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Butler, John E
Strategic Management Journal (1986-1998); Jan/Feb 1988; 9, 1; ProQuest Central
pg. 15

Strategic Management Journal, Vol. 9. 15–29 (1988)

THEORIES OF TECHNOLOGICAL INNOVATION AS USEFUL TOOLS FOR CORPORATE STRATEGY

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Three theories of technology and innovation; the product–process concept, the meta-learning concept, and the concept of technological interdependence, are used to relate technology and innovation to strategic management. This paper attempts to identify complementary and unifying concepts in these theories, which are useful to strategic planners. Performance indicators, from the commercial airline industry, are used to illustrate how theoretical assumptions can be related to practical applications. Type of innovation, stage of development, learning at all levels, interdependence between technologies, and users' expectations all appear to play a role in the emergence of technologies and the rate of innovation.

Attention is increasingly being devoted to the importance of technology and innovation at the macroeconomic level. This ranges from presidential encouragement (Reagan, 1985), to more specific advice on how to build new technology-based industries (Rhyne, 1985), to debate on the value of protectionist policies (Barton, 1984). In strategic management research, technology has also been suggested as an important consideration (e.g. Drucker, 1985; Frohman, 1985; O'Connell and Zimmerman, 1979). The suggestion being made is not that technology should replace any existing tool but that 'a critical link between technology and strategy exists' (Kantrow, 1980: 7) and that the attempt should be made to view technology in strategic terms. Different perspectives have been brought to bear on the strategy–technology relationship but all share the belief that technology can play a role in enhancing a firm's performance.

This may be because it can actually alter the structure of an industry (e.g. Willard and Cooper, 1985) and 'is important because it affects competitive advantage' (Porter, 1985: 165). Technology also has strategic importance because it often represents either an opportunity or threat, which should be considered during the scanning effort (e.g. Grinyer, Al-Bazzaz and Yasai-Ardekani, 1986, O'Connell and Zimmerman, 1979). Quinn (1985) has suggested that its real value, at least as related to innovation, lies in controlling 'chaos' through achievement of a degree of congruency between strategy, structure and technology. This position was echoed by Smart and Vertinsky (1984) who found that technology may be a useful dimension on which to base competition during crisis situations.

Other stategy–technology research has explored its role in inducing innovation (e.g. Kanter, 1982; Ronstadt and Kramer, 1982), helping to tie manufacturing to the strategy formulation process (e.g. Hayes and Wheelwright,1979; Hyer and Wemmerlov, 1984; Skinner, 1986; Wheelwright, 1984), and its impact on the degree of vertical integration (Balakrishnan

0143–2095/88/010015–15$07.50

Received 15 April 1985
Revised 23 February 1987

and Wernerfelt, 1986). At the implementation stage concerns have ranged from the impact that a technology has on exiting managerial practices (e.g. Goldhar and Jelinek, 1983), to industrial relations issues (Sibbernsen, 1986), to exploration of the relationship between technology and other factors associated with successful implementation of a new product (Leonard-Barton and Kraus, 1985).

The thrust, of much of this research, has been to look at technology and innovation to determine the extent to which valid prescriptions can be identified for its incorporation into the strategic management process. Supplementing this research is another stream that seeks to explain the underlying patterns of technology. This second stream may, ultimately, prove just as valuable to the strategic management process because it allows the firm to incorporate, into their planning framework, considerations related to the evolution of technology. This paper attempts to explore this second stream of research to identify complementary and unifying concepts in three existing theories: the product–process concept of Utterback and Abernathy (1975), the meta-learning concept of Sahal (1981); and the concept of technological interdependence developed by Rosenberg (1982). An attempt is made to relate these approaches to the strategy formulation process. Data from the commercial aircraft industry are used to examine the practical-application feasibility of using these technological indicators to help support the strategic planning process.

UNDERLYING CAUSES OF TECHNOLOGICAL INNOVATION

The pattern of technological innovation that occurs, with respect to a given product or process, has been theorized to be the result of many different factors. These factors include demand (Myers and Marquis, 1969; Schmookler, 1962), public and governmental support (Schwartz and Vertinsky, 1980), imitation (Schumpeter, 1934) and research intensity (Mansfield, 1968, 1971, 1981). When attempting to explain technology, the patterns which emerge can be used to provide support for the causal factors selected, or methodology advocated, by the researcher (e.g. Elster, 1983). What many approaches tend to ignore are in-depth explanations of how the evolution of technology might be important to strategic management. Managers can position their firm to maximize opportunity if they can correctly interpret, or have the power to act on, these technological signals (e.g. Kanter, 1982; Quinn, 1985) but the exact prescriptions for doing this have been somewhat vague.

Several attempts have emerged (e.g. Rosenberg, 1982; Sahal, 1981; Utterback and Abernathy, 1975) that attempt to develop more comprehensive, multiple-factor, theories designed to explain the underlying patterns of technological innovation. Several of these appear sufficiently rich to allow technology to be included in the strategic management framework. When attempting to examine the time frame and process by which a technology develops, these approaches take into account a great number of factors. Innovation patterns that emerge, with respect to a product or process, are sometimes used to support strategic positions, although these approaches have concentrated more on explanation and less on using innovation as a policy input variable.

It may be possible to more fully understand and exploit the strategy–technology linkage by anticipating patterns of technological innovation as part of an evolutionary process. These theories suggest an enlarged scope for planning, which relates goals developed in the formulation process to technological explanations. The product–process life cycle theory of Utterback and Abernathy (1975; Abernathy and Utterback, 1978) and the meta-learning concept of Sahal (1981) are two attempts to explain the actual pattern of technological progress. The attempt by Rosenberg (1982) to explain productivity improvement at the macro-level, through technological interdependence and 'learning by doing', serves as a useful vehicle to help understand the compatibility between these two approaches. Each is valuable, and they will be discussed individually before attempting to view their value as a set.

Product–process life cycle

This theory attempts to relate technological innovation to the stages of a product's life cycle. By identifying, and then separating, process and product innovations the pattern of innovation that appeared could be related to three different

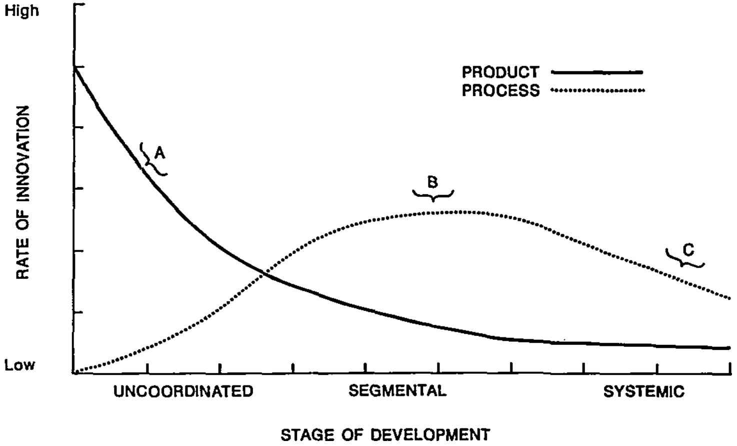

Figure 1. Product process model of innovation (Adapted from Utterback and Abernathy, 1975)

stages of a product's development; the uncoordinated, the segmental, and the systemic. Utterback and Abernathy (1975) theorized that the rate of product or process innovation is, and should be, a function of the stage of development presently occupied by the product. Figure 1 depicts the expected patterns for product and process innovations over all three stages.

In the first stage, labeled uncoordinated (see Figure 1), product changes are frequent because nonstandardized production processes, and competition based on product performance, allow numerous product-related changes. Both the production equipment and material inputs are limited to what is available, because demand is not yet sufficient to justify the costs associated with securing specialized production equipment. Thus, a production system emerges that contains some excess slack. This inefficiency also creates the conditions that allow and encourage product changes, because customization is not disruptive. Toleration of change acts to encourage product improvements but discourages process-type innovations, which would make the system more rigid.

Gradually, most industries move into the segmental stage (see Figure 1). Here, there is less emphasis on product performance and more on the external variation that exists between the products of competitors. During this stage fewer product innovations occur. We expect to see an increase in process innovations because specialized production equipment and inputs, which are now volume-justified, are introduced. Expectations relating to product form and performance become standardized across market segments, and product innovations requiring a radical change in form are less welcomed by producers. In some industries, recent advances in computer-aided manufacturing may permit product variation to continue into this stage, but this concept still appears to be valid for most industrial settings (Goldhar and Jelinek, 1983).

The systemic stage is theorized as the final stage, and marks the point where we begin to see both fewer process and product innovations, as indicated by the downward slopes in Figure 1. Cost minimization becomes an important goal. If combined with sluggish growth in demand, this focus on cost minimization encourages firms to further standardize their production systems, which reinforces the trend toward standardization. This standardization, at both the product and process level, reduces the probability that new innovations will be adopted. Skinner (1986) found that cost-cutting is usually the first tool selected to achieve productivity improvements, and often acts to hamper innovation. Thus, firms in this stage have less incentive to be 'first-movers' with respect to innovations or new technology.

The source of the stimuli for innovation is also theorized to be a function of the stage of a product's development. As producers attempt to generate additional demand, when attempting product innovations during the uncoordinated stage, the needs of customers are a primary consideration (point A on Figure 1). This is especially important for new types of products where lead-users are the only source of customers expectations (von Hippel, 1978). During the segmental stage producers attempt to differentiate their products, while at the same time reducing product variations so that they can be manufactured on standardized equipment (point B on Figure 1). This accounts for the balance between product and process innovation. In the systemic stage firms seek ways to reduce the cost of securing and transforming inputs, which accounts for their adherence to current techniques unless process innovations offer significant cost advantages (point C on Figure 1).

The product–process approach is both descriptive and normative. Abernathy (1978) found that the pattern of process and product innovations, which occurred in the automobile industry, followed this pattern of innovation. Further support was found in his re-examination of 567 commercially successful innovations, first identified by Myers and Marquis (1969). Galbraith and Schendel (1983) found product and process R&D is useful in helping to classify firms' strategies. If managers can determine the current life cycle stage for their products, this theory provides a framework that should be useful for managing the tradeoffs that must be made between product variations and production standardization. While sounding simplistic, implementation presents serious problems because product and process investments have often been found to be lacking in focus (Hitt and Ireland, 1985), which may lead to the inappropriate funding of new processes or mature products.

The essence of their 'argument is that characteristics of the innovative process and of a firm's innovative attempts will vary systematically with differences in the firm's environment and its stategy for competition and growth, and with the state of development of process technology used by the firm and its competitors' (Utterback and Abernathy, 1975: 640). In terms of 'generic strategies' (Porter, 1980, 1985), a diversification strategy based on developing products for various segments seems more appropriate during the uncoordinated stage. Later on, a low-cost strategy may be more appropriate because production systems are no longer sufficiently flexibile to tolerate product changes, and thus technology plays a role in supporting price-based competition. Complicating this is the fact that the rate of evolution for product and manufacturing process will vary by industry, and thus requires strategic planners to recognize this fact and 'select and manage the evolving mix of product and product technologies that best manage the organization's core skill base' (Williams, 1983: 58).

Meta-learning

Sahal (1979, 1981) developed the concept of meta-learning around the metaprogress function (Sahal, 1982). The metaprogress function relates technological innovation to learning via scaling, doing, planning and sharing. The source of the learning depends on whether the innovation is occurring at the level of the equipment, plant, firm or industry. Unlike the product–process model this concept operates on the notion that innovation is a probabilistic process, operates across firms, and that 'product and process technology constitute an integrated system' and 'that the mutual dependence between the two generally grows stronger over the course of time' (Sahal, 1981: 113). The probabilistic nature of innovation may account for research that fails to find a statistically significant relationship between R&D and performance (e.g. Hambrick, MacMillan and Barbosa, 1983; Hitt and Ireland, 1985). Increasing geographic dispersion of innovations reflects this growth in the total pool of R&D expenditures, which determines the rate for innovations but not their location (e.g. Barton, 1984: Kiser, 1982).

Since the metaprogress function is operating on several levels, a different mode of learning is occurring at each level. At the equipment level certain benefits are possible from scale. These benefits occur because equipment beyond a certain size, once adopted, increases the complexity of the system. This 'may warrant the development of a new technology' (Sahal, 1981: 118). At the plant level the concept rests on the notion that production costs decrease with accumulated experience, and that this occurs in a predictable manner. This aspect is an outgrowth

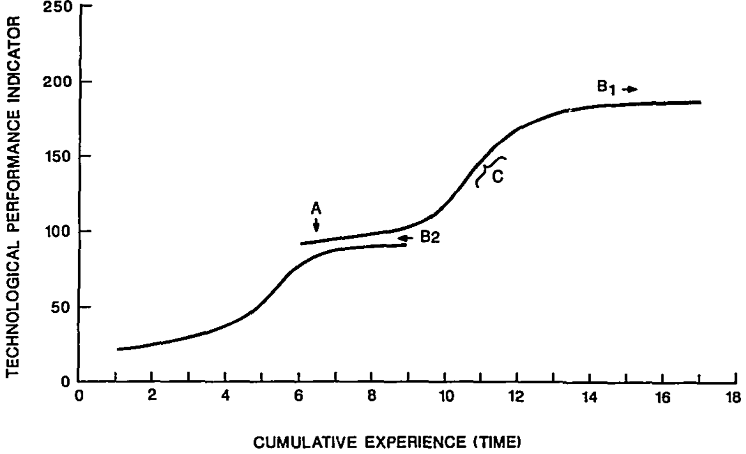

Figure 2. S-shaped patterns of technological innovation as predicted by meta-learning theory

of a body of research started by Wright (1936), who found that the amount of labor involved in airplane assembly operation decreased predictably with experience. The 'learning by doing' concept also relates to these efficiency/experience related dynamics (Arrow, 1962). This concept of predictability has a particular attraction to strategic planners.

At the plant level learning by sharing, which occurs through diffusion, becomes important. The communication and transfer of technical knowledge, which occurs within an industry, also results in a certain amount of technological advancement related to 'learning by sharing' (Sahal, 1982). Because sharing often results in incorporating technological improvements in the second generation of a product, this type of learning may have some relationship to the notion that there may be some disadvantages associated with early adoption (Frankel, 1955). All four types of learning help to explain technological progress. The metaprogress function incorporates these and other activities related to the design, production, diffusion and sharing of technological knowledge in explaining the patterns of innovation that emerge.

Because technology is also viewed as a function of its scale of utilization at several levels an s-shaped curve, rather than a straight line, emerges when actual measures of innovation are examined (see Figure 2). This occurs because constraints (indicated by point A on Figure 2) become effective when there is a mismatch between a given technology and either the environment or the internal scale of production. On the other hand, when complementary technology does exist, the new technology should make the old obsolete (Grinyer *et al.*, 1986). More specifically, these constraints occur because a component of required complementary technology has not moved in parallel with the new innovation. With respect to the current level of technology this has been described as a movement toward equilibrium (indicated by points B_1 and B_2 on Figure 2), which is then usually followed by an innovation leading to a new period of disequilibrium (indicated by point C on Figure 2). These s-shaped curves take on the appearance of a straight line when viewed as an envelope encompassing several of the smaller curves, which helps explain their utility for predicting long-term technological patterns.

From a planning and control perspective this predictability becomes important because the 'scientists and engineers most closely associated with the work of innovation are painfully aware of the consequences and misconceptions about the rate, direction and character of technological progress' (Steele, 1983: 133). They are usually aware of what can be achieved in the long term but Steele (1983) found they tend to underestimate, when asked for predictions. Because Sahal ties his explanation of technological evolution to actual performance indicators, it allows managers to assess these scientific predictions. Mathematically, this process was formulated by Sahal (1981: 125–7) using a Gompert function. The integral form of this function is depicted in equation 1.

$$Y = K\alpha^{b^t} \tag{1}$$

By making a log conversion and substituting that into the differentiated equation Sahal (1981: 126) was able to isolate the variables of interest (see equation 2).

$$\frac{d\log Y}{dt} = -\log b(\log K - \log Y) \tag{2}$$

where: Y = a measure of technology,
K = the upper limit of growth,
α = a parameter,
t = time, and
$-\log b$ = the rate of growth.

Equation 2 was used to derive the meta-progress function, which includes the impact of the rate of growth and experience. One form of the meta-progress function is depicted in equation 3 (Sahal, 1981: 127).

$$\log Y_t = \alpha(1-\lambda) + B(1-\lambda)\log X_t + \lambda \log Y_{t-1} \tag{3}$$

where: $\lambda = 1/(1+B)$ = the coefficient of disequilibrium
X = experience, and
$B = -\log b$
$Y = f(Y_{t-1}, Y_t)$.

When the rate of growth is high (B is large, λ approaches 0), the upper limit is reached rapidly and equilibrium results. λ thus provides a measure of return from, or the scope, of meta-learning. As a policy mechanism Sahal's concept is appealing because it provides a guideline as to when future technology is likely to be available.

Technological interdependence and improvement

Rosenberg (1982) attempted to look inside the 'black box' containing technology, and used the characteristics of different technologies to explain its impact on productivity. Although Rosenberg was primarily concerned with the impact of technology on productivity growth, at the macro-level, his notions about the rate and direction of improvement are complementary both to the product–process and meta-learning concepts. The role that knowledge plays in developing new products and industries is related to growth in productivity. More importantly, for strategic management purposes, he also looked at the 'side-effects' that help explain technical progress. This was accomplished by identifying the impact of technological expectations and 'learning by using'. Expectations of future technological development were related to current decisions about adoption, while 'learning by using' refers to 'gains that are generated as a result of subsequent use of the product' (Rosenberg, 1982: 122).

He deals with a central problem relating uncertainty to expectations. Uncertainty occurs because there are differences in perceptions about both the rate of development and future cost of any given technology. Expectations act as a major force because they affect both the present form of the output and the future direction of technology (Rosenberg, 1982; Williamson, 1971). If the dominant expectation is one of rapid technological advancement, the present form of the product is likely to reflet this limited time frame. Users adopting a product take on an element of risk because delay may result in the purchase of a technologically improved product. If the firm believes the product will be shortly obsolete they will be reluctant to make the purchase. Thus expectation of rapid technological advancement may slow down the diffusion process because postponement, for the firm contemplating adoption, may be the more profitable strategy. If this occurs on a large scale it can reduce the incentive to develop more sophisticated models. For the producer, the strategic problem is 'to persuade potential buyers of product stability at the same time one commits resources to the search for product improvement' (Rosenberg, 1982: 12). Because there tend to be substantial improvements in products, after their first introduction, it is important for buyers to make sure they are committing to new technologies at the appropriate time.

The constraint, which Sahal believed was caused by a lack of complementary technology, can also be explained by concentrating on interdependence between technologies. Rosenberg believed that by viewing innovation in terms of related sets, their value and impact become more apparent. This occurs because, in the related set, each new innovation enhances the value of others. Each innovation is also going through a process of continual improvement, which enhances not only its own value but also those of related innovations. One way this process can be seen occurring is by examining input–output tables and noticing changes in the type and quantities of inputs.

'Learning by using' extends the concept of 'learning by doing', and is related to the high volume of product variation seen during the early stages of a product's life. After a product is purchased, productivity gains are still possible. The user is often the one who identifies the maximum performance capabilities and minimum service requirement. In some cases they may actually result in product modifications (von Hippel, 1978). While these user extensions and improvements have an impact on national productivity they also suggest that manufacturers may want to design products in ways that encourage user improvement activities.

User improvements were found to be important in the commerical aircraft industry, which appears to be a case where 'technological knowledge has preceded scientific knowledge' (Rosenberg, 1982: 144). User inputs suggested design limits, which were then incorporated into subsequent versions of the aircraft. In some cases this took on strategic implications, as manufacturers of airplanes designed them to facilitate subsequent stretching of the fuselage (*Economist*, 1985). This also results in much more attention being paid to the interrelated nature of components because this may constrain the ability of users to fully exploit the potential for productivity gains. Thus, in commercial jet transports, engine size can constrain users and limit their ability to suggest technological improvement or implement user-identified innovations. As products become increasingly complex there may be even greater potential to benefit from 'learning by using', because it is unlikely that the full extent of productivity-related possibilities will be anticipated.

The incremental improvements made by product users is what determines performance capabilities, and by extending the product's performance capabilities they produce productivity improvements. From a strategic perspective, Rosenberg (1982) felt that 'learning by using' might be equally as important as 'learning by doing'. This may vary by industry, but he suggests that it may be optimal for the producer to fully exploit this advantage by designing initial product versions so as to encourage user extensions. This ties in with both meta-learning and the product–process concept, because it helps explain the large numbers of innovations during the early stages of a product's life. Obviously this will not be possible with all products, but in some cases, such as computer software, the practice has almost become institutionalized.

Rosenberg's concepts are appealing because they relate a number of factors, relevant to technological innovation, to a set with strategic significance. Thus, firms capable of noticing advantage by linking innovations, or capable of applying R&D from unrelated areas, can capture the benefits of a technological innovation. Users can also share, and benefit competitively, by taking steps that enhance the capability of products. Users can also benefit manufacturers by sharing this information, although they may be reluctant to do this if they feel the product improvement suggested will benefit competitors.

UNIFYING CONCEPTS FOR STRATEGIC MANAGEMENT

From a strategy perspective all three theories are valuable because they relate factors previously considered in isolation. From a technological perspective they combine to suggest points at which different product/market strategies may be more appropriate. The rate of product development, cost-differentiation tradeoffs, and user-related improvements that affect product offerings can be incorporated using these approaches. Although more difficult to manage, these multiple foci are valuble for strategy formulation purposes.

Figure 3 depicts the interrelated nature of these concepts, and helps to show how they can be united in the strategy-making process. In this figure the meta-learning projections of Sahal, as modified by the 'learning by using' notion of Rosenberg, are mapped on the product–process

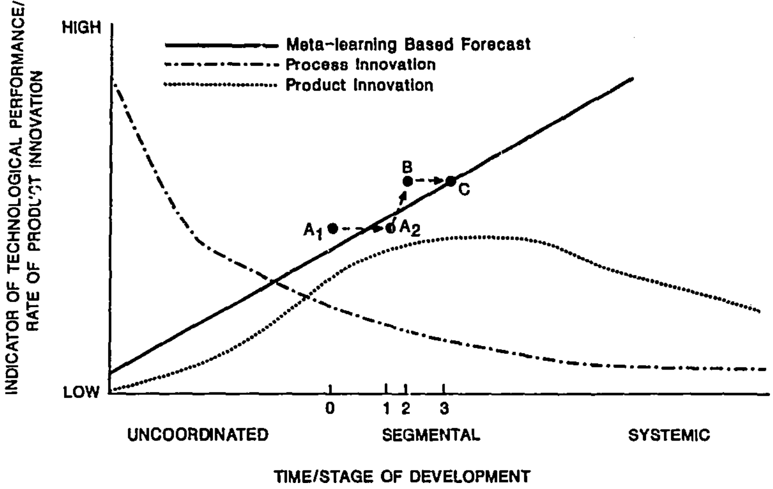

Figure 3. Mapping of technological expectations, on product process model

model of Abernathy and Utterback. Initially, the firm must make decisions relating to technological appropriateness of a product. Assume $t = 0$ represents the present time period, and point A_1 the design/engineering-based estimate of performance capabilities for the product being considered. Complicating the analysis is the fact that the product will not be manufactured and marketed until some future point in time ($t = 1$. Thus, what appears to be a technologically advanced product at one time ($t = 0$), may appear to be lagging at another time ($t = 1$). At point A_1 the product appears to be highly differentiated technologically, but at the point when it will be introduced, A_2, the expectation is that it will lag on technological dimensions or at least be difficult to differentiate.

The 'learning by using' dimension, introduced by Rosenberg, suggests that an additional source of technological improvement should be incorporated into the model. There is a period after the product is introduced, reflecting the time frame between $t = 1$ and $t = 2$, when user improvements should occur. On Figure 3 the movement between point A_2 and B illustrates a typical pattern of performance improvement, associated with 'learning by using'. When these user improvements are incorporated into the forecast they alter the differentiation prospects considerably.

The notions of complementarities and constraints, raised by both Sahal and Rosenberg, are also important because they help us understand why there are limits to the extent that a product with above-average performance characteristics will enjoy market success. On Figure 3 the technologically differentiated shelf-life of the product is represented by the time frame between $t = 2$ and $t = 3$. Thus, at point C the product will no longer be differentiated on its technological dimensions. The temptation exists to produce a product far above the forecast horizon in order to extend the technologically differentiated life of the product. However, if the gap between point A_2 and the trend line is too large, the lack of existing complementary technologies may act as a constraint to product acceptance and make market success less likely.

The product–process concept is relevant because, in a competitive sense, the period over which the product maintains its competitive advantage is directly related to its stage of development. In the Figure 3 example the segmental stage covers the entire period from product inception to obsolescence. Thus the nature of the product should guide the producer's design. For example, if the product being introduced is used in the production process of a group of customers who find themselves competing in the segmental or systemic stage, product success seems more likely. However, if the producer was considering a consumer-type product and perceived himself as entering the systemic stage of development, the implications associated with the product–process concept would suggest a more cautious approach with respect to product innovations.

Policy-makers, by incorporating these concepts into their strategic management frameworks, may be able to enhance their competitive position. Understanding the nature of technological innovation, when combined with the monitoring of relevant technologies, provides a means to incorporate innovation into the firm's planning framework. When appropriately incorporated, technology has been found to help explain relative advantage (e.g. Butler and Carney, 1986; Wernerfelt, 1984). The illustrative example that follows attempts to treat some of these incorporation issues.

EMPIRICAL ILLUSTRATION

Sample

The aircraft industry was selected as the sample because it has a well-documented technological history, and thus offers greater opportunities with respect to pattern recognition. The regulated nature of this industry has enhanced the quality of available data, which is supplemented by qualitative and statistical research (e.g. Civil Aeronautics Board, 1970–81; Mowery and Rosenberg, 1981; Phillips, 1971). Like all industries, this one has certain characteristics that are unique but it 'is one where we would expect continuous product R&D. The flexibility of the production process would also allow us to expect a continuous search for the new material and components' (Porter, 1985: 197). Improvements in the manufacturing process are well documented (e.g. Alchian, 1963; Asher, 1956; Dutton, Thomas and Butler, 1984) and demonstrate the fact that intangible innovations, associated with learning and progress, affect this industry. Thus, for purposes of attempting a theoretical application this would appear to be a suitable industry. The unique characteristics of this and most industries limit generalizability and suggest that industry differences are important when incorporating technological innovation into the firm's strategic planning process.

Data

Two sets of performance data were used to examine the patterns of innovation in this industry. The first set covers the period from 1932 to 1965 and includes the following variables:

t = time
CTRM = cumulative total route miles,
SPED = average air speed,
SEAT = average seating capacity, and
FATL = fatalities per 100 million passenger-miles

Time (t) and cumulative passenger miles (CTRM) served as proxies for experience, while each of the independent variables (SPED, SEAT, FATL) were intended to capture different dimensions associated with the effects of innovation in either the manufacture or use of aircraft (Rosenberg, 1982). This first set of data reflects improvements by several manufacturers incorporated into many aircraft models, and should reflect the experience of users. The 1932–65 period is also sufficiently long to capture any lagged effects associated with production-related or user innovations. This long-range data trace is also useful for examining broad general trends.

The second set of data covers the period from 1970 to 1980 and deals with the operating experience of the domestic trunk lines, for the wide-body 747 only, and includes the following variables:

t = time,
CFLY = cumulative total airborn hours,
SPAM = average available seats per aircraft miles,
ATON = average revenue ton per aircraft flying hour, and
REVM = average revenue per aircraft mile.

Here the independent variables (SPAM, ATON, REVM) were selected to determine if the carriers were able to affect product innovations by causing the types of variations hypothesized in the product–process model, and expected as 'learning by using' extends product capabilities. This aircraft had a single manufacturer and this data set provides a useful base for speculating about how this may affect product extensions.

Data analysis

Pattern identification was the first step. The independent variables were plotted against their respective measures of experience to determine if these patterns supported the product–process and meta-learning concepts. A common form for the s-curve was then selected for ordinary least square regression (see equation 4).

$$X_t = \mathrm{e}\,\alpha-(b/t) \qquad (4)$$

Although there are many mathematical forms for the s-curve, estimating parameters using this equation is simplified by taking logarithms of both sides of the equation and then using ordinary least squares regression to estimate the parameters (α and b). Once calculated these parameters provide the basis for technological forecasts. Additional regression equations were calculated following the form presented in equation (3). This allows calculation of the coefficient of disequilibrium (λ), associated with learning from experience, which is related to the next stage of development for the 747 aircraft.

RESULTS AND DISCUSSION

Figure 4 depicts a time trace for the long-term indicators of technological progress for all commercial aircraft operated by domestic trunk lines. This figure, over the period 1932 to 1965, shows average air speed (SPED), seating capacity (SEAT), and fatalities per 100 million passenger-miles (FATL). For exposition purposes the data have been normalized (1947 = 100) and a larger outlier, for FATL in 1932, has been compressed.

To a degree all three time traces show the s-shaped curve pattern, hypothesized by the meta-progress function. Recurring periods of rapid improvement appear to follow periods of marginal progress. For instance, we see a rapid decline in FATL in the early years (1932–42), which is then followed by a period where improvement levels off. Then in 1951 (indicated by point A on Figure

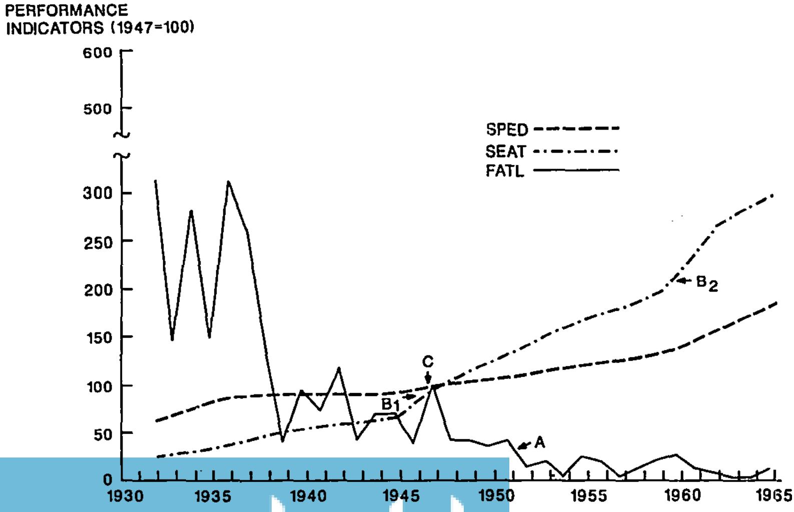

Figure 4. Pattern of improvement for various performance indicators for all commercial aircraft operated by domestic trunk lines, 1932–65

4) we see what appears to be the end of this period of stagnation. This may be a case where needed complementary technology was finally developed, which allowed for the elimination of constraints to progress. This abrupt progress, following a period of stagnation, can also be seen in the time trace for SEAT in the period right after World War II and in the early 1960s (indicated by points B_1 and B_2 on Figure 4). Although the break points between stagnation and new progress are less apparent with respect to SPED, there does appear to be a break between two periods of progress occurring in the late 1940s (indicated by point C in Figure 4).

The data also suggest that, during slower periods of progress, product improvement may be more closely associated with both supplier and user learning. During periods of stagnation process improvements may become more important, especially if the coefficient of disequilibrium (λ) suggests a longer time period between periods of equilibrium. We also get an indication from these time traces that the attempt to fit the data to an s-curve holds some promise.

Figure 5 shows the time traces for three indicators of technological progress, related to the Boeing 747. Multiple s-curve patterns are not expected here because we are concentrating on a single product version, but it does allow a more in-depth view of product variations prompted by either the manufacturer's decision to exploit demand or by user-experience. We appear to be seeing, when examining the entire period, a high degree of performance improvement for both seats per flying hour (SPAM) and revenue per flying hour (ATON). This is consistent with the product–process notion because firms are expected to incorporate improvements that are identified early in the product cycle while the sharp decline, beginning in 1979, suggests that the time for product standardization may be fast approaching. We see a more linear pattern with respect to revenue per aircraft mile (REVM) but this may be the result of the fact that this variable reflects low-cost pricing strategies more directly than technological evolution.

Seating capacity growth for the 747 aircraft suggests an area where the supplier–user relationship may be important. Users may be able to provide information that allows the supplier to enlarge the fuselage, which leads to more seats. In other cases users may find that load-capacities have been underestimated and that a larger number of smaller seats can be substituted. This later approach has become especially valuable as airlines have adjusted fares downward in attempts to attract more passengers. The gradual rise in the time traces for these technological indicators depicts the interrelated nature of the benefits possible. Although aircraft manufacturing does not lend itself to the same degree of process standardization as some other types of products

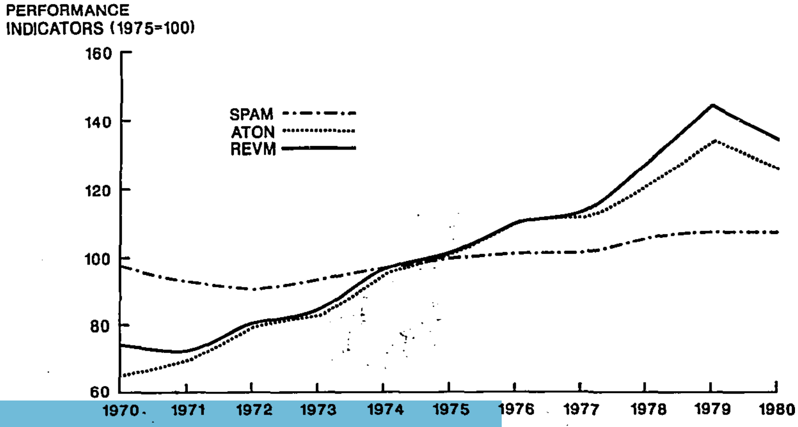

Figure 5. Patterns of improvement for various performance indicators for the Boeing 747, 1970–1980

the time traces provide indications as to the type of innovations now appropriate, especially if the planner is familiar with the product–process framework. Thus, if the technological capabilities of the 747 aircraft have been fully extended, the focus should move toward cost reduction with respect to production, while focusing on the development of the next generation of aircraft.

The time traces depicted in Figures 4 and 5 provide a vehicle for supplementing the industry and firm-specific knowledge of the planner. Using an s-curve equation (see equation 4) to regress time on technological performance allows the regression coefficient (b) for time, which is the slope of the logarithmic progress function, to be converted to a rate of progress $(1-[2^{-b}])$. These regression results are presented in Table 1. Although the rates of progress are low, less than 8 percent in all cases, they suggest that a certain degree of improvement can be expected with each doubling of cumulative experience. The R^2 and F statistics indicate a good fit, in a statistical sense. An advantage of using time as the proxy for experience is now obvious because it is much easier to forecast. The future state for any given indicator of technology can be calculated by substituting $t + n$ into the equation. Of course, if future levels of experience can be accurately predicted, the measure of cumulative experience can be substituted for t in the regression equation. Product planning can be facilitated by projecting the future state for a number of relevant technological indicators. This will help insure that needed complementary technology is on line, and that the product is on the high side of the technology–performance scale (above the meta-learning projection line in Figure 3).

The regression results, depicted in Table 1, also allow the long-term expectation (equations 1, 2 and 3), with respect to commercial aircraft in general, to be mapped on the technological expectations with respect to the Boeing 747 (equations 4, 5 and 6). Projections, with respect to both sets of data, allow a more educated determination to be made with respect to whether the Boeing 747 will technologically lead, or begin to constrain, technological progress in this industry. Although only a small number of technological indicators have been presented here, they are representative of other existing measures. The results suggest lower rates of technological improvement associated with learning, which may mean the industry is in a period of temporary equilibrium.

The coefficient of disequilibrium (λ) was suggested by Sahal (1981) as an indicator of the length of time between periods of equilibrium. It also appears that the dynamics involved in the product–process model will be closely associated with the size of λ. The regression results, presented in Table 2, look at this coefficient with respect to experience although, as Sahal (1981) points out, it could also be calculated with respect to scale. In these equations, measures of user experience (CTRM and CFLY) have been used as proxies because here we are trying to determine

Table 1. S-curve regression results for various technology indicators

Estimated relationship					Equation
log SPED =	4.77 (204)	+0.023t (21.4)	$F(1,32) = 457.7$	$R^2 = 0.95$	(1)
log SEAT =	2.22 (64.2)	+0.08t (44.7)	$F(1,32) = 1968$	$R^2 = 0.98$	(2)
log FATL =	4.17 (18)	−0.12t (−10.4)	$F(1,32) = 109$	$R^2 = 0.77$	(3)
log SPAM =	5.14 (43)	+0.016t (6.02)	$F(1,9) = 36.2$	$R^2 = 0.80$	(4)
log ATON =	− 0.12 (−.54	+0.073t (14.9)	$F(1,9) = 223$	$R^2 = 0.96$	(5)
log REVM =	2.03 (4.82)	+0.072t (4.61)	$F(1,9) = 239$	$R^2 = 0.96$	(6)

Table 2. Regression results for learning via experience for various technological indicators

Estimated relationship	Equation
$\log \text{SPED} = -0.12 - 0.023 \log \text{CTRM} + 1.08 \log \text{SPED}_{t-1}$ $(-0.7) \quad (-1.4) \quad (15.9)$ $F(2,30) = 859.6 \quad R^2 = 0.98$	(1)
$\log \text{SEAT} = 0.16 - 0.002 \log \text{CTRM} + 0.96 \log \text{SEAT}_{t-1}$ $(0.34) \quad (0.04) \quad (13.9)$ $F(2,30) = 3406 \quad R^2 = 0.99$	(2)
$\log \text{FATL} = 13.4 - 0.99 \log \text{CTRM} + 0.09 \log \text{FATL}_{t-1}$ $(3.9) \quad (-3.94) \quad (0.48)$ $F(2,30) = 38.5 \quad R^2 = 0.72$	(3)
$\log \text{SPAM} = 1.8 + 0.05 \log \text{CFLY} + 0.57 \log \text{SPAM}_{t-1}$ $(2.5) \quad (4.1) \quad (4.0)$ $F(2,7) = 50.4 \quad R^2 = 0.94$	(4)
$\log \text{ATON} = -0.59 + 0.18 \log \text{CFLY} + 0.43 \log \text{ATON}_{t-1}$ $(-1.1) \quad (2.06) \quad (1.87)$ $F(2,7) = 81.7 \quad R^2 = 0.96$	(5)
$\log \text{REVM} = 0.23 + 0.19 \log \text{CFLY} + 0.48 \log \text{REVM}_{t-1}$ $(0.52) \quad (2.62) \quad (2.46)$ $F(2,7) = 63.6 \quad R^2 = 0.95$	(6)

the rapidity of technological advances, which are valuable when developing timetables for new products.

Equations 1, 2 and 3 in Table 2 present the results for the long-term manufacturing data. The regression coefficients on the lagged terms (SPED_{t-1}, SEAT_{t-1} and FATL_{t-1}) can be interpreted as the coefficient of disequilibrium (λ) (Sahal, 1981). λ provides an indication of the speed at which we can expect any of these technological measures to move from one state of equilibrium to the next. For equations 1 and 2 λ is large, while λ is small in equation 3, indicating that a longer time frame between periods of equilibrium is likely with respect to passenger aircraft in general. The regression coefficients on CTRM indicate the short-term impact of experience on learning is important only with respect to fatalities (FATL). The long-term impact can be determined by dividing the regression coefficient on CTRM by $1 - \lambda$. As expected, this suggests that the impact of experience for a mature industry is lessening, and that the time frame between major eras of technological advancement is lengthening.

When examining the regression results for the Boeing 747 only (equations 4, 5 and 6), we get a different level of indication as to the impact of λ. Here the regression coefficients are uniformly smaller, suggesting that the movement to a new point of equilibrium may be more rapid. Thus while we expect the technological shelf-life of commercial aircraft to increase, it appears that certain technological qualities of the 747 aircraft are approaching a period of equilibrium. The regression coefficients on the measure of experience (CFLY) also suggest a large impact, in both the short and long term, for learning associated with experience. When combined with the earlier results this suggests that gains from experience will be greater for the Boeing 747 than for the industry in general, and that the technological superiority of this aircraft, on certain dimensions, may be sustainable in the long-term. Technologically this may suggest that the aircraft that succeeds the 747 may choose to further exploit some of its existing technological characteristics while attempting to make major advances on those that appear to be approaching equilibrium.

CONCLUSIONS

The effects of experience, step-wise growth, and substitution, as incorporated into the meta-learning concept, seem to provide an adequate explanation for the long-term patterns of innovation, which occurred in the aircraft industry.

The impact of both the introduction and subsequent adoption of new technology seemed to be reflected in the performance data. The data also supported the step-wise pattern of growth by revealing a scenario where product, process and user innovations all appear to play a role in the continuous development of larger, faster and safer aircraft.

The product–process model can be easily mapped on the short-term results for the Boeing 747 aircraft. Product adaptation occurs as seats and freight-carrying capacity were added, increasing total revenue and reducing the profit penalties associated with fare reductions. Even though production volume was limited, configurations did become somewhat standardized as the producer attempted to incorporate users' capacity and operating demands. These forces eventually provide the impetus needed to produce a new model of aircraft.

For the policy-maker, interested in explaining and using innovation and technological progress as planning tools, all three theories provide valuable complementary lessons. Rosenberg's notions about the interrelated nature of technology and the contributions of users forces the planner to recognize that the high-leverage theories of Sahal and Utterback and Abernathy do not capture all relevant dimensions. Sahal's framework provides a good long-term planning tool, allowing the strategic planner to assess both the competitive life of any given technology as well as the extent to which cumulative experience is contributing to progress. The product–process model provides additional richness by presenting a normative guide for the planning of innovations. It serves as a short-term guide as to when and where innovations should be targeted. It can also be used as a guide to industrial policy because it suggests guidelines as to where the expenses associated with innovation may be warranted (Abernathy, Clark and Kantrow, 1983) rather than just providing a broad general prescription (e.g. Babbitt, 1984).

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