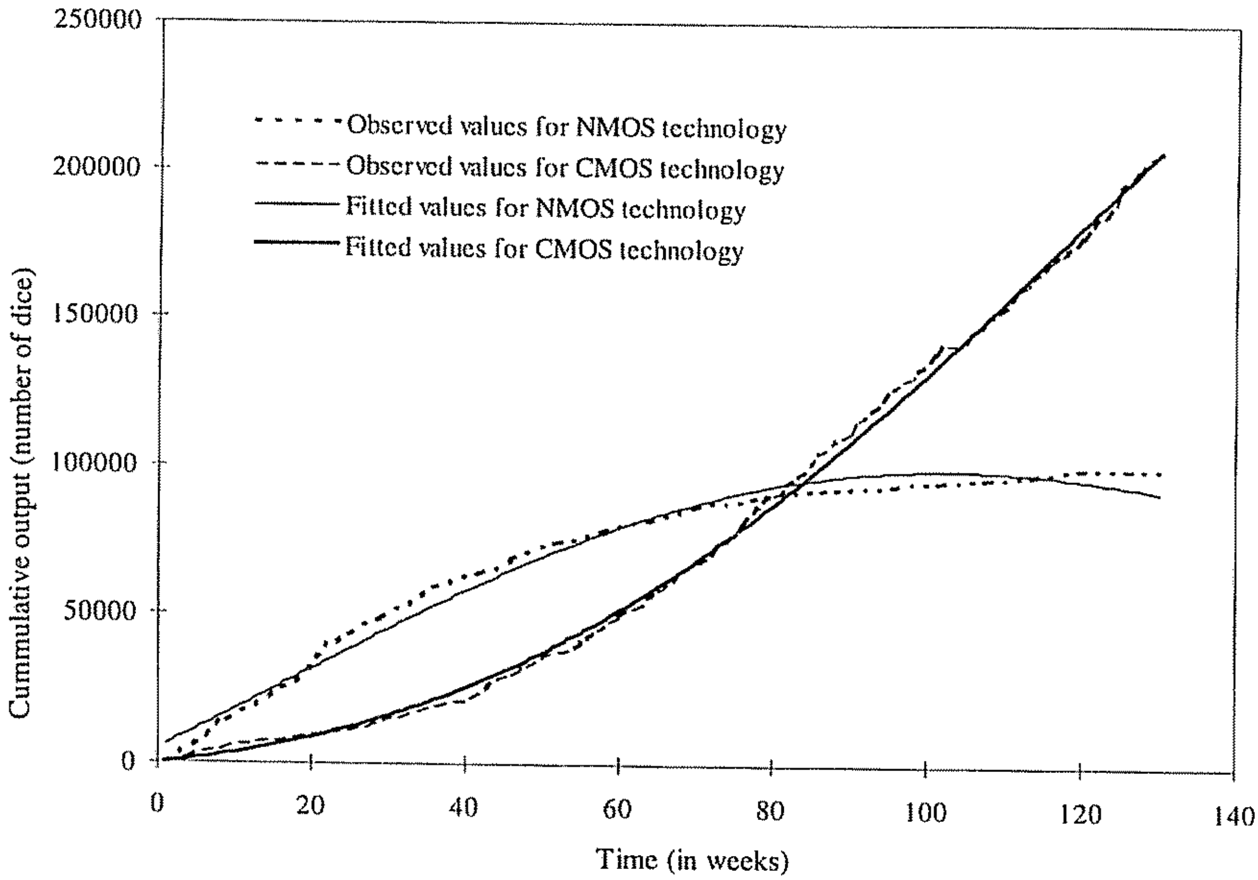


Figure 2. Observed and fitted values of cumulative output for NMOS and CMOS process technologies



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