Developments in Manufacturing Technology and Economic Evaluation Models

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DEVELOPMENTS IN MANUFACTURING TECHNOLOGY AND ECONOMIC EVALUATION MODELS

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I. INTRODUCTION

Driven by international competition and aided by application of computer technology, manufacturing firms have been pursuing persistently two principal trajectories during the 1980's: automation and integration. Automation is the substitution of machine for human function; integration is the reduction of buffers between physical or organizational entities. With the aims of reducing their needs for low-skilled labor and liberating human resources for knowledge work, firms have automated away simple, repetitive, or unpleasant functions in their offices, factories, and laboratories. To improve quality, cost, and responsiveness to their customers, firms are reducing the physical, temporal, and organizational buffers between productive entities in their operations. Such buffer reduction has been implemented by the elimination of waste, the substitution of information for inventory, the insertion of computer technology, or some combination of these.

In most process industries, automation and integration have been critical trends for decades. However, in discrete goods manufacture, significant movement in these directions is a recent phenomenon. In most cases, factory automation and integration require significant capital outlays. Therefore, the advent of new computerized manufacturing technology for automation and integration has also spawned a flurry of scholarly research into the development of models for economic evaluation of investment opportunities in these technologies.

This paper addresses technologies that support the trends toward more automation and integration in discrete goods manufacturing. In Section II describes more fully the trends toward automation and integration in manufacturing as well as the technological hardware and software that has been evolving to support these trends. Section III discusses a number of management challenges and opportunities created by these technologies. Section IV provides an overview of some of the issues in the technology evaluation problem and a brief discussion of manufacturing performance evaluation models and their relationship to the economic evaluation literature. Section V provides some historical perspective on the economic modelling literature, and then surveys recent work on economic evaluation models for technology adoption. Section VI describes related empirical work, discusses the usefulness of the modelling literature for the economic evaluation of new manufacturing technology, and presents a research agenda for the area.

II. THE NEW MANUFACTURING TECHNOLOGIES

This section describes the technology that is supporting automation and integration in manufacturing. Some of this technology, such as computer-aided design (CAD) and robotics, is reasonably well established and productively employed in many locations. Other technologies, computer-integrated manufacturing (CIM), for example, are still in the future for most firms. Despite these differences, all of the technologies described below are expected to play important roles in international competitiveness in the coming decade.

Automation in Manufacturing

As characterized, for example, by Toshiba (1986), automation in manufacturing can be divided into three categories: factory automation, engineering automation, and planning and control automation. Automation in these three areas can occur independently, but coordination among the three drives opportunities for computer-integrated manufacturing, discussed below.

Factory Automation

Although software plays an equally important role, factory automation is typically described by the technological hardware used in manufacturing: robots, numerically controlled (NC) machine tools, automated inspection systems, and automated material handling systems. Increasingly, these technologies are used in integrated systems, known as manufacturing cells or flexible manufacturing systems (FMSs).

The term *robot* refers to a piece of automated equipment, typically programmable, that can be used for moving material to be worked on (pick and place) or assembling components into a larger device. Robots are also used to substitute for direct human labor in the use of tools or equipment, as is done, for example, by a painting robot, or a welding robot, which both positions the welder and welds joints and seams. Robots can vary significantly in complexity, from simple single-axis programmable controllers to sophisticated multi-axis machines with microprocessor control and real-time, closed-loop feedback and adjustment.

A numerically-controlled (NC) machine tool is a machine tool that can be run by a computer program that directs the machine in its operations. A stand-alone NC machine needs to have the workpieces, tools, and NC programs loaded and unloaded by an operator. However, once an NC machine is running a program on a workpiece, it requires significantly less operator involvement than a manually-operated machine. A CNC (computer numerically-controlled) tool typically has a small computer dedicated to it, so that programs can be developed and stored locally. In addition, some CNC tools have automated parts loading and tool changing. CNC tools typically have real-time, on-line program development capabilities, so that operators can implement engineering changes rapidly. A DNC (distributed numerically-controlled) system consists of numerous CNC tools linked together by a larger computer system that downloads NC programs to the distributed machine tools. Such a system is necessary for the ultimate integration of parts machining with production planning and scheduling.

Inspection of work can also be automated with, for example, vision systems or pressure-sensitive sensors. Inspection work tends to be tedious and prone to errors, so it is a good candidate for automation. However, automated inspection (especially with diagnosis capability) tends to be very difficult and expensive. This situation, where automated inspection systems are expensive to develop, but human inspection is error-prone, demonstrates the value of automated manufacturing systems with very high reliability: In such systems, inspection and test strategies can be developed to exploit the high-reliability features, with the potential to reduce significantly the total cost of manufacture and test.

Automated material handling systems move workpieces among work centers, storage locations, and shipping points. These systems may include autonomous guided vehicles, conveyor systems, or systems of rails. By connecting separate points in the production system, automated material handling systems serve an integration function, reducing the time delays between different points in the production process. These systems force process layout designers to depict clearly the path of each workpiece and often make it economical to transport workpieces in small batches, providing the potential for reduced wait times and idleness.

An FMS is a system that connects automated workstations with a material handling system to provide a multi-stage automated manufacturing capability for a wider range of parts than is typically made on a highly-automated transfer line. These systems provide flexibility because both the operations performed at each work station and the routing of parts among work stations can be varied with software controls. The promise of FMS technology is to provide the capability for flexibility approaching that available in a job shop with equipment utilizations approaching what can be achieved with a transfer line. In fact, an FMS is a technology intermediate to these two extremes, but good management can help in pushing both frontiers simultaneously (Jaikumar (1986)).

Automated factories can differ significantly with respect to their strategic purpose and impact. Two examples may be instructive. In Osaka, Japan, Matsushita Electric Industrial Company has a plant that produces video cassette recorders (VCRs). The heart of the operation features a highly automated robotic assembly line with 100-plus work stations. Except for a number of trouble-shooting operators and process improvement engineers, this line can run, with very little human intervention, for close to 24 hours per day, turning out any combination of 200 VCR models. As of August 1988, the facility was underutilized, and Matsushita was poised to increase production, by running the facility more hours per month, as demand materialized. The marginal costs of producing more output are quite low. As a consequence, Matsushita could price very aggressively against any potential new competitor attempting to enter into the VCR business. Thus, Matsushita seems to have achieved strong product-market benefits from its automated factory.

As a second example, consider Plant III in General Electric's Aircraft Engine Group in Lynn, Massachusetts. This fully automated plant machines a small set of parts that are used by the Aircraft Engine Group's assembly plant. In contrast to Matsushita's plant, which provides strategic advantage in the VCR *product* market, the strategic advantage provided by GE's plant seems to address its *labor* market. Plant III's investment is now sunk. Eventually, it will run around the clock at very high utilization rates with a very small crew. As volume is ramped up, GE has the ability to use Plant III's capacity and cost structure as leverage with its unionized labor force which is currently making many of the parts that could be transferred to Plant III. Thus, factory automation can address a variety of types of strategic needs, from product market considerations to labor market concerns. (However, the work of Kulatilaka and Marks (1988) illustrates how the type of strategy employed by General Electric may not always be beneficial to the firm.)

Engineering Automation

From analyzing initial concepts to finalizing process plans, engineering functions that precede and support manufacturing are becoming increasingly automated. Computer-aided design (CAD), sometimes used as an umbrella term for computer-aided drafting, computer-aided engineering analysis, and computer-aided process planning, eliminates significant amounts of the drudgery from engineering design work, so that engineers can concentrate more of their time and energy being creative and evaluating a wider range of possible design ideas.

Computer-aided drafting is a software tool that increases productivity in the drafting and drawing functions of the engineer. The technology permits engineers to make incremental modifications to drawings or to try many "what if" conceptual experiments with great ease. Computer-aided engineering allows the user to apply necessary engineering analysis, such as finite element analysis, to proposed designs during the drawing-board stage. This capability can reduce dramatically the time-consuming prototype workup and test stages of the product development process. Computer-aided process planning helps to automate the manufacturing engineer's work of developing process plans for a product, once it has been designed.

In many respects, engineering automation is very similar to factory automation. Both phenomena can improve dramatically labor productivity and both increase the proportion of knowledge work for the remaining employees. However, for many companies, the economic payback structure and the justification procedures for the two technologies can be quite different. This difference stems from a difference in the scale economies of the two types of technologies. In many settings, the minimum efficient scale for engineering automation is quite low. Investment in an engineering workstation can often be justified whether or not it is networked and integrated into the larger system. The first-order improvement of the engineer's productivity is sufficient. For factory automation, the reverse is more frequently the case. The term "island of automation" has come to connote a small investment in factory automation that, by itself, provides a poor return on investment. Many firms believe that factory automation investment must be well integrated and widespread in the operation before the strategic benefits of quality, lead time, and flexibility manifest themselves. This issue is discussed further in later sections.

Planning and Control Automation

Planning and control automation is most closely associated with material requirements planning (MRP). Classical MRP develops production plans and schedules by using product bills of materials and production lead times to explode customer orders and demand forecasts netted against current and projected inventory levels. MRP II systems (second-generation MRP) are manufacturing resource planning systems that build on the basic MRP logic, but also include modules for shop floor control, resource requirements planning, inventory analysis, forecasting, purchasing, order processing, cost accounting, and capacity planning in various levels of detail.

The economic considerations for investment in planning and control automation are more similar to that for investment in factory automation than that for engineering automation. The returns from an investment in an MRP II system can only be estimated by analyzing the entire manufacturing operation, as is also the case for factory automation. The *integration* function of the technology provides a significant portion of the benefits.

Integration in Manufacturing

Four important movements in the manufacturing arena are pushing the implementation of greater integration in manufacturing: Just-in-Time manufacturing (JIT), Design for Manufacturability (DFM), Quality Function Deployment (QFD), and Computer-integrated Manufacturing

(CIM). Of these, CIM is the only one directly related to new computer technology. JIT, DFM, and QFD, which are organization management approaches, are not inherently computer-oriented and do not rely on any new technological developments. Therefore, in later sections, they will not be addressed. I describe them briefly here because they are important to the changes that many manufacturing organizations are undertaking and because their integration objectives are very consonant with those of CIM.

Management Tools for Integration

JIT embodies the idea of pursuing streamlined or continuous-flow production for the manufacture of discrete goods. Central to the philosophy is the idea of reducing manufacturing setup times, variability, inventory buffers, and lead times in the entire production system, from vendors through to customers, in order to achieve high product quality (conformity), fast and reliable delivery performance, and low costs. The reduction of time and inventory buffers between work stations in a factory, and between a vendor and its customers, creates a more integrated production system. People at each work center develop a better awareness of the needs and problems of their predecessors and successors. This awareness, coupled with a cooperative work culture, can help significantly with quality improvement and variability reduction. Schonberger (1980) and Hall (1980) are useful references on JIT.

Investment in technology, that is, machines and computers, is not required for the implementation of JIT. Rather, JIT is a management technology that relies primarily on persistence in pursuing continuous incremental improvement in manufacturing operations. JIT is important because it accomplishes some of the same integration objectives achieved by CIM, without significant capital investment. Just as it is difficult to quantify the costs and benefits of investments in (hard) factory automation, it is also difficult to quantify costs and benefits of a "soft" technology such as JIT. Some recent models have attempted to do such a quantification (Fine and Porteus, 1989), but that body of work has not yet been widely applied.

Design for Manufacturability (sometimes called concurrent design or simultaneous engineering), is a set of concepts related to pursuing closer communication and cooperation among design engineers, process engineers, and manufacturing personnel. In many engineering organizations, traditional product development practice was to have product designers finish their work before process designers could even start theirs. Products developed in such a fashion would inevitably require significant engineering changes as the manufacturing engineers struggled to find a way to produce the product in volume at low cost with high uniformity.

Closely related to Design for Manufacturability is the concept of Quality Function Deployment (QFD) which requires increased communication among product designers, marketing personnel, and the ultimate product users. In many organizations, once an initial product concept was developed, long periods would pass without significant interaction between marketing personnel and the engineering designers. As a result, as the designers confronted a myriad of technical decisions and tradeoffs, they would make choices with little marketing or customer input. Such practices often led to long delays in product introduction because redesign work was necessary once the marketing people finally got to see the prototypes. QFD formalizes interaction between marketing and engineering groups throughout the product development cycle, assuring that design decisions are made with full knowledge of all technical and market tradeoff considerations.

Taken together, Design for Manufacturability and Quality Function Deployment promote integration among engineering, marketing, and manufacturing to shorten the total product development cycle and to improve the quality of the product design, as perceived by both the manufacturing organization and the customers who will buy the product. Like JIT, Design for Manufacturability and Quality Function Deployment are not primarily technological in nature. However, computer technologies such as computer-aided design can be useful for fostering engineering/manufacturing/marketing integration. In a sense, such usage can be considered as the application of computer-integrated manufacturing concepts for implementing these policy choices.

Computer-integrated Manufacturing

Computer-integrated manufacturing refers to the use of computer technology to link together all functions related to the manufacture of a product. CIM is therefore both an information system and a manufacturing control system. Because its intent is so all-encompassing, even describing CIM in a meaningful way can be difficult.

We describe briefly one relatively simple conceptual model (developed by Fine, et al, 1989) that covers the principal information needs and flows in a manufacturing firm. The model consists of two types of system components: departments that supply and/or use information, and processes that transform, combine, or manipulate information in some manner. The nine departments in the model are:

1. production
2. purchasing
3. sales/marketing
4. industrial amd manufacturing engineering
5. product design engineering
6. materials management and production planning
7. controller/finance/accounting
8. plant and corporate management
9. quality assurance.

The nine processes that transform, combine, or manipulate information in some manner are:

1. cost analysis
2. inventory analysis
3. product line analysis
4. quality analysis
5. workforce analysis
6. master scheduling
7. material requirements planning (MRP)
8. plant and equipment investment
9. process design and layout.

To complete the specification of the model for a specific manufacturing system, one must catalog the information flows among the departments and information processes listed above. Such an information flow map can serve as a conceptual blueprint for CIM design, and can aid in visualizing the scope and function requirements for a CIM information system.

Design and implementation of a computer system to link together all of these information suppliers, processors, and users is typically a long, difficult, and expensive task. Such a system must serve the needs of a diverse group of users, and must typically bridge a variety of different software and hardware subsystems. The economic benefits from such a system come from faster and more reliable communication among employees within the organization and the resulting improvements in product quality and lead times.

Since many of the benefits of a CIM system are either intangible or very difficult to quantify, the decision to pursue a CIM program must be based on a long term, strategic commitment to improve manufacturing capabilities. Traditional return-on-investment evaluation procedures that characterize the decision-making processes of many U.S. manufacturing concerns will not justify the tremendous amount of capital and time required to aggressively pursue CIM. Despite the high cost and uncertainty associated with CIM implementation, most large U.S. manufacturing companies are investing some resources to explore the feasibility of using computerized information sytems to integrate the various functions of their organizations. Some observers (Harhalakis, et al, 1988) believe that existing CAD and MRP II systems will form the foundation of future CIM systems.

The remainder of this paper restricts attention primarily to factory automation and CIM, defining the latter as: the computer-based information system to support integration of the entire manufacturing system. I will sometimes refer to CIM and factory automation, collectively, as "the new manufacturing technologies."

III. CHALLENGES CREATED BY THE NEW MANUFACTURING TECHNOLOGIES

As explained above, investments in factory automation and CIM move a firm in the direction of more automation and integration. To fully evaluate such investment opportunities, one must consider two derivative effects of these characteristics: (1) the flexibility of the manufacturing operation, and (2) the capital intensiveness of the operation. In this section, I briefly discuss these two effects before presenting six challenges created by the new manufacturing technologies.

By shortening lead times within the manufacturing system and by automating setups and changeovers for different products, the new technologies achieve greater manufacturing flexibility: flexibility to change product mix, to change production rate, and to introduce new products. The importance of manufacturing flexibility for firm competitiveness has become apparent over the past decade as the rate of economic and technological change has accelerated and as many consumer and industrial markets have become increasingly internationalized. As a consequence of this increased competition, product life cycles shorten as each firm tries to keep up with the new offerings of a larger group of industrial rivals. To survive, companies must respond quickly and flexibly to competitive threats. The discussion in Section V pays particular attention to evaluating the flexibility component of the new manufacturing technologies.

By definition, automation on a large scale replaces humans with machines and therefore, increases the capital intensiveness of an operation. Such a transformation has two important effects. First, the resulting change in cost structure, from one with low fixed investment and high unit variable costs, to one with high fixed investment and low variable costs, can affect significantly a firm's ability to weather competitive challenges. Models capturing this characteristic are discussed in Section V. Second, the changes in both employment levels and work responsibilities brought about by automation require significant organizational adjustment. These changes are discussed briefly below, but a full treatment is beyond the scope of this paper.

In the remainder of this section, I discuss six challenges created by the new manufacturing technologies.

1. Design and Development of CIM Systems

Because of their ambitious integration objectives, CIM systems will be large, complex information systems. Ideally, the design process should start with the enunciation of the CIM mission, followed by a statement of specific goals and tasks. A top-down design approach insures that the hardware and software components are engineered into a cohesive system. In addition, since the foundation of CIM consists of an integrated central database plus distributed databases, database design is critical. Since many people in the organization will be responsible for entering data into the system, they must understand how their functions interact with the entire system. Input from users must be considered at the design stage, and systems for checking database accuracy and integrity must be included. In addition, hardware and software standardization must also be considered at the system design stage. At many companies, computing and database capabilities have come from a wide variety of vendors whose products are not particularly compatible. Either retooling, or developing systems to link these computers together, requires significant resources. Obviously, designing a system that will be recognized as a success, both inside and outside the organization, is a formidable challenge.

2. Human Resource Management System

As mentioned above, significant adjustment is required for an organization to coalesce behind the implementation of new factory automation and CIM technology. If the new technology is installed in an existing plant, then layoffs are often one consequence of the change. Reductions in force are inevitably associated with morale problems for the remaining employees who may view the layoffs as a sign of corporate retreat rather than revitalization. Furthermore, workforce problems are not typically limited to simply laying off a set number of people and then just moving forward with the remaining group. CIM and automation technologies place significantly greater skill demands on the organization. Retraining and continuous education must be the rule for firms that hope to be competitive with these technologies; the firm must undergo a cultural transformation.

Requirements for retraining and continuous education are at least as stringent for managers and engineers who work with these new technologies as for the factory workers on the plant floor. Designing automated factories, managing automated factories, and designing products for automated factories all require supplemental knowledge and skills compared with those required for a traditional, labor-intensive plant. Senior managers, who must evaluate CIM technologies, *ex ante* and *ex post*, and evaluate the people who work with them, also can benefit significantly from education about the technologies.

3. Product Development System

Factory automation and CIM can make product designers' jobs more difficult. Human-driven production systems are infinitely more adaptable than automated manufacturing systems. When setting requirements for a manually built product, a designer can afford some sloppiness in the specifications, knowing that the human assemblers can either accomodate unexpected machining or assembly problems as they occur, or at least can recognize problems and communicate them back to the designer for redesign.

In an automated setting, designers cannot rely on the manufacturing system to easily discover and recover from design errors. There are severe limits to the levels of intelligence and adaptability that can be designed into automated manufacturing systems, so product designers must have either intimate knowledge of the manufacturing system or intimate communication with those who do. Developing such a design capability in the organization is difficult, but necessary for world-class implementation of the manufacturing system.

4. Managing Dynamic Process Improvement

In most well-run, labor-intensive manufacturing systems, continuous improvement results from a highly motivated workforce that constantly strives to discover better methods for performing its work. In a highly automated factory, there are few workers to observe, test, experiment with, think about, and learn about the system and how to make it better. As a consequence, some observers claim that factory automation will will mean the end of the learning curve as an important factor in manufacturing competitiveness. Such an assertion runs counter to a very long history of progress in industrial productivity, resulting from a collection of radical technological innovations, each followed by a long series of incremental improvements that help perfect the new technology. According to Rosenberg (1982, p. 68), ". . . a large portion of the total growth in productivity takes the form of a slow and often invisible accretion of individually small improvements in innovations." Rosenberg goes on to cite several empirical studies, including that of Hollander (1965) who sought to explain the sources of cost reduction in du Pont's rayon plants. In Rosenberg's (1982, p. 68) words, Hollander found that, "the cumulative effect of minor technical changes on cost reduction was actually greater than the effect of major technical change. In essence, any radical innovation may be thought of as a first pass innovation which will require much work before it reaches its maximum potential.

To presume that factory automation and CIM will reverse this historic pattern is premature at best, and potentially very misleading to managers and implementers of these technologies. Because these technologies are so new and so complex, one cannot expect to capture all of the relevant knowledge at the system design stage. If a firm assumes that once in place, the technology will not be subject to very much improvement, it will evaluate, design, and manage the system much differently than under the assumption that much benefit can be achieved by learning more about how best to use the system once it is in place. One might expect to observe self-fulfilling prophecies in this regard. Even though an automated factory has far fewer people (potential innovators) in it, firms who invest in this technology would be wise to assure that those people who are present are trained to discover, capture, and apply as much new knowledge as possible.

5. Technology Procurement and Ex Ante Evaluation

Much of the remainder of this paper is concerned with *ex ante* evaluation of manufacturing technology. Before evaluating a specific technological option, that option must be reasonably well defined. A firm needs to choose equipment and software vendors, and to decide how much of the design, production, installation, and integration of the technology will be performed with in-house staff. Hayes, Wheelwright, and Clark (1988) make a strong case for doing as much technology development in house as possible to minimize information leaks about the firm's process technology, and to assure a proper fit between the firm's new technology and its existing strategy, people, and capital assets.

In any event, technological options must be generated before they can be evaluated. In developing these options, a firm must consider its current assets, environment, and market position, as well as those of its competitors. Equipment vendors should also be consulted. In addition, technology evaluation criteria must be developed and disseminated within the organization. Such criteria are discussed in Section IV.

6. Ex Post Technology Evaluation

Once a technology investment choice has been implemented, managers typically want to track the efficacy of that investment. Much has been written recently (for example, Kaplan 1983; Cooper and Kaplan 1988a, 1988b; Berliner and Brimson 1988) on the difficulties of measuring manufacturing performance with traditional cost accounting methods. The problems stem, in part, from the fact that most modern manufacturing systems are for more complex than the traditional cost accounting model used measure and monitor them. Kaplan (1984) describes how that model was developed at a time when most firms had one product, one technology, much labor, and little capital investment, compared with today's firms. Firms need better models to improve their control and ealuation systems. Problems also arise because many cost accounting methods can be manipulated to make current results look good at the expense of future results. When managers spend only a small fraction of their careers in one facility or position, they often have an incentive to engage in such manipulations.

Increasingly, firms are using multidimensional measures of manufacturing performance. Rather than depending on just a profitability summary statistic, measures on quality, cost of quality, lead times, delivery performance, and total factor productivity are being utilized to evaluate performance. Despite this trend, firms could benefit from more research on how, for example to set standards for productivity and learning rates, for example, in a highly automated, integrated environment. The work of Clark and Hayes (1985) provides an example of this type of research.

IV. TECHNOLOGY EVALUATION ISSUES

This section discusses qualitatively the costs and benefits to be considered in manufacturing technology evaluation, and the modelling issues for capturing these costs and benefits. The literature on manufacturing performance evaluation models, which is related to economic evaluation of technology, is also discussed briefly.

Costs and Benefits of New Technology Adoption

The technology adoption costs that are the most visible, and easiest to estimate in advance, are the up-front capital outlays for purchased hardware, software, and services. Most models consider only these costs. Also important, however, are (1) costs of laying off people whose skills will not be used in the new system, (2) costs of plant disruption caused by the introduction of new technology into an operating facility, and (3) costs of developing the human resources required to design, build, manage, maintain, and operate the new system. Layoff costs are structurally quite simple to capture, and many models (Gaimon 1985, for example) include them. Plant disruption costs have been studied by Hayes and Clark (1985). Although, their work could be used as a base for formulating a technology choice model that includes disruption costs, I am unaware of any models that attempt to do this. Because of a dearth of quantitative empirical research in the area, estimating total human resource costs arising from a decision to adopt a new technology is by far the most difficult of these costs to model.

In the domain of capturing the benefits that flow from CIM technology adoption, there are many modelling challenges to be pursued. Academicians (Johnson and Kaplan, 1987) and practitioners (Berliner and Brimson, 1988) have noted that standard capital budgeting models are insufficient decision aids for evaluating the benefits of new manufacturing technologies. These benefits relate to changes in a firm's cost structure, increased process repeatability and product conformance, increased flexibility, lower inventories, and shorter flow and communication lines.

With respect to cost structure, investment in CIM and factory automation tends to represent a large up-front cost that leads to a reduction in variable costs per unit of output. This characteristic results primarily from replacement of labor by machines. As is illustrated by some of the models discussed in the next section, low variable costs can provide significant competitive advantage when interfirm rivalry is high. In addition, reduced variable costs sometimes lead firms to cut prices, increasing market share and (sometimes) revenues.

The advantages arising from the increased repeatability and product conformance afforded by CIM and factory automation can also have significant competitive impact. Decreased process variability reduces scrap and rework costs, a source of variable cost savings that can be as important as the reduction of direct labor costs by automation. In addition, improved product conformance can provide significant sales gains in product markets. Secondary effects include improved morale (and consequent reduced absenteeism and turnover) of employees happy to work in a system that runs well.

Manufacturing flexibility is frequently mentioned as a key strategic advantage offered by CIM and factory automation. Quick tool and equipment changeovers enable firms to rapidly change product mix in response to varying market demands. In addition, NC programming and computer-aided process planning shorten the time to market and time to volume for new products introduced into the factory. Fully-automated manufacturing systems provide volume flexibility as well. The highly-automated Matsushita VCR factory mentioned in Section II can change its output rate with relatively low adjustment costs by increasing or decreasing the number of hours it runs each month. Because the factory's direct labor force is quite small, output declines will not lead to dramatic underemployment, and increases do not require major hiring and training efforts.

Inventory reduction following automation and integration investments can arise from several sources. First, factory automation can reduce setup times for some types of operations, reducing the need for cycle stocks. Second, decreased process variability can decrease uncertainty in the entire manufacturing system, reducing the need for safety stocks. Finally, reduced lead times between work stations will lower the flow times of work between stations, thus decreasing the need for WIP in the system. As inventories and lead times are reduced, firms may increase their profit margins by charging more for rapid delivery or may increase market share by offering better service without raising prices.

Manufacturing Performance Evaluation Models

An important set of models, related to models for economic evaluation of technology, are manufacturing performance evaluation models. These models are used to analyze the physical performance, rather than the economic performance, of a manufacturing system or technology. Typically, such models capture the flow of parts and products in a system, and predict means and/or variances of measures such as production rate, inventories, lead times, and queueing times. Queueing network models are the basis for perhaps the largest bulk of this type of work. Perturbation analysis provides another methodology used for manufacturing system performance analysis. Buzacott and Yao (1986) provide many references for work on performance evaluation that has been applied to modelling flexible manufacturing systems. Chapter xx in this volume describes this literature.

One would expect that the outputs from performance evaluation models of manufacturing systems and technologies could be used as inputs for cash flow analysis and economic models. However, the two literatures, performance evaluation and economic evaluation, have not grown up that way. Rather, most economic models are formulated at a much more aggregate level than the performance evaluation models, and there has been little intersection in the literatures. Despite this separate development, each area has been quite productive in its own right. Both have made valuable contributions. In addition, there has been some cross-fertilization. Fu, et al (1987) provide one notable example of a paper that develops a performance model of a manufacturing system, and uses the output of that model directly in a cash flow analysis. Although their analysis does not include a great number of the issues treated in the economic evaluation literature, it begins to fill a gap where more work is needed.

V. ECONOMIC EVALUATION MODELS FOR TECHNOLOGY ADOPTION

One conceptual approach related to the problem of economic evaluation of new technology is to examine the forces that drive innovation in an economy and drives firms to adopt those innovations in the form of new technological acquisitions. The work of Schumpeter (1943), which has been enormously influential in this area, introduces the concept of "creative destruction," whereby the discovery and adoption of a new, better innovation effectively destroys the old technology by rendering it obsolete. Schumpeter asserted that innovation competition was far more important to firm success and industrial progress than was the classic notion of price competition. Attendant to these ideas are the hypotheses that large, profitable, market-dominating firms are (1) most able to afford the investments to develop new technologies, and (2) most likely to be the drivers of innovation, creative destruction, and industrial progress.

Kamien and Schwartz (1982), in their excellent survey of this literature, discuss three reasons why firms with monopoly power are likely to develop a disproportionate fraction of important innovations. First, profitable firms have the financial capability to underwrite types of risky research projects that small firms could not convince outside lenders or investors to fund. Second, large firms, by virtue of their hiring of large numbers of researchers, are more likely to discover and nourish the intellectual stars who develop pathbreaking innovations. Third, incumbent large firms have significant existing bases of skills and assets, for example in marketing, sales, and manufacturing, likely to be complementary to and necessary for the exploitation of new innovations. By making it easier for such large firms to profit by new discoveries, these pre-existing assets provide significant incentives to invest in research projects. Teece (1986) elaborates on the implications of this third point, focusing on its implications for firms who might think they can survive as concept innovators without having the complementary capabilities in manufacturing necessary to deliver their concepts to the market as competitive products.

Arrow (1962) provides one important reason, related to the "fat cat effect" of Fudenberg and Tirole (1984), that large firms may not be so likely to innovate in their industries. Suppose the possibility exists in an industry to develop a new technology, either product or process, that delivers monopoly power to its developer. Then the payoff to a "fat cat" incumbent of developing this technology is only the **difference** between its present profits and the total potential profits achievable through using the innovation. However, if a new entrant develops the technology, its payoff is the **entire** monopoly profit from the new technology. Therefore, the new entrant has a much higher return on its research investment, if it develops the new technology. This argument is countered, to some extent, by Schmalensee (1983) and Gilbert and Newberry (1982) who suggest that an entrant's potential profits provide an incumbent incentive to innovate in order to prevent the loss of its entire market position. Fudenberg and Tirole (1986) provide an excellent discussion of this "persistence of monopoly" debate. Bresnahan (1985) finds evidence in the market for plain paper copiers that Xerox may have suffered from the fat cat effect leading to its dramatic loss of market share in the mid 1970's.

Rosenberg (1982), provides an excellent examination of economic forces that affect firms' decisions to adopt new technologies. Of particlar interest are his discussions of the effects on technology adoption outcomes of technological expectations and the role of multi-industry technological interdependence: Firms that anticipate significant technological improvement in the near future, may not invest in the state-of-the-art processes even in projects that are clearly superior to those presently in use. Rosenberg suggests that adoption rates will be slow when the rate of technological change is fast, and adoption rates will increase when the rate of change slows. In the single-firm model of Balcer and Lippman (1984), described below, a high pace of technological development does lead firms to postpone adoption of the best available technology. With respect to interindustry effects, developments in one field, aeronautics or factory automation, for example, must often await technological progress in other fields, materials or microelectronics, for example. On the other hand, adoption may not come at the time of innovation, but rather, when the innovation becomes profitable.

The remainder of this section discusses the modelling literature on technology adoption. Much of this literature takes the perspective of an optimizing firm or firms, and asks what investments should be made given the environment and available opportunities. I have divided this literature into two categories. The first of these addresses the optimal timing of investment in new technology. This literature assumes that the best available technology is known and available to all firms, and confines itself to determining when, or at what rate, this technology should be adopted. The second category of models addresses the question of what technology should be adopted. Models in this group typically assume that multiple technological options are available to firms, who must choose among them.

These are the works that have been spawned recently by the advent of new computerized manufacturing technology.

A second way to categorize the theoretical technology adoption literature is to divide the models by whether they take the perspective of a single-firm optimizing its technology portfolio or of several firms who will noncooperatively reach an equilibrium in technology strategies. Although game-theoretic models do not have as long a history in the analysis of technology adoption as do single-firm models, in many industry settings the technology decisions of firms are interdependent, so that a firm cannot prudently ignore the plans and reactions of its rivals while planning its own technological course. The game-theoretic models attempt to reflect this reality of technological interdependence. Kreps and Spence (1984), Fudenberg and Tirole (1986), and Tirole (1988) provide excellent introductions to the relevant game-theoretic literature. In the coverage that follows, for both the single-firm and game-theoretic models, I have limited myself to work that focuses on technology choice and adoption. Therefore, the work surveyed by Luss (1982), for example, that exclusively treats capacity expansion models, has been excluded.

Optimal Timing of New Technology Investments

The models discussed below all address timing of the adoption of a new technology. In most cases, a new technology is characterized as having lower operating costs than previous technologies. I have divided the optimal timing literature into three principal groups. One group assumes that only one innovation, with uncertain payoff, is available. In these models, the firm sequentially collects information until it decides whether or not to adopt. In another group, there is a constant stream of innovations that only can be adopted with lumpy, periodic acquisitions. In this case, a firm must decide the intervals at which to abandon its old technology and acquire the latest innovation. The third group examines the optimal rate at which to acquire new technology, assuming that new technology acquisition takes place continuously over time, rather than all at once.

Consideration of a One-Time Innovation

As an example of the first group, McCardle (1985) analyzes an optimal stopping model where a firm has the option to adopt a single, exogenously-given technology with unknown profitability. The firm can sequentially collect costly information to refine its priors on the likely profitability of the innovation. McCardle characterizes the form of the optimal process for gathering information and deciding whether to adopt the technology, and examines how this policy is affected by changes in model parameters. Jensen (1982) presents a similar model where delaying the decision to adopt explicitly costs the firm in terms of foregone benefits from using the new technology. (Although McCardle's model does not explicitly capture these delay costs, his model could easily be reformulated so that the information collection costs included delay costs.) Jensen also provides comparative statics for his model and emphasizes how firms that differ with respect their prior beliefs about the technology will adopt a "good" technology at different times. This result is consistent with the commonly observed diffusion of technology adoption times in industry.

Neither of the above models considers the aspect of competition, although both mention its potential importance on firms' adoption decisions. Mamer and McCardle (1987) analyze a two-firm, game-theoretic version of McCardle's earlier paper. The model is essentially a two-stage game: In the first stage, each firm independently collects information about the likely profitability of the innovation. In the second stage, the firms simultaneously decide whether to adopt the technology, each knowing only its own information collection outcome. Two cases are compared: The firms produce substitute products or they produce complementary products. In the substitutes case, adoption is less likely because firms require the signals about the benefits of the technology to be especially good, since competition will reduce the extent that the firm will benefit. One aspect of this model, relative to those to be discussed shortly, is that firms make their adoption decisions independently and simultaneously, so that temporal competition is absent. That is, in this model there are no benefits to a firm from adopting first and preempting its competitor(s). Thus, this model actually only addresses *whether* each firm should adopt the technology, rather than *when* each should adopt.

Choosing from a Stream of Innovations

The second group of models on when to adopt has evolved out of the capital replacement and equipment replacement literatures. Hotelling (1925) and Preinrich (1940) each worked on the problem of determining the "optimal economic life" of capital equipment for a single firm. Meyer (1971), who reviews both models, points out that each is computationally quite burdensome, and each neglects the possibility of technological improvement in successive generations.

Terborgh (1949) remedies both of these complaints with a dynamic, determinsitic, constant-demand-rate model that assumes that a firm's current technology depreciates over time such that its operating costs increase at a rate β, whereas the best available new technology is improving such that the lowest available operating costs are decreasing at a rate α. Therefore, the "inferiority gap" of the currently installed technology versus the best available technology grows at the rate $\alpha + \beta$. With this formulation, Terborgh derives the optimal replacement policy, which is dictates adopting the new technology at fixed intervals, every time the inferiority gap exceeds a certain critical value.

Several different researchers have built on the basic ideas from Terborgh's work combined with the work on capacity expansion stimulated by Manne (1961) and surveyed by Luss (1982). Hinomoto (1965) formulates a deterministic model in which both capacity requirements and technology productivity may vary. He provides conditions on optimal timing and sizing of new facilities, as well as on production levels in those facilities. Klincewicz and Luss (1985) analyze optimal adoption timing when demand is growing linearly and an improved technology is available.

Meyer (1971) extends Terborgh's model by assuming that the rate of change in the inferiority gap is stochastic. As with Terborgh's analysis, the solution for Meyer's model is also to adopt the newest technology every time the inferiority gap exceeds a critical number. However, since the change in $\alpha + \beta$ is stochastic, the intervals between adoption times are random variables. The relationship between Terborgh's model and Meyer's model is similar to the relationship between the EOQ inventory model and the (s,S) inventory model.

The stochastic dynamic programming model of Balcer and Lippman (1984) provides an excellent extension of the Meyer's work, including an analysis of how technological expectations can affect a firm's adoption decisions. The model assumes that an exogenous, stochastic stream of new technologies becomes available to a firm over time. At any point in time the likelihood of the discovery of an improved technology depends on (1) the current state of technology, (2) the inherent "discovery potential" at that time, and (3) the length of time since the last innovation. As above, their results show that the optimal adoption policy takes the form of a cutoff policy, i.e., adopt the new technology if and only if the technological lag (inferiority gap) exceeds a cutoff, which is a function of the time since the last innovation and the current discovery potential. The innovative aspect of the Balcer-Lippman analysis is their demonstration that if the pace of technological progress (i.e., the discovery potential) increases (decreases) then the cutoff increases (decreases) causing a slower (faster) rate of adoption, thus confirming the intuition of Rosenberg (1982) mentioned above.

Two observations on this model may be of interest: First, Balcer and Lippman discuss how a preemptive announcement of a new technology could cause a buyer to revise upward its estimate of the discovery potential and postpone its adoption decision. They cite IBM's August 1964 announcement of its (then nonexistent) model 360/91 just before the delivery of CDC's model 6600 as a possible example of an attempt to influence customers' estimates of the discovery potential, so that they would postpone their decisions to buy the CDC machine. This example suggests how sellers of technology can influence how their customers evaluate their technological options, an issue that is also addressed in the standards and compatibility literature, discussed below. Second, the result that adoption should be postponed when the rate of technical change is fast is derived in a model without competition. Hayes and Jaikumar (1988) suggest that such delay may not be possible in a world in which rapid change is the rule and the competition is moving rapidly with new technology adoption. That observation is addressed to some extent by some of the game-theoretic models described below. However, development of a full game-theoretic version of the Balcer-Lippman model, addressing this issue, would be a valuable contribution to the literature.

The game-theoretic literature on optimal timing of technology adoption focuses primarily on issues of preemption, the advantages of being first to adopt the newest technology, and diffusion, the temporal "spreading out" of adoption dates. Barzel (1968) was one of the first to describe and model the intuition that, in a multifirm environment, competition to preempt one's rivals would lead to earlier adoption of new technologies than would be observed in a monopolistic industry. Stimulated by Barzel, Kamien and Schwartz (1982) developed a large body of work on decision-theoretic models that provided some of the groundwork for the game-theoretic work that followed. With the maturation of game-theoretic modelling in economics, Reinganum (1981a, 1981b) used a precommitment equilibrium analysis to derive adoption times in a model where (1) all firms are *ex ante* identical, (2) no firm has incentive to adopt at or before time zero, (3) firms experience decreasing returns in the rank of adoption, and (4) in finite time, adoption becomes a dominant strategy for each firm. Any equilibrium to her model exhibits diffusion in adoption times. However, the analysis is subject to the criticism that noncredible threats are required to achieve the equilibria she derived.

Fudenberg and Tirole (1985) derive perfect equilibria for Reinganum's model: In a duopoly market, in equilibrium, both firms earn equal profits. There are two ways in which this may occur: Either one firm will preempt and adopt early while the other adopts very late (and possibly never), or both may wait until they can adopt simultaneously and be profitable. In either case the rent equalization result obtains because very early adoption in the first case is very costly, following from Reinganum's assumption (2) above. Analysis for three or more firms becomes quite complex, but the authors do demonstrate that rent equalization will not obtain in the three-firm case. Throughout their analysis, firms' motives are toward early adoption (relative to when a monopolist would adopt) to preempt the competition. Tirole (1988) demonstrates how the structure of industry payoffs could also drive firms to delay adoption, perhaps indefinitely, to maximize profits.

Technology Acquisition Over Time

In the third group, addressing the optimal rate of dynamic technology adoption, several models of interest have been developed by Gaimon. These deterministic models capture more of the operational detail of technological change, compared with the models described above. For example, Gaimon (1986a) models the details of production and inventory costs, and how they are affected by new technology. In Gaimon (1986b) the model examines aspects of how automation affects the capital/labor mix utilized, and in Gaimon (1985) the affect of automation on labor productivity is considered. These papers seem to be aimed at practitioners, suggesting how specific automation projects may be modelled and optimized.

Building on some of the features in Gaimon's deterministic model formulations, Monahan and Smunt (1989) develop a Markov decision model in which interest rates and technological progress are random variables. In their model, in each period the firm chooses the fraction of its technology which is automated, to minimize the expected costs of production, inventory, and financing its automation investments. Monahan and Smunt (1987) describes a decision support system that incorporates this model.

In the game-theoretic domain, Fudenberg and Tirole (1983) derive perfect equilibria for a model of Spence (1979) on the optimal rate of new technology adoption when preemption incentives are present. In this model, competing firms expand their capital stocks as fast as possible, attempting to achieve as much market share as possible, while denying it to competitors. The Fudenberg-Tirole analysis clearly shows the advantage of being an early adopter or a fast adopter: The leader can expand beyond the level that would be expected in a symmetric outcome, leaving the follower with a small share (or none) of the market.

To summarize, the work on optimal timing of technology adoption has raised a number of important issues for the economic evaluation of new manufacturing technology. In particular, firms must be concerned with (1) the processes that generate the magnitude of technology lag (i.e, the rates of capital depreciation and technological innovation), (2) expectations about these processes, and (3) how industry adoption sequences and preemption affect payoffs from new technology.

Models to Analyze What New Technology to Adopt

Most of the work analyzing what technology to adopt is relatively recent. Some of these models were stimulated specifically by the advent of computer-driven innovations in manufacturing and other application areas, such as telecomunications. The models of this section fall into three groups. The first group consists of several models that allow firms to choose among technologies that differ with respect to their cost structure. These models address the issues of capital intensiveness, mentioned in Section II, as a characteristic of firms that have invested heavily in factory automation. The second group examines technology adoption when standards setting and technological compatibility play an important role in firms' decisions on which technology to adopt. The third group models technologies that differ with respect to their manufacturing flexibility, another important characteristic of factory automation mentioned earlier.

Choosing Among Technologies with Different Cost Structures

The models concerning cost structure choice address a range of issues. Lederer and Singhal (1988) use the reasoning of the capital asset pricing model to argue that the payoffs from automated technologies with low operating costs should be risk-adjusted in any *ex ante* economic evaluation of such technologies. Their model shows how correct risk adjustment, in turn, influences a firm's ultimate technology choice.

Cohen and Halperin (1986) develop a single-product, dynamic, stochastic model that allows a firm to choose among technologies that differ with respect to cost structure. Each technology is characterized by three parameters: the purchase cost, the fixed per-period operating cost, and the variable per-unit production cost. Their principal result gives conditions sufficient to guarantee that an optimal technology sequence exhibits nonincreasing variable costs. That result could be interpreted as giving conditions under which each successive technology acquisition will be more automated than the previous one.

In a related model, where demand deterministically follows the classic product life cycle pattern, Fine and Li (1988) show conditions under which a firm would switch from a labor intensive (low fixed costs, high variable costs) technology to a capital-intensive (high fixed costs, low variable costs) technology, as well as conditions in which no switch occurs or the reverse switch occurs. As a foundation for extending this model to the more complex stochastic, game-theoretic settings, Fine and Li (1989) develop a stochastic, game-theoretic model of exit from an industry in the declining stages of its product life cycle. More work is required to fully explore the implications of a model that combines the features of both these papers.

In what might be considered a stripped-down game-theoretic version of the Cohen-Halperin or the Fine-Li (1988) model, Spence (1977, 1979) and Dixit (1979, 1980) develop a model of cost structure choice where one firm can move first and commit itself to the market by sinking its investment into a low-variable-cost technology, significantly reducing (or eliminating) the profit opportunities of its rival who moves second. Related work by de Groote (1988) shows how observability by one's competitor(s) of the cost structure of one's technology influences technology investment and production output decisions. In particular, if a firm knows that its cost structure will be learned by its rival(s), it will choose a low cost technology to discourage rivals from competing aggressively. These results provide strategic motivation both for investing in a technology that locks in low variable costs, as in the automated Matsushita VCR factory mentioned in Section II, and for letting observers into the factory to see the automation running.

Technology Adoption with Network Externalities: Standards and Compatibility

When technologies exhibit increasing returns in the number of firms adopting, then a single firm will typically make its technology choices only after consideration of what technologies others are likely to adopt. As pointed out by Arthur (1988), such positive network externalities can arise from a number of sources. For example, if an innovation is viewed as particularly risky when it is first developed, a firm will view it as less risky if many other firms are adopting. Pure technological compatibility, as with computers and software, or with video recording and playing equiupment, will also affect adoption decisions. There may also be economies of scale associated with the manufacture, service, distribution of a technology, such that significant benefits accrue from adopting the technology with the largest market share. Historically, in the computer business, for example, "no one ever got fired for buying IBM."

In the model of Farrell and Saloner (1985), if a new technology is developed, and each industry participant knows that this technology is viewed as superior by all other industry participants, then each firm will independently decide to adopt the new technology. However, if the technology preferences of others are unknown, then a superior technology may not be adopted because no single firm has the confidence to adopt it without knowing that others will follow. In other cases with unknown preferences, a few firms may prefer the new technology to such a degree that they adopt independent of the others. This can start a "bandwagon effect," leading the rest of the industry to follow suit.

Farrell and Saloner (1986) present a more extensive model in which equilibrium adoption decisions depend upon the size of the installed base of the old technology, when the new technology is introduced, how quickly the network benefits of the new technology are realized, and the relative superiority of the new technology. Their analysis shows that a technology preannouncement, like that of the 1964 IBM model 360/91 mentioned by Balcer and Lippman (1984), can lead an industry to eventually adopt the newly announced technology when it would not have been adopted absent the announcement, and when the industry would have been better off staying with the old technology.

Evaluating Flexible Manufacturing Technologies

As mentioned earlier, flexibility is an important characteristic of CIM and factory automation. This section focuses particularly on papers that address the flexibility component of technology. Interest in the management science community for analyzing manufacturing flexibility has followed the increasing interest, viability, and use of flexible manufacturing systems by industry. This new interest has spurred a significant amount of work, both in the economics of flexibility and on the design, planning, and control of flexible manufacturing systems. For examples of the extent and breadth of this work, see Stecke and Suri (1984, 1986), Adler (1985), and Buzacott and Yao (1986). As will become evident below, different researchers have chosen to model different aspects of flexibility.

Hutchinson (1976) and Hutchinson and Holland (1982) developed some of the earliest modelling work that considered the economics of flexible manufacturing systems (FMSs). The two models are similar, so only the latter is described. The objective of the Hutchinson and Holland model is to determine when an FMS would be economically superior to a transfer line. They assume that FMSs have higher variable costs, but exhibit two types of flexibility: capacity can be added incrementally rather than all at once, and capacity can be converted to produce more than one product. The model assumes that industry demand follows a classic product life cycle pattern over time: demand starts low, increases over time to some peak, and then decreases as the product goes into its decline stage. The authors simulate manufacturing system performance for a stochastic product stream, first assuming that all technologies are inflexible transfer lines, and again, assuming that all technologies are FMSs. The 192 simulation runs suggest that the value of flexible systems, relative to transfer lines, increases as the rate of new product introductions and the maximum capacity of FMSs increase, and decreases in the interest rate and the average volume per part produced.

Fine and Li (1988) developed an analytical model that builds on the Hutchinson-Holland idea of flexibility playing an important role in manufacturing a portfolio of products in different stages of their life cycles. The Fine-Li model assumes that the firm can choose to invest in two generic types of technology: dedicated technology that can only produce the one product and flexible technology that can produce more than one product. The model captures an intertemporal economies-of-scope incentive for investing in flexible technology and illustrates how high interest rates can dull this incentive. In addition, the paper discusses how optimal utilization of flexible technology may exhibit use of the technology for a narrow range of products in some time intervals and for a wide range of products at other times.

The remainder of the models described here are divided into three groups, based on the economic phenomena they consider: (1) flexibility as a hedge against uncertainty, (2) interactions between flexibility and inventory, (3) flexibility as a strategic variable that influences competitors' actions. An important motivation for some of this work has been to improve the set of conceptual and capital budgeting tools available to managers who make technology investment decisions. Kulatilaka (1984) surveys the capital budgeting issues related to evaluating manufacturing automation projects.

In group (1), the model of Kulatilaka (1988), building on capital budgeting concepts from finance theory, provides a versatile tool for valuing the flexibility of flexible technology. His stochastic dynamic program can be used to calculate a value of the ability of FMSs to cope with a range of types of uncertainty. The paper also illustrates the optimal operational use of flexible technology as it switches into its various possible modes of operation, and use of the model for making other operating decisions such as the timing of temporary shutdowns and project abandonment.

Also addressing the use of flexible technology as a hedge against uncertainty, Fine and Freund (1986, 1988) develop a two-stage stochastic quadratic programming model in which a firm chooses a capacity and technology portfolio from among dedicated technologies, each of which can manufacture only one product, and a flexible technology that can manufacture all products. The firm makes its technology and capacity decisions in the first period, then observes an outcome of random demand, and then makes production decisions, constrained by its earlier capital investments. Flexible capacity has value because product demand quantities and mix are unknown at the time of investment. The paper derives necessary and sufficient conditions for acquiring flexible capacity, characterizes optimal technology investment portfolios, and develops comparative-statics results to explore the sensitivity of optimal technology acquisitions to the technology purchase costs and the demand probability distributions. A two-product example illustrates that flexible technology has its maximum (minimum) value when product demands are perfectly negatively (positively) correlated.

The above analysis has been extended in several directions. Gupta, Buzacott, and Gerchak (1988), noting that the Fine-Freund model characterizes technologies as either completely flexible or completely inflexible, develop a flexibility parameter that spans these extremes. They characterize optimal investment decisions when the firm can also choose the degree of flexibility achieved. He and Pindyck (1989) use the options methodology from the finance literature to develop a dynamic model of flexible versus dedicated technology choice. Their model captures the irreversibility character of technology investment, which has been studied by Pindyck (1988). The authors derive conditions to evaluate when flexible technology maximizes the firm's market value.

In group (2), the work addresses how flexible technology affects three types of inventories, differentiated by the economic motive for holding them: cycle stocks, safety stocks, and seasonal stocks. Porteus (1985) extends the EOQ framework to investigate investments to reduce setup costs. Porteus (1986) extends this framework to also investigate the interactions between investments to reduce setup costs and to improve process quality. Karmarkar and Kekre (1987) use an EPQ-like model to analyze the tradeoff between owning one large, flexible machine that cycles between two products, and two small, machines, each dedicated to a single product. Total capital costs for the single large machine are lower than for the two small machines, but the large-machine option generates lost capacity due to changeover downtime and inventory holding costs due to cycle stocks.

The authors provide conditions to show when each option dominates the other. Vander Veen and Jordan (1988) develop an n-product, m-machine version of this model, where part allocation decisions must also be taken into account. They present an algorithm to optimize both the investment decisions and the production cycling decisions.

A number of useful extensions to these models would be quite interesting to pursue. First, unlike most of the other technology investment models described here, both of these models annualize the investment costs, rather than treating them as one lump sum that must be sunk in order for production to commence. As pointed out by Pindyck (1988), for example, irreversibility is an important strategic characteristic of a capital investment decision. Therefore the sunk investment character of technology acquisition ought to be taken into account in developing a model that realistically captures both the operational and strategic characteristics of technology investment. A second interesting extension to these models would be to allow a range of technology options that vary with respect to the changeover costs associated with them, as is done by Porteus (1985), combined with the questions asked by Karmar-Kekre and Vander Veen-Jordan. Then the models would allow optimizing over what might be considered to be a flexibility parameter, as is done by Gupta, Buzacott, and Gerchak (1988).

Graves (1988) presents a model to analyze the interaction between safety inventories and the production rate flexibility of a manufacturing station. He provides a method for calculating the required safety stock level as a function of the rate flexibility and the mix flexibility. Although he does not endow his model with cost and revenue parameters to enable economic optimization of inventory and flexibility, the model sets the stage for such an analysis to be performed.

Caulkins and Fine (1988) develop a model to explore the interaction between product-flexible manufacturing technology and seasonal inventories. Initial intuition might suggest that inventories and flexible capacity should be substitutes: The optimal amount of product-flexible capacity to acquire should increase in the cost of holding interperiod inventory because flexible capacity can help production smoothing for products with negatively correlated demand. (The classic case of building one factory to produce both lawn mowers and snow blowers, two seasonal products whose manufacturing requirements are similar and whose demand patterns are negatively correlated, illustrates this point.) However, the analysis shows that flexible capacity and inventory can be either substitutes or complements, depending upon demand patterns. The authors make it clear that more work is needed on this problem and on its relationship to the safety stock model.

To date, there are few papers in group (3), game-theoretic models to analyze the competitive dynamics involving flexible manufacturing technology. Considering the wealth of observers who tout the strategic benefits of flexible manufacturing systems, this shortage is a little surprising. Thus, this area may be a growth area in the field.

Gaimon (1988) uses a two-firm, continuous-time model to compare how firms' technology acquisition strategies compare under the assumptions of open-loop or closed-loop dynamics. The decision variables for each firm are the price charged, the rate of acquisition of new technology, and total capacity from old and new technology. The results show that firms charge higher prices, acquire less new technology, buy less total capacity, and earn higher profits in the closed-loop game. Gaimon also analyzes the case when one firm is an "open-loop player" who must commit at the start of the game to an entire technology and price strategy, and the other firm is a "closed-loop player" who dynamically adjusts technology and price variables in response to his rival's actions. In equilibrium, the open-loop player, who can commit to an aggressive strategy, outperforms the closed-loop player who, to his detriment, has the flexibility to contract as his rival expands. Gaimon draws the analogy to the worldwide automobile manufacturing industry, where Japanese (open-loop) no-layoff policies serve to make firms unable to adjust their production downward, while the U.S. companies have the (closed-loop) flexibility to shut down plants and lay off workers. Thus, in this setting, flexibility (to shrink) makes a firm worse off than if it had a technology that committed it to high output.

Tombak (1988b) presents a continuous-time spatial competition model in which each firm can choose between staying with its old, inflexible transfer line or switching to a flexible manufacturing system. The intuition from the model can be illustrated with the two-firm case. For any time during which one firm has switched to the FMS, and its competitor has not, the market share of the first firm will grow at the expense of the second firm, thus giving each firm incentive to preempt its rival. In the n-firm case, this result also holds, leading Tombak to conclude that technology adoption will occur in "swarms", as predicted by Schumpeter (1939).

Fine and Pappu (1988) present a supergame model whose results complement those of both Gaimon and Tombak. (See, e.g., Kreps and Spence (1984) and Fudenberg and Tirole (1986) for explanations and examples of supergames.) The Fine-Pappu model assumes that there are two firms and two markets. Initially, each firm has a monopoly in its own market. The existence of flexible technology gives each firm a relatively inexpensive avenue for invading its rival's market. Two possible types of equilibria are possible. In one, each firm buys the flexible technology, invades its rival's market, and ends up with duopoly profits in both markets, which yields lower total profits than monopoly profits in one market. In the other equilibrium, each firm buys the flexible technology, but stays only in its own market, deterred from invading its rival's market by the credible threat that such entry will be met with a retaliatory invasion, but needing the flexible technology to credibly threaten such retaliation if invaded itself. In both types of equilibria, the existence of flexible technology makes both firms worse off. Each would earn higher profits if flexible technology did not exist, it needed only to invest in the less expensive dedicated technology, and its initial monopoly position were less easily threatened. As in Gaimon's model, flexibility, and an inability to commit to a certain course of action (in this case, not to invade a rival's market), makes a firm worse off.

To summarize, the modelling literature on what technology to adopt has exploded in recent years. To date the literature has focused primarily on the areas of cost structure, compatibility, and flexibility. These models have enriched significantly our understanding of technology evaluation and adoption. The next section speculates on productive avenues for the future.

VI. OVERVIEW AND CONCLUSIONS

This section briefly describes some empirical research related to the theoretical research described above, evaluates the potential usefulness of the modelling literature for the economic evaluation of new manufacturing technology, and presents a research agenda for the area.

Empirical Work

Due to the recency of the development of much of the work described above and to the lags in technology transfer of new ideas from academia to industry in management science, limited information is available to evaluate the utility to industry of many of the models described. In addition, many of the papers have been written primarily for a theory-oriented academic audience, and have not trickled down, through publication of applications, to the practitioner literature.

There is, however, an extensive empirical research literature on technology adoption that predates the development of most of the technology described in Section II. Reviewing that literature is beyond the scope of this work. However, Kamien and Schwartz (1982) and Rosenberg (1982) each include a chapter with significant coverage of this literature. In the FMS domain, empirical work is much more scarce, but a few relevant papers are described here.

Tombak (1988a) has pursued the question of whether flexibility has an important effect on firm performance. Based on an sample of 1455 business units from the extensive PIMS (Profit Impact of Marketing Strategy) database, he develops a regression model which finds flexibility to be an important explanatory variable for firm performance. Using two other databases that cover 410 European and 168 U. S. firms, Tombak and De Meyer (1988) find that managers use flexible manufacturing systems to accomodate variability in their inputs and to enable them to produce a wider variety of outputs. Based on a sample of 60 FMSs installed in Japan and 35 in the United States, Jaikumar (1986) finds that Japanese firms are much farther along in the application of the technology and that the flexibility offered by the technology is an important strategic variable for them. Overall, the available evidence is consistent with the hypothesis that flexibility has become an important concern for a significant number of manufacturing firms.

Gerwin (1981) presents an excellent case study of one firm's process of evaluating an FMS investment opportunity. In this case, the Net Present Value (NPV) investment tool was the only quantitative model used, but champions of the FMS investment attempted to quantify cash flow items that typically would be considered intangible, and left out of the analysis. Little formal analysis was employed in evaluating the flexibility component of the FMS, but subjectively this flexibility seemed to play a significant role in convincing the decisionmakers of the merits of the FMS over the transfer line alternative. Since this case study predates the development of many of the models described above, and since this was one of the early FMS implementations in the United States, one would not have expected extensive sophisticated analysis reflecting the concepts described above. Additional case studies and industrial perspectives may be found in Meredith (1986).

Evaluation of the Existing Literature on Technology Adoption Models

Rodgers (1983) lists five attributes of innovations that may affect the rate at which adoption occurs: (1) relative advantage, (2) compatibility, (3) complexity, (4) trialability, and (5) observability. Relative advantage is the direct difference in profitability brought about by the new technology. Compatibility of a new technology can refer either to organizational issues or technical issues. Complexity refers to the degree of difficulty in understanding and using an innovation. Trialability is the ease with which one can experiment with a new technology, before making an adoption commitment. Observability is the degree of transparency of the innovation's results to any observer. If a technology's benefits are self-evident, firms will perceive less risk in their technology decisionmaking.

Most of the technology adoption models discussed here deal only with relative advantage. Exceptions are the Farrell and Saloner papers on compatibility and the de Groote work on observability. (Although, de Groote's observability effect, which influences a rival's evaluation of potential profit opportunities, is different from that of Rodgers.) The ideas of trialability and experimentation are explored by Bohn (1988), but not in the context of the economic evaluation of new technologies. That work, however, could serve as a useful launching point for analysis of trialability as it affects technology adoption decisions. Therefore, considering Rodgers' list, significantly more work could be done to develop models for attributes (2)-(5). In addition, there are many open questions, some of which have been alluded to above, just in consideration of relative advantage of the new manufacturing technologies.

Overall, the technology evaluation and adoption literature is in a state of rapid innovation, reflecting the rapid rate of change of technological options in industry. If one accepts the analysis of Balcer and Lippman (1984), then in such a period, potential adopters of these methods are advised to take a wait-and-see posture, with the expectation that this rate of innovation will slow and some consolidation and formation of dominant practice will arise. (As mentioned above, this prescription assumes that one's rivals will not develop a lock on the market in the meantime.)

This literature review suggests that a consolidation has not yet occurred for technology evaluation models (although the work of Fudenberg and Tirole (1986) and Tirole (1988) contribute significantly to such eventual consolidation in the game-theoretic literature). Since the rate of innovation is still high, consolidation into a few dominant models and paradigms may not be on the immediate horizon.

Despite the state of flux for this research area, some speculation as to the usefulness of this literature is possible. First, these models will may prove to be helpful for teachers and practitioners to refine their intuition about the economics of new technology investment. Aside from direct use by practitioners, the models described here might also be expected to be used in two other domains: education of management and engineering students and development of decision support systems. Casual obvservation suggests that a number of schools are beginning to teach the concepts and models described here, so that some faculty interested in technology evaluation problems find these models to be useful. Some new methods and ideas in management do not become widely used until a generation of students who has learned these ideas in school moves high enough in organizations so that they have decisionmaking power. So judging this channel for potential utilization and application would be premature. A potential route for near-term application of these models is in the development of decision support systems that would be used by practitioners. The Monahan-Smunt (1987) system is an example of this type of outlet for these models.

Research Agenda

The existing modelling literature discussed in this paper has great potential in two areas: (1) development of a more unified theory of the economics of technology evaluation and (2) helping practitioners make better investment decisions. With respect to developing a unified theory, work is required in several areas. First, Rodgers (1983) paper on five attributes of innovations could serve as an excellent guidebook to a set of issues that has not been sufficiently well modelled or explored. In addition, case-based sources might be used to discover other important aspects of the technology evaluation problem that have not been modelled. Second, the industry interdependence characteristics of technological advance, described in Rosenberg (1982), whereby adoption of an innovation in one industry often must await some technological development in another industry, has not been captured well by the existing modelling literature. Third, work is needed to take the many features of technology adoption decisions, each of which has been modelled separately, and knit them together to as great an extent as possible. The Balcer and Lippman (1984) paper did an excellent job of this for the single-firm, optimal adoption timing literature, and might potentially serve as a base from which to build a game-theoretic model. Additional features such as product life cycles, flexibility, compatibility, asymmetric information, and inventories might also eventually be included. Developing one tractable model to include all of these features may be impossible, but learning how these different features of technology adoption decisions interact is an important goal for deepening our understanding of the problem.

To move toward helping practitioners make better investment decisions, and toward helping theoreticians build better models, theoreticians and practitioners must communicate, and, in the best of all worlds, work together on real problems. Achieving this goal is often difficult because the two groups are typically separated by organizational walls, different mindsets, and different timetables. However, for some who have tried it, such joint efforts have proven rewarding and productive.

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