Manufacturing Flexibility: A Strategic Perspective

Donald Gerwin
School of Business and Department of Systems and Computer Engineering, Carleton University, Ottawa, Ontario, Canada K1S 5B6

To help meet competitive realities operations managers need to know more about the strategic aspects of manufacturing flexibility. This paper takes steps toward meeting that need by critically reviewing the literature and establishing a research agenda for the area. A conceptual model, which places flexibility within a broad context, helps to identify certain assumptions of theoretical studies which need to be challenged. The model also provides a basis for identifying specific flexibility dimensions. The manner in which these dimensions may limit the effectiveness of a manufacturing process, and the problems in operationalizing them are discussed. Focusing next on the neglected area of applied work, concepts are presented for analyzing whether desired amounts of flexibility are being achieved and whether the potential for flexibility built into a manufacturing process is being tapped. Once more, a procedure is outlined for altering a plant's types and amounts of flexibility over time. The research agenda, which grows out of the appraisal of theoretical and applied work, indicates the value in studying generic flexibility strategies, the flexibility dimensions, methods of delivery, ways of evaluating and changing a process's flexibility, and above all measurement problems. The conclusions indicate principles for strategic research, some of which have relevance for the development of mathematical models.

(*Manufacturing Flexibility; Manufacturing Strategy; Environmental Uncertainty; Performance Measurement; Focused Factory*)

1. Introduction

An industrial nation's economic future may lie in so-called flexible systems of production, technically advanced and skill intensive industries which make customized products (Ayres 1984, Cohen and Zysman 1987, Hall and Tonkin 1990, Nagel and Dove 1991, Reich 1983). From this point of view the only way to respond to low-cost standardized items from abroad is to offer wide varieties of technologically superior products aimed at specific market niches. This requirement for increased flexibility applies to both traditional smoke-stack industries and completely new industries.

It appears that the Japanese are ahead in recognizing the growing salience of flexibility. The 1986 Manufacturing Futures Survey queried manufacturing managers in over 500 corporations worldwide (DeMeyer et al. 1987). Japanese companies ranked flexibility to introduce new products and to adjust production volume as their second and fourth competitive priorities. Quality was third. North American and European firms ranked these two flexibilities as sixth and eighth while quality was first. The authors concluded that the Japanese, after successfully overcoming quality problems, are turning their attention to flexibility. Western enterprises are still concentrating on deficiencies in quality.

Decision makers therefore have a growing need for research on the strategic aspects of manufacturing flexibility. This paper helps to meet the need by critically reviewing the existing literature and developing a research agenda. The next section employs a conceptual model to help bring together existing theoretical research so that it can be evaluated. The focus is on generic

0025-1909/93/3904/0395$01.25
Copyright © 1993, The Institute of Management Sciences

strategies with implications for flexibility, specific flexibility dimensions, and measuring the dimensions. An investigation of the neglected applied side of work on flexibility is the theme of the third section. It discusses concepts and procedures for helping manufacturing managers evaluate and change the flexibility of their operations. A theoretical and applied research agenda, based on the previous discussions, is presented in the fourth section. The final section presents some conclusions. A much more comprehensive treatment of flexibility within the context of advanced manufacturing technology is found in Gerwin and Kolodny (1992).

2. Concepts for Analyzing Flexibility

In order to unify theoretical research on flexibility, and to critically review the literature, it is useful to embed the construct in a framework and explore its interactions with other variables. The framework in Figure 1, at the level of a company and its environment, is based on ideas from the organization theory and manufacturing strategy literatures (e.g., Child 1972, Skinner 1985). It links five variables: environmental uncertainty, strategy, required manufacturing flexibility, methods for delivering flexibility, and performance measurement. They will be discussed in turn.

2.1. The Context of Flexibility

Management must learn to cope with uncertainty whether it is based in product markets, or manufacturing processes and their inputs. The extent of learning is reflected in a company and manufacturing strategy which attempts to defensively adjust to uncertainty or proactively control it (Swamidass 1988). Management is accordingly not solely a passive reactor to environmental cues; it can also seize the initiative and try to bend the environment to its will.

Perhaps the model's most significant lesson is that flexibility is required whether the game plan is defensive or proactive. A variety of methods, including production equipment, product design, work organization, planning and control procedures, materials management, and information technology are available to meet needs for flexibility. Too little is known about how to achieve flexibility by properly balancing these methods (Whitney 1986). North American managers may place too much emphasis on advanced manufacturing technologies (Keller 1989).

The performance measurement system insures that strategic and operational decisions are integrated. At the strategic level it is easy to concentrate on flexibility's role in handling uncertainties. At the operational level, however, concern is with designing specific methods of delivery. The link with vague strategic pronouncements is easily broken. Achieving the flexibility to deal with uncertainties in the product mix reduces to achieving small setup times. Having the flexibility to cope with uncertain product life cycles becomes a problem in minimizing hard tooling. The solution is to translate flexibility requirements into performance objectives and measure whether the methods' results match. Consequently, one cannot lose sight of those requirements in designing methods.

The framework's various paths trace out the workings of four generic strategies labelled adaptation, redefinition, banking, and reduction. These are classified in Table 1 according to whether they are defensive or proactive in nature, and according to their implications for flexibility. Adaptation represents the path in Figure 1 from uncertainty to strategy to flexibility and beyond. This defensive approach incorporates the traditional use of flexibility. Research conducted by Tombak and DeMeyer (1988) provides some theoretical support. Their utility maximizing model of a firm considers the costs of flexibility in the manufacturing process. As process or market uncertainties increase flexibility mounts. Specifically, more random variation in the coefficients of the production function or in market price leads to more investment in the ability to vary input proportions. Empirical support comes from a mail survey of manufacturing companies in Minnesota (Wharton and White 1988). They found that as market unpredictability and competitiveness increased, the flexibility of the production process went up.

Flexibility is normally considered solely as an adaptive response to environmental uncertainty (Gupta and Goyal 1989). Most researchers look at it in this way. American managers also view it in this way when they talk about adjusting to the changing needs of customers. An enterprise, however, may try to proactively redefine market uncertainties as indicated by one path in the model emanating from strategy to uncertainty and to

Table 1 Generic Strategies

Strategy	Posture	Implication for Flexibility
Adaptation	Defensive	Requires flexibility
Redefinition	Proactive	Requires flexibility
Banking	Defensive/Proactive	Requires flexibility
Reduction	Proactive	Reduces need for flexibility

flexibility. Market needs are influenced by what customers have come to expect from a particular industry (Hayes and Abernathy 1980, von Hippel 1988). A firm can encourage customers to see the benefits of shorter lead times or more frequent new product introductions and then provide these higher levels of service through superior manufacturing flexibility. Once more, by creating more uncertainties for its rivals the firm has established a powerful competitive advantage. Honda, by significantly augmenting its rate of change of new motorcycles, induced customers to expect more frequent changes from the industry. Yamaha, which had attempted to overtake Honda, found new competitive uncertainties with which it could not cope and had to withdraw its challenge (Stalk and Hout 1990).

A firm may decide to "bank" flexibility, that is hold it in reserve to meet future needs. In this sense flexibility is an investment which creates options for a company. It may eventually be used defensively to adapt to a sudden dramatic change in market conditions. One example is the "surge capacity" maintained by military contractors to quickly increase production volume during a national emergency. Alternatively, a reserve of flexibility may be employed proactively to redefine competitive conditions as was done by Honda. Banking's significance is illustrated by a research program on the future of Japanese manufacturing which indicates that companies will have to plan for reserve equipment, slack in computer systems, and capable people on call to meet their competitive challenges (Hall and Tonkin 1990). Banking requires that investment alternatives with long run intangible returns are not unduly penalized in a firm's capital appropriation process.

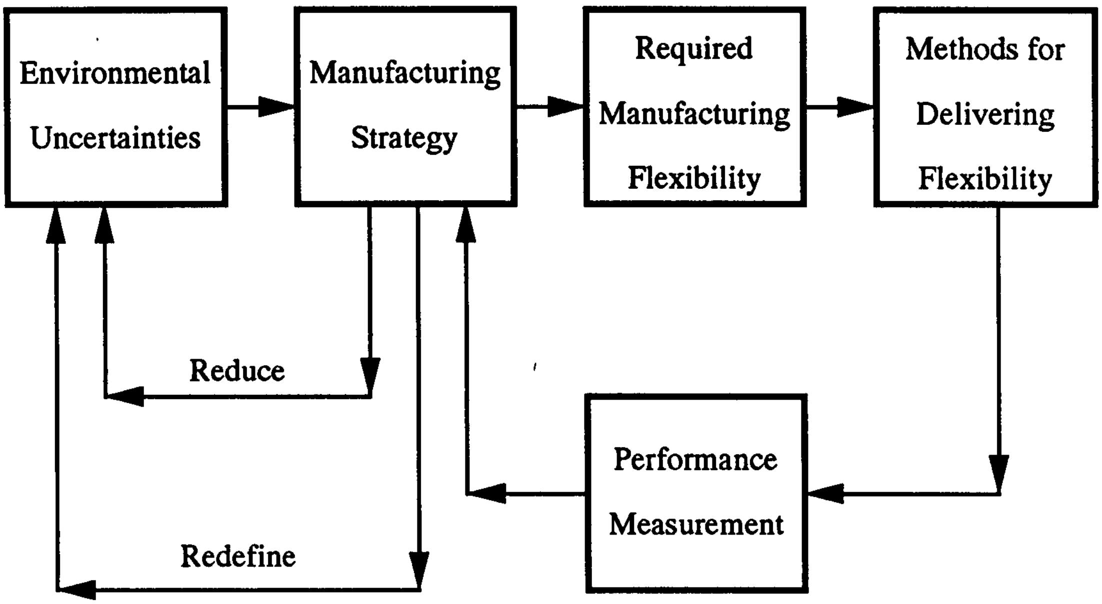
Reduction is a proactive approach which is not based on the use of flexibility, although it has important implications for that concept. It represents a path leading from strategy to uncertainty and to flexibility. A company may reduce environmental uncertainty through, for example, long-term contracts with customers and suppliers, design for manufacturability, preventive maintenance, and total quality control. Then, needs for flexibility are reduced at least up to a point. Power in the market, that is large size relative to customers and competitors, is usually required, as well as a manufacturing process which is understood well enough to be controlled.

Relation to Other Frameworks. Although the conceptual model contains only five variables, it subsumes other frameworks which have been proposed. The frameworks to be discussed involve only one of the generic strategies, that is, flexibility as an adaptive response. Swamidass and Newell (1987) started from environmental uncertainty influencing strategy. Their strategy variable incorporates required flexibility; it includes goals for the frequency of new product introductions, and the range of product variety and product features. Strategy in turn is hypothesized to directly affect performance; there is no variable for methods of delivering flexibility. Feedback loops do not exist. Tests of their model provide indirect confirmation of some of the conceptual framework's links. They found a significant positive relationship between uncertainty and strategy, and between strategy and performance.

Slack's (1988) flexibility hierarchy is similar to that part of the framework involving strategy, flexibility and methods. Strategy determination includes a priority ranking of the need for productivity, product availability and product dependability. Next a firm determines the significance of various production flexibilities by analyzing how each contributes to the three strategic objectives. Then, the information on flexibility guides the selection of various resources such as production technology.

Suarez et al.'s (1991) framework begins with variables representing market uncertainty and strategy. They do not distinguish between the two concepts. These variables determine the types and amounts of required flexibility. Various methods of delivery are represented by seven variables. Akin to performance measurement is a comparison of required flexibility to that being delivered by the methods which in turn influences business performance. There is also a feedback loop from performance back to the choice of methods.

Figure 1 Conceptual Framework



2.2. Dimensions of Flexibility

Most treatments of flexibility assume it is a multidimensional concept but provide no theoretical basis for finding its relevant dimensions. The conceptual model suggests that by identifying specific uncertainties and associated strategies one can identify critical dimensions a priori. In Table 2, the first four sets of uncertainties, strategies and dimensions are market-oriented as the relevant uncertainties exist in the demand for products. The next two sets are manufacturing process-oriented because their uncertainties exist in the manufacturing technology or its inputs. This distinction corresponds to Buzacott's (1982) division between the external and internal variations with which a system must cope. Table 2 also considers a meta-level set based on uncontrollable changes in the types and intensities of the uncertainties which have to be handled.

Each type of flexibility is considered to have two aspects: range and time (Slack 1983). One production system is more flexible than another if it can handle a wider range of possibilities. It may be able, for example, to vary production through a greater range of volumes. A production system is also more flexible than a second if it can attain a new possibility in the range in a shorter period of time. While the cost of providing flexibility is sometimes used as a third aspect, here it is considered as part of the economic consequences.

Mix flexibility. Uncertainty as to which products customers will accept leads to the strategic objective of product diversity. A firm desires a number of broad product lines and/or numerous variations within a line. In this situation mix flexibility is a useful ingredient of the manufacturing process. It represents being able to handle a range of products or variants with fast setups. The range aspect signifies the extent of product variety;

Table 2 Dimensions of Flexibility

Type of Uncertainty	Strategic Objective	Flexibility Dimension
Market acceptance of kinds of products	Diverse product line	Mix
Length of product life cycles	Product innovation	Changeover
Specific product characteristics	Responsiveness to customers' specs	Modification
Aggregate product demand	Market share	Volume
Machine downtime	Customers' due dates	Rerouting
Characteristics of materials	Product quality	Material
Changes in the above uncertainties	Strategic adaptability	Flexibility responsiveness

the temporal aspect reflects setup time, an essential ingredient of manufacturing lead time.

Mix flexibility's significance lies in its being an alternative to focused manufacturing. A focused factory reduces costs by relying on the benefits of task specialization (Hayes and Wheelwright 1984, Skinner 1985). Narrowing the range of demands placed on a facility allows its technological and human resources to concentrate on a few key priorities. Some evidence of the cost advantages of focus exists, but it is not based on statistical tests of significance and does not control for size, vertical integration and other factors (Hayes and Wheelwright 1984, Abegglen and Stalk 1985). Kekre and Srinivasan (1990), however, found that for companies selling to industrial markets product line breadth had a small but significant *negative* association with manufacturing costs.

Two disadvantages of the focused factory are the increased risks of inefficiently using resources, and of being unresponsive to the market if the existing competitive situation changes. During the recession of the early 1980s focused factories in the oil rig equipment industry were closed (Rohan 1981).

In a plant with mix flexibility ways have been found through just-in-time (JIT) production and computer integrated manufacturing (CIM) to enjoy the benefits of product variety and short lead times without incurring increases in costs due to lack of specialization (Stalk and Hout 1990). Such a factory may exhibit economies of scope; it can make a range of items at lower unit cost than separate focused plants each producing a single item (Goldhar and Jelinek 1983). At the same time, due to product variety, there is less risk of inefficient use of resources and lack of responsiveness to market changes.

Changeover Flexibility. Uncertainty as to the length of product life cycles is especially troublesome when life cycles are shortening on average. A statistical analysis of household appliances over a 50 year period indicated that more recently introduced products had shorter life spans (Qualls et al. 1981). An enterprise handles this type of uncertainty through the strategic objective of product innovation. Changeover flexibility, an ability to quickly substitute new products for those currently being offered, is required in the manufacturing process. The range aspect indicates the variety of major design changes which can be accommodated, while the temporal aspect refers to that portion of new product introduction time which occurs in the manufacturing function (manufacturing startup time).

Conflicting viewpoints exist as to the need for changeover flexibility. The pro argument is based on the cost savings from using essentially the same equipment for different products over time, and the service benefits of being able to introduce a new product faster. The con argument maintains that new technological developments will probably render a flexible manufacturing process obsolete by the time new products are introduced (Sakurai 1990). Another argument makes the utility of changeover flexibility contingent upon the degree of market uncertainty. If the market is too erratic a company investing in a given range of this type of flexibility takes a gamble that the manufacturing process will be able to make the next generation of products. Can models reflecting these characteristics be developed to help indicate when changeover flexibility is appropriate?

Other Flexibility Dimensions. When a new product is introduced or a standardized design is customized uncertainty arises as to which product attributes customers desire. Modification flexibility allows a manufacturing process to implement minor design changes in a given product. The range aspect reflects how many different kinds of minor changes are possible, while the time component indicates the speed with which a given change is accomplished. This type of flexibility is associated with the strategic objective of responsiveness to customers' specifications.

Volume flexibility permits increases or decreases in the aggregate production level. The amount of change reflects its range aspect, while the length of time to make a change represents the time aspect. A need for volume flexibility occurs in response to uncertainty in the amount of customer demand. Firms in the computer industry are subject to the "hockey stick" effect in which, due to discounting, as much as fifty percent of quarterly sales may occur in the last two weeks. These problems are exacerbated by the dynamics of production-distribution systems with long lead times. The associated strategic objective is maintaining or increasing market share.

Machine downtime has a short run component derived from equipment or quality problems, and a long run component based on accommodating major product design changes. Rerouting flexibility compensates for these uncertainties by adjusting the sequence of machines through which a part flows. The range aspect indicates the variety of parts for which rerouting occurs and the extent to which a part can be rerouted. The temporal aspect considers how long it takes to make the adjustment. This type of flexibility is associated with the strategic need to meet customers' due dates.

Suppliers or a firm's upstream activities are sources of uncertainty for the composition and dimensions of the materials being processed. There is consequently a need for material flexibility, the ability of the manufacturing function to handle unexpected variations in inputs. The range aspect includes the number of different kinds of variations susceptible to adjustment as well as their magnitudes. The temporal aspect reflects how long it takes to make an adjustment. Material flexibility contributes to reducing defects; hence it facilitates the strategic objective of product quality.

Suppose the types and intensities of the uncertainties in Table 2 shift uncontrollably over time. This metalevel uncertainty requires a company to have strategic adaptability in order to quickly adjust its objectives to meet the new conditions. With flexibility responsiveness the manufacturing unit can readily change the types, ranges and times of the six dimensions. The key is being able to make changes within and among the methods of delivery. The Japanese program on manufacturing in the next century calls for individual production systems to transform themselves freely as changes in their flexibility needs take place. Equipment from existing manufacturing cells, for example, should be designed to be easily rearranged into new combinations of cells (Hall and Tonkin 1990).

2.3. Relation to Other Classifications

The flexibility classification developed here represents a multilevel scheme. Each dimension, with minor exceptions, is meant to apply at different hierarchical levels including the individual machine, manufacturing system or cell, plant, or multiplant levels. It remains to empirically determine whether the dimensions are conceptually distinct. Another hierarchical approach identifies different flexibilities at different levels and assumes that those at one level are necessary to have those at the next highest (Browne et al. 1984, Sethi and Sethi 1989). At the machine level, for example, machine flexibility refers to the types of operations performed without difficulty in switching from one to the other. Mix, changeover, volume, routing and other types occur at the manufacturing system level. The aggregate (presumably factory) level includes production flexibility, the universe of part types which can be produced without major capital investment, and market flexibility, the ease in adapting to a changing environment.

The hierarchical approach has at least three limitations with respect to the approach advocated here. First, it has led to a proliferation of flexibility dimensions (Chung and Chen 1990). The multilevel framework can apply with suitable modification to different types of technologies so there is no need for separate flexibilities for machines, material handling systems, and computer systems. It also assumes that a particular level, the manufacturing system, for example, consists of interacting technological, organizational, and human elements. It is not necessary to distinguish between different flexibilities for them. Second, the hierarchical approach, by assuming that flexibility is merely a way of adapting to changing environments, neglects the concept's proactive function. Third, by defining flexibility dimensions solely in terms of their range characteristics it does not consider their temporal aspects. These limitations, however, are not necessarily inherent. Ways may be found to overcome them through future research.

2.4. Measuring Flexibility

Researchers need flexibility measures to test theories, operations managers require them to help in making capital investment decisions and in determining performance levels. In spite of the need no well-accepted operationalizations exist. Attempts to measure the range aspect have flaws. The time aspect has not received sufficient attention presumably because it is not viewed as being connected with flexibility.

Why is operationalizing flexibility such a difficult task? (1) No rigorous method exists for establishing a priori the domain of flexibility, that is the relevant dimensions of the concept. Therefore little agreement exists on which dimensions to include. By basing dimensions on the types of uncertainties faced by operations managers, the approach advocated here helps to alleviate the problem. It is easier to come to agreement on the relevant uncertainties because they have been studied for a longer time.

(2) Multidimensionality compounds the effort that must go into creating scales, testing them and collecting data.

(3) One can study flexibility at a number of different hierarchical levels. While measures developed at one level may apply to other levels, the measures require collection of disparate data sets. Once more, research results derived at one level may not apply to others.

(4) Operationalizations which span industries are more useful for research purposes than those limited to a single industry. The former, however, are much more difficult to create. Dixon (1991) used factor analysis to construct scales for mix, changeover and modification flexibility, but the application was limited to the greige cloth manufacturing segment of the U.S. textile industry.

(5) A lack of communication exists between those doing formal work with implications for measurement, and those constructing scales to do empirical work.

One may consider flexibility as arising from a formal decision problem in which the choices among future options are affected by the choice made now. This outlook leads to analytical models which are often difficult to solve unless restrictive assumptions are made. On the other hand, some implications for measurement have been drawn. Mandelbaum and Buzacott (1990) using decision theory in a two-period problem justified measuring range in terms of the number of options available, but *not* under all circumstances. Once more, if utilities are independent and identically distributed, most of the value of flexibility can be obtained from having just a few options. In practice, therefore, it is not necessary to precisely count options when the number is large and difficult to calculate.

Undoubtedly, the most common measurement approach in practice is to count the number of options at a given point in time. Mix flexibility is often operationalized using the number of different outputs from a system such as the number of parts produced by a flexible manufacturing system (Ettlie 1988, Jaikumar 1986). Kumar (1987) suggested entropy as a measure for various dimensions. It is based not only on the number of options, but also on the freedom or opportunity to select a given option. Entropy has intuitive appeal as it mirrors the degree of randomness or uncertainty in a system. These types of measures, however, do not consider that a small number of outputs may be more different in kind from each other than a large number (Gerwin 1987). An alternative is, therefore, the range of some defining characteristic of the outputs. Instead of using the number of car models produced one might employ the range of the wheelbases.

Measures are also based on the physical characteristics of a manufacturing process. They do not reflect the combination of factors that determine flexibility (Gupta and Buzacott 1989). Operationalizing the rerouting dimension of a flexible manufacturing system in terms of the number of alternative paths fails to consider that the control system may do an inadequate job of scheduling and routing. Another approach is based on the impact of flexibility on a given performance criterion (Gupta and Buzacott 1989). To assess the rerouting dimension Buzacott (1982) suggested the average drop in the production rate when a machine breakdown occurs. Results, however, may vary considerably depending upon which criterion is selected. A qualitative approach is sometimes used. To assess the change in each of the first six dimensions, Gerwin and Tarondeau (1989) had managers use a five-point scale running from decreased a lot to increased a lot. Swamidass and Newell (1987) asked managers to qualitatively rate their companies' goals for flexibility on a ten-point scale. Managers' perceptions, however, are subject to biases which distort responses.

Due to the obstacles in measuring flexibility in physical units some researchers have suggested using economic impacts such as value or cost (Gupta and Buzacott 1989, Son and Park 1987). Economic value is normally the difference in expected profits with flexibility and without it, the divergence, for example, between having a flexible manufacturing system or transfer lines for a given product mix. Costs should include the impact of exercising an option such as the degradation in performance from selecting an alternative routing. They should also include indirect impacts such as the reduction in pressures to get designs right the first time arising from modification flexibility. Value and cost measures for each flexibility dimension are readily aggregated into single overall scales which are relevant to managers. Well-known problems exist, however, in identifying and operationalizing their intangible components.

It is not feasible here to provide an in-depth critique of the issues in determining economic consequences, but three general observations can be made. First, while the major hurdle is dealing with intangibles, too much attention has been paid to the benefit side and not enough to the cost side. An unintentional bias therefore exists in favor of recommending more flexibility than is economically appropriate. Second, there is too much concentration on the consequences of advanced manufacturing technology versus other methods of delivery. Third, some evidence exists that most of the value of flexibility can be obtained at low cost because only a few options are necessary (Jordan and Graves 1991, Mandelbaum and Buzacott 1990). The former study indicates, however, that the options must be selected judiciously.

3. Utilizing Flexibility Concepts in Industry

Research on flexibility should do more than develop and test theory. It should also show manufacturing managers how to evaluate and change the flexibility of their operations. Little attention has been paid to developing procedures to meet this need.

3.1. Analyzing the Need for Flexibility

To analyze whether more or less flexibility is needed in a particular setting it is necessary to distinguish between required, potential and actual flexibility for each range or time aspect of the previously identified dimensions. Requirements represent strategic management's determination of how much is needed of a particular type of flexibility. Potential indicates what can occur given the existing plant design if external conditions are appropriate. Actual flexibility stems from utilization of the plant and is determined on the basis of experience.

Inappropriate amounts of flexibility are revealed by discrepancies between the required, potential and actual conditions. Three critical misalignments are discussed here: required greater than potential, potential greater than actual, and potential greater than required. Once more, some hypotheses which account for those discrepancies are indicated. They are based on the use of advanced manufacturing technology (AMT) since so much has been written about it.

Required Greater Than Potential. What factors cause required flexibility, the amount needed of a given dimension, to be greater than potential, the amount designed into a factory? The state of the art in AMT is one factor. Computerized automation has not evolved to the point where it can compete with the flexibility of humans (Whitney 1986). Gerwin and Tarondeau (1989) provided some evidence by examining changes in the first six flexibility dimensions accompanying AMT's introduction. In factories starting from a rigidly automated manufacturing process installing AMT is likely to increase most dimensions since originally there was little flexibility. Factories starting from a labor-intensive technology already have a high degree of flexibility. Installing AMT is likely to produce mixed results. While a host of factors acting in concert undoubtedly impede AMT's potential for flexibility, control systems appear to be salient (Dilts et al. 1991, Gupta and Buzacott 1989, Hall and Tonkin 1990).

A second issue is that decisions on the selection and design of AMT are unavoidably biased against flexibility. It is difficult to explicitly consider tradeoffs between the concept and other manufacturing criteria. Since, for example, the efficiency benefits of productivity are more measurable than the strategic benefits of flexibility, the former may be emphasized over the latter. Emphasizing productivity leads to a disproportionate amount of hard automation in a new manufacturing system versus programmable and human elements.

Closing this gap calls for diminishing required flexibility through the various methods for uncertainty reduction. Alternatively, it is possible to raise potential flexibility by increasing a factory's adaptive capacity. When the state of the art in AMT hinders adaptation firms can consider other means of delivering flexibility such as organizing the work force into teams of multiskilled individuals who rotate tasks and are not under close supervision. To avoid a poor balance between flexibility and productivity in AMT managers must be prepared to make judgment calls. One useful heuristic is that the proportion of total cost due to process components dedicated to a given product should be directly related to the proportion of time the system will spend handling the product (Scott 1984). Managers can also insure that the team which purchases AMT represents a balance between hardware, software, and human resources (Graham and Rosenthal 1986).

Potential Greater Than Actual. This discrepancy is between the amount of flexibility designed into a system, and the amount obtained in practice. Attaining AMT's potential is hampered by the way it is operated at least in North America and Europe (Graham and Rosenthal 1986, Jaikumar 1986, Reich 1983). Managers steeped in the values and assumptions of high volume standardized production are not always concerned with the technology's strategic potential.

Supporting evidence comes from Farley et al.'s (1987) study of U.S. firms' plans for expanding their flexible automation. Cost reduction was viewed as the major benefit while shorter new product lead time, the temporal aspect of changeover flexibility, was seen as the least important. Jaikumar's (1986) survey of Japanese and American flexible manufacturing systems (FMSs) found that average mix flexibility (number of parts produced), and average changeover flexibility (number of new parts introduced per year) was much greater in the former country. Margirier's (1986) survey of computerized automation in France revealed that it was selected more to reduce unit costs than to increase product diversity or decrease lead time.

Data subsequently collected by Ettlie (1988) in the U.S. has more optimistic findings. He found the average number of parts scheduled on FMSs was 187 ($n = 12$). Either managers are learning over time to use computerized automation more effectively, or the discrepancies are due to differences in the companies, parts, and manufacturing technologies surveyed.

To close this type of gap it is necessary to increase actual adaptation through new managerial policies. Jaikumar (1986) suggested that managers should shift from directing day-to-day operations to developing support systems and structures, emphasizing long-term planning, and training employees. Graham and Rosenthal (1986) suggested doing away with traditional functional structures which prevent all roles needed for successful operation from being assigned to an FMS.

Potential Greater Than Required. This situation, in which the amount of flexibility designed into a system is greater than the amount needed, arises when pressures from certain departments lead to acquiring potential over and above what is required. As one example, excess product variety may exist because of the marketing department's short-sighted fixation on meeting customers' immediate needs.

When potential is greater than required an opportunity exists to explore proactive or defensive strategies. Redefining market uncertainties allows a firm to immediately employ excess flexibility to its competitive advantage. A company may instead decide to bank flexibility for later use. Alternatively, it may reduce adaptive potential and distribute any freed resources elsewhere. Due to the current emphasis on increasing flexibility it is easy to overlook the savings which may occur from reducing potential.

Since companies usually have no guidelines for determining whether to contract product variety or expand it, they are susceptible to the current fad in their industry. Discrepancy analysis, however, implies that a choice between focus and flexibility depends upon at least two contingencies facing a company. One is the state of the market as mirrored in required flexibility and the other is the state of a firm's manufacturing process as indicated by potential flexibility. If required is less than potential and actual more focus should be considered. If required is greater than potential and actual more flexibility is an option.

3.2. Implementing Changes in Flexibility

This section integrates many of the concepts previously discussed by sketching out a procedure for implementing desired changes in flexibility. The procedure, currently more of a rough guideline than a finished product, has four phases. Phase I identifies flexibility dimensions requiring investigation. Phase II measures gaps. Phase III selects methods for closing the gaps and Phase IV involves continuous assessment.

In Phase I senior managers at the business unit level initially chose which range and time aspects of the flexibility dimensions are relevant for competition in the industry. In telecommunications, for example, the time aspect of changeover flexibility is critical. Being first to market a successful new product is almost a guarantee of substantial market share. Making these choices is different from and prior to determining which aspects need improvement. Business unit management also selects those relevant aspects for which excess flexibility is desired. They will be used to redefine market uncertainties or to bank flexibility.

In Phase II at the plant level requirements, potentials and actuals are determined for each relevant flexibility aspect. Requirements information on existing incremental needs comes from customer surveys inquiring into, for example, the product range and lead time desired. Future radical needs can be derived from "lead users" of a product, especially where market needs change rapidly (von Hippel 1988). Evaluations of potentials are likely to come from the company's manufacturing engineers. Actual flexibilities are determined from performance data. Based on discussions with business unit management the resulting gaps are prioritized. Slack (1988) provided an illustration of how Phase II could be operationalized.

In Phase III the factory identifies methods for dealing with the gaps. To reduce the gaps it may select methods which eliminate uncertainties, thus decreasing requirements, or which raise potential, thus adapting to uncertainties. In order to redefine market uncertainties or bank flexibility, ways of improving potential beyond customers' immediate requirements must be found. The prioritized gaps and other factors act as specifications in the design of the selected methods. The costs of each method are estimated. Business unit management judges whether the benefits outweigh the costs. One implication is that it may not be possible to handle all the gaps. If measurement problems could be addressed there is room here for mathematical models to reduce the heuristic nature of the procedure.

Phase IV involves continuous assessment. First, a performance measurement system should provide the traditional control function of monitoring each gap to see if it is moving in the desired direction. Flexibility indicators do not have to precisely determine the values of concepts which are so difficult to measure. Instead, they should identify broad trends. The system also needs to respond to changes in the values of required flexibilities as customers' needs shift. In one approach used at Wang Labs a change in customers' needs reverberates backwards through the workflow as each subunit communicates new requirements to its upstream neighbor (Cross and Lynch 1988/89). Second, top management should provide a steering function (Burton et al. 1988). It must detect the need for changing which flexibilities are considered relevant.

There are at least three issues to consider in designing a program of this nature. First, changes in flexibility must be traded off against cost, productivity, quality and other objectives. As one example domestic sourcing may reduce lead times but lower quality. Second, conflict is likely to surface in determining the size and priority of gaps especially when the necessary information is subjective. The marketing department, for example, is likely to aim for a wider range of products than the manufacturing unit. Evidence from studies of cross-functional groups indicates that when the issues are confronted, as opposed to referred upwards or buried, the chances for resolution are high (Davis and Lawrence 1977).

Third, it is necessary to design the organization of the improvement process. Phase I is best handled at the business unit level by a task force of top managers from all major business functions. Options exist for the organization of Phases II, III and IV. Each plant may have its own interdepartmental task force which tries to improve all relevant flexibility aspects. Consequently, the plans for any one aspect are readily coordinated with plans for the others. Alternatively, there is a separate task force across all plants for each relevant aspect. Each aspect therefore receives focused attention and there is a better sharing of information among the plants.

4. Research Agenda

The first major point in developing an agenda is that research on manufacturing flexibility needs to have both a theoretical and an applied orientation. Special attention must be paid to the latter type of work as it is less developed than the former. The second major point is that both theoretical and applied investigations will continue to be severely hampered until the problems of developing valid and reliable measures of flexibility and its value are resolved. Testing hypotheses, determining the appropriate level of flexibility, analyzing discrepancies, and developing performance measurement systems all require measures. Operationalizing flexibility is therefore the single most important research priority.

4.1. Generic Strategies

North American manufacturers are utilizing adaptation and uncertainty reduction as part of their revitalization campaigns. There are at least three ways in which research can help to improve their efforts. First, will achieving a balance between the two approaches lead to higher organizational effectiveness than concentrating on just one of them? Achieving a balance does *not* mean overemphasizing one approach for market uncertainties and the other for process contingencies. In the past our firms, in adhering to a mass production model, overutilized reduction of market uncertainties thus putting them at a disadvantage in adapting to large-scale uncontrollable environmental changes. Simultaneously, North American firms overemphasized adaptation to uncertainties in the manufacturing process, which reduced pressures to eliminate the causes of machine breakdowns or quality problems. Currently, many firms see adapting to market demand, as opposed to also reducing uncertainty, as the key strategy. At the same time they are eliminating machine breakdowns and quality problems without considering that the requirement to adjust to manufacturing process uncertainties will never disappear completely. It is therefore useful to compare firms which balance both approaches in handling market (process) uncertainties to companies which emphasize just one.

Second, research needs to show how plans for adaptation and uncertainty reduction can be integrated with each other. Operations managers often employ a variety of methods without understanding their interactions. Are preventive maintenance, an example of reducing machine breakdowns, and redundant equipment, an example of adapting to breakdowns, typically part of a common plan? Any planned changes in a preventive maintenance program should be meshed with decisions on redundant equipment in a new flexible manufacturing system. Integrating the methods for improving competitive performance is one of the major challenges facing our manufacturing enterprises (Skinner 1989).

Third, research into balancing and integrating the strategic approaches should also consider a role for redefining uncertainties and banking flexibility. Without them a firm becomes a follower in its industry as opposed to a pacesetter. Many American companies are merely playing catch-up with the Japanese in the battle over product variety and lead times. An ability to redefine uncertainties requires preeminent manufacturing flexibility and imaginative strategies for using it. Banking depends upon having a long-term orientation.

4.2. The Flexibility Dimensions

The relationships between flexibility and other performance criteria need to be studied. First, research is needed into the extent to which manufacturing flexibility impacts on company performance. Kekre and Srinivasan (1990) provided some empirical support for the benefits of mix flexibility by demonstrating that a broader product line is associated with higher market share and profitability. Fiegenbaum and Karnani (1991) found no relationship between volume flexibility and return on assets (sales). Second, what happens to other manufacturing objectives when flexibility is changed? This is a significant issue if it is true that having flexibility, productivity and quality simultaneously is now necessary to compete. For a conventional manufacturing process flexibility is considered to be negatively associated with productivity (Abernathy 1978). Does the same relationship hold when the process is computer-controlled? There is much speculation that a positive association exists, but little empirical work has been done. Possible relationships between flexibility dimensions and quality have received even less attention. Gerwin (1987) developed some hypotheses based on a study of computerized body framing in the auto industry.

Most research, arguing from the existence of rapidly changing competitive environments, views flexibility as an unqualified good for a manufacturing process. Arguments exist, however, that increasing flexibility encourages waste. Waste arises in a number of different ways including adapting to uncertainties that should have been eliminated in the first place. A better understanding of these indirect costs will lead to more appropriate determinations of the optimal level of flexibility. This in turn will aid in specifying the proper balance between adaptation and uncertainty reduction. The following hypotheses represent a starting point:

Increasing product variety (mix flexibility) leads to complexity and confusion which raises overhead costs (Skinner 1985).

By the time the current product is out of date, developments in process technology will make existing flexible equipment obsolete. Its changeover capability will probably not be utilized (Sakurai 1990).

Modification flexibility reduces pressures to get designs right the first time leading to unnecessary engineering change orders.

Investment in excess capacity, empty floor space, and slack time in the production schedule is necessary to have volume flexibility.

Rerouting flexibility, by creating alternative production paths, discourages efforts to eliminate machine breakdowns.

Material flexibility reduces pressures on upstream activities to eliminate quality problems (Nevins et al. 1989).

4.3. Methods of Delivery

For each type of uncertainty are there specific methods of uncertainty reduction and complementary methods of adapting through flexibility? Table 3 is designed to stimulate further research by providing an initial affirmative answer. Among the uncertainty reduction devices are marketing methods such as long-term contracts, product life extension practices (creating new uses, finding new customers, inducing more use by existing customers), and leveling demand which is employed in conjunction with JIT production. Production approaches include preventive maintenance and Total Quality Control. A cross-functional team is a joint engineering-production-marketing technique, while large size is a business unit characteristic. The adaptive devices are almost all examples of production methods.

Table 3 Coping with Uncertainty

Nature of Uncertainty	Uncertainty Reduction Method	Adaptive Method
Market acceptance of kinds of products	Long-term contracts with customers	Small setup times, modular products
Length of product life cycles	Life extension practices	Less hard tooling and backward integration
Specific product characteristics	Cross-functional design teams	CNC machines
Aggregate product demand	Leveling demand	High capacity limits, subcontracting
Machine downtime	Preventive maintenance	Redundant equipment
Characteristics of materials	Total quality control	Automated monitoring devices, human imputs
Changes in the above uncertainties	Large size	Reconfigurable equipment

Table 3's significance goes beyond illustrating the complementarity between uncertainty reduction and adaptation. It begins to put various methods currently being used to improve a firm's competitiveness into a unified framework. One can begin to see how they relate to each other and the conditions under which each is appropriate. In the future we may learn whether the methods used for adaptation also apply to redefinition and banking or whether those two approaches require special means of delivering flexibility. Information of this sort is necessary for developing a coherent plan to revitalize a plant.

The table also helps in analyzing individual methods of delivery. Instead of having to deal in generalities about the effect of say JIT, one has a framework for determining its specific impacts, or those of its constituents such as setup time reduction. It would be of particular interest to identify methods which exhibit *versatility*; they can be used for uncertainty reduction as well as adaptation and/or they can deal with more than one type of uncertainty. One can also investigate whether a certain method exhibits *interference*, that is improvements in dealing with one type of uncertainty come at the expense of reductions in coping with others.

In line with Table 3, studying given methods of delivery should mean investigation of which uncertainties are affected and through which strategies (reduction, adaptation, redefinition or banking). It should not mean an exclusive concentration on adaptation through flexibility. The following discussion of product design and information technology illustrates some of the specific issues available for exploration.

Product design strategy represents the general philosophy and approach taken in creating a new product. Some interrelated examples include design for manufacturability, incremental design, the use of hierarchical building blocks, and "overdesign" in which an entire market receives a new product although some segments do not require all the features. Since there have been so few scientific investigations of the impacts of these approaches on Table 3's categories only a few observations can be made here to guide prospective research. First, these design strategies may not unreservedly facilitate coping with market and process uncertainties. Ulrich et al. (1991) found that designing larger, more complex parts, a principle of design for manufacturability, creates longer tooling procurement times, thus lengthening the temporal aspect of changeover flexibility. Second, some design approaches affect where in the production process flexibility is needed. Using common parts and building blocks, for example, tends to push the need for flexibility downstream. Large chunks of a process, in which the final stages exhibit high flexibility, may in fact be specialized. Third, overdesign strategies serve to disrupt the causal connection between market uncertainty and required flexibility. Market demands for product variety no longer uniquely determine required mix flexibility. Less product variety is needed than if overdesign did not exist.

What role do information technologies play in handling uncertainties? Within the firm computer integrated manufacturing (CIM) is a likely target for investigation. Mainstream CIM applications may not achieve promised improvements in flexibility because a hierarchical control structure prevents subsystems from exhibiting sufficient autonomy (Dilts et al. 1991, Gupta and Buzacott 1989, Hall and Tonkin 1990). It appears that flexibility responsiveness, a characteristic that is assuming greater significance, is particularly affected. For example, reconfiguring the manufacturing equipment being controlled is a problem. Empirical studies of these issues could check for the hypothesized adverse effects on flexibility and for any compensatory impacts in terms of uncertainty reduction. If current CIM applications are in fact poor in coping with uncertainty, this knowledge would contribute towards speeding the development of applications based on distributed processing. They should exhibit more flexibility responsiveness since a machine and its control component can be readily connected to (disconnected from) the entire system.

Information technology between firms is represented by electronic data interchange (EDI) networks. They are just beginning to be analyzed in terms of Table 3's categories. Current evidence suggests that EDI is versatile; it reduces uncertainties as well as providing adaptability. Srinivasan et al. (1991) found that EDI reduces process uncertainties for companies arising from human errors by their vendors: shipping to the wrong site, shipping the wrong item, and shipping late. At the same time when process uncertainties do arise EDI, by quickly reporting on them, facilitates making adjustments to handle them (Kekre and Mukhopadhyay 1991).

4.4. Evaluating and Changing Operations

Research is needed which utilizes theoretical and conceptual material to help managers improve their operations. The four step procedure outlined here still requires a good deal of work before it can accomplish this task. While it contains many of the basic concepts it is also subject to many of the problems raised here. In order to identify the relevant flexibility dimensions in Phase I, senior managers must know more about tradeoffs with other manufacturing criteria. Operationalizing Phase II, in which gaps are established, demands an ability to measure the various dimensions and their economic value. There is also a need to determine the likely causes of discrepancies between required, potential and actual. Some possible reasons have been discussed here. In order to select the appropriate methods in Phase III, investigations are required of their implications for handling uncertainty. Phase IV in which gaps are monitored emphasizes an issue underlying the entire four phase procedure, that is, how to find acceptance within firms for performance measurement systems based on strategically oriented physical measures as well as on short-term oriented financial measures.

5. Conclusions

Research into manufacturing flexibility has concentrated on production planning, scheduling, control, and investment (especially for advanced manufacturing technology). This paper adds a strategic focus which is summarized by the following principles. Some of them also act as guidelines for the development of mathematical models.

The conceptual model serves as a foundation for work on the strategic aspects of flexibility. It helps in drawing the following conclusions:

- Flexibility is not just an adaptive response to an uncertain environment. It has a proactive function in creating uncertainties that competitors can not deal with.
- Advanced manufacturing technology is only one way of delivering flexibility.
- Enumerating the types of uncertainties faced by manufacturing managers provides a basis for identifying specific flexibility dimensions.
- If market uncertainties continue to intensify over the next few years flexibility responsiveness may become the most significant dimension.
- Management scientists have devoted too much emphasis to the range aspect of flexibility as compared to the temporal aspect.

The following conclusions emerge as the result of examining how flexibility concepts may be used in industry:

- Analysis of the discrepancies between required, potential and actual flexibility can help operations managers evaluate their needs for the various dimensions.
- Managers should not overlook the opportunity to identify excess flexibility and eliminate it.
- Discrepancy analysis provides a rational basis for determining whether to become more flexible or more focused.
- It is possible to outline a procedure which aids managers in changing existing amounts and types of flexibility.

The research agenda, in building upon the previous sections, makes the following major points:

- Research on flexibility needs to have more of an applied focus to complement the existing theoretical work.
- The main stumbling block to advances on both the theoretical and applied fronts is the lack of measures for flexibility and its economic value.
- We must investigate how to balance the defensive and proactive strategies that have implications for flexibility.
- Properly integrating the strategies so that they complement rather than unintentionally impede each other is also a priority.
- The impacts of a method of delivery should be analyzed in terms of Table 3 rather than just in terms of any possible contributions to flexibility.
- We do not know enough about the indirect costs, such as encouragement of wasteful activities and concentration on customers' short-term needs, which accompany increases in flexibility. Understanding these costs will contribute towards determining optimal levels of flexibility.
- Research is needed to uncover the reasons for gaps between required, potential and actual flexibility.
- Detailed practical procedures for implementing changes in flexibility must be developed from existing guidelines.[1]

[1] The author gratefully acknowledges financial support from the sponsors of the Research Program in Managing Technological Change in Manufacturing: The Natural Sciences and Engineering Research Council, The Social Sciences and Humanities Research Council, The Semiconductor Components Group of Northern Telecom Ltd., Mitel Corp., Gandalf Data Ltd., and Lumonics Inc. Financial support also came from Consortium for Advanced Manufacturing International (CAM-I).

References

Abegglen, James C. and George Stalk, Jr., *Kaisha*, The Japanese Corporation, Basic Books, New York, 1985.

Abernathy, William J., *The Productivity Dilemma: Roadblock to Innovation in the Automobile Industry*, The Johns Hopkins University Press, Baltimore, MD, 1978.

Ayres, Robert V., *The Next Industrial Revolution: Renewing Industry Through Innovation*, Ballinger Publishing Co., Cambridge, MA, 1984.

Browne, J., D. Dubois, K. Rathmill, S. Sethi and K. Stecke, "Classification of FMS," *FMS Magazine*, April, 1984.

Burton, Richard M., John D. Forsyth and Donald M. Melick, "Searching for Viability Under Changing Environmental Conditions," *Technovation*, 8 (1988), 111–131.

Buzacott, J. A., "The Fundamental Principles of Flexibility in Manufacturing Systems," *Proc. First International Congress on Flexible Manufacturing Systems*, Brighton, England, 1982, 13–22.

Child, John, "Organizational Structure, Environment and Performance: The Role of Strategic Choice," *Sociology*, 6 (1972), 1–22.

Chung, C. and I. Chen, "Managing the Flexibility of Flexible Manufacturing Systems for Competitive Edge," in M. J. Liberatore (Ed.), *Selection and Evaluation of Advanced Manufacturing Technologies*, Springer-Verlag, New York, 1990, 280–305.

Cohen, Stephen, S. and John Zysman, *Manufacturing Matters: The Myth of the Post-Industrial Economy*, Basic Books, New York, 1987.

Cross, Kelvin F. and Richard L. Lynch, "The 'SMART' Way to Define and Sustain Success," *National Productivity Review*, 8, 1 (Winter 1988/89), 23–33.

Davis, Stanley M. and Paul R. Lawrence, *Matrix*, Addison-Wesley, Reading, MA, 1977.

DeMeyer, A., J. Nakane, J. G. Miller and K. Ferdows, "Flexibility: The Next Competitive Battle," Manufacturing Roundtable Research Report Series, Boston University, School of Management, Boston, MA, 1987.

Dilts, D. M., N. P. Boyd and H. H. Whorms, "The Evolution of Control Architectures for Automated Manufacturing Systems," *J. Manufacturing Systems*, 10, 1 (1991), 79–93.

Dixon, J. Robb, "Measuring Manufacturing Flexibility: An Empirical Investigation," *School of Management*, Boston University, Boston, MA, 1991.

Ettlie, John E., *Taking Charge of Manufacturing*, Jossey-Bass, San Francisco, CA, 1988.

Farley, John V., Barbara Kahn, Donald R. Lehmann and William L. Moore, "Modeling the Choice to Automate," *Sloan Management Review*, 28, 2 (Winter 1987), 5–15.

Fiegenbaum, Avi and Aneel Karnani, "Output Flexibility—A Competitive Advantage for Small Firms," *Strategic Management J.*, 12, 2 (February 1991), 101–114.

Gerwin, Donald, "An Agenda for Research on the Flexibility of Manufacturing Processes," *International J. Oper. and Prod. Management*, 7, (1987), 38–49.

—— and Harvey Kolodny, *Management of Advanced Manufacturing Technology: Strategy, Organization and Innovation*, John Wiley, New York, 1992.

—— and Jean-Claude Tarondeau, "International Comparisons of Manufacturing Flexibility," in Kasra Ferdows (Ed.), *Managing International Manufacturing*, Elsevier North-Holland, Amsterdam, 1989, 169–185.

Graham, Margaret B. W. and Stephen R. Rosenthal, "Institutional Aspects of Process Procurement for Flexible Machining Systems," Boston University, School of Management, Boston, MA, September 1986.

Goldhar, Joel D. and Mariann Jelinek, "Plan For Economies of Scope," *Harvard Business Review*, 61, 6 (November-December 1983), 141–148.

Gupta, D. and J. A. Buzacott, "A Framework for Understanding Flexibility of Manufacturing Systems," *J. Manufacturing Systems*, 8, 2 (1989), 89–97.

Gupta, Y. P. and S. Goyal, "Flexibility of Manufacturing Systems: Concepts and Measurements," *European J. Oper. Res.*, 43 (1989), 119–135.

Hall, Robert and Lea Tonkin (Eds.), *Manufacturing 21 Report: The Future of Japanese Manufacturing*, Association for Manufacturing Excellence, Wheeling, IL, 1990.

Hayes, Robert H. and William J. Abernathy, "Managing Our Way to Economic Decline," *Harvard Business Review*, July-August (1980), 67–77.

—— and Steven C. Wheelwright, *Restoring Our Competitive Edge: Competing Through Manufacturing*, John Wiley, New York, 1984.

Jaikumar, R., "Postindustrial Manufacturing," *Harvard Business Review*, November-December (1986), 69–76.

Jordan, William C. and Stephen C. Graves, "Principles on the Benefits of Manufacturing Process Flexibility," General Motors Research Labs, Warren, MI, 1991.

Kekre S. and T. Mukhopadhyay, "Impact of Electronic Data Interchange Technology on Quality Improvement and Inventory Reduction Programs: A Field Study," Graduate School of Industrial Administration, Carnegie Mellon University, Pittsburgh, PA, 1991.

—— and Kannan Srinivasan, "Broader Product Line: A Necessity to Achieve Success?", *Management Sci.*, 36, 10 (October 1990), 1216–1231.

Keller, Maryann, *Rude Awakening: The Rise, Fall and Struggle for Recovery of General Motors*, William Morrow, New York, 1989.

Kumar, Vinod, "Entropic Measures of Manufacturing Flexibility," *International J. Production Res.*, 25, 7 (1987), 957–966.

Mandelbaum, Marvin and John Buzacott, "Flexibility and Decision Making," *European J. Oper. Res.*, 44, 1 (January 1990), 17–27.

Margirier, Gilles, "Flexible Automation in Machining in France: Results of a Survey," Institute of Economic Research, University of Social Sciences of Grenoble, Grenoble, France, 1986.

Nagel, Roger and Rick Dove (Eds.), *21st Century Manufacturing Enterprise Strategy*, Iacocca Institute, Lehigh University, Bethlehem, PA, 1991.

Nevins, James L., Daniel E. Whitney, and Thomas L. DeFazio, *Concurrent Design of Products and Processes: A Strategy for the Next Generation in Manufacturing*, McGraw Hill, New York, 1989.

Qualls, William, Richard W. Olshavsky and Ronald E. Michaels, "Shortening of the PLC-An Empirical Test," *J. Marketing*, 45, 4 (Fall 1981), 76–80.

Reich, Robert B., *The Next American Frontier*, Times Books, New York, 1983.

Rohan, T., "Thinking Small Helps Spur Production," *Industry Week*, September 21 (1981), 98–100.

Sakurai, Michiharu, "The Influence of Factory Automation on Management Accounting Practices: A Study of Japanese Companies," in R. S. Kaplan (Ed.), *Measures for Manufacturing Excellence*, Harvard Business School Press, Boston, MA, 1990, 39–62.

Scott, Peter B., "Towards Optimized Robotic Assembly," *Omega*, 12, 3 (1984), 283–290.

Sethi, Andrea Krasa and Suresh Pal Sethi, "Flexibility in Manufacturing: A Survey," *International J. Flexible Manufacturing Systems*, 2 (1990), 289–328.

Skinner, Wickham, "Report of the Production and Operations Management Research Needs Committee," *Oper. Management Review*, 7, 1 and 2 (Fall 1988 and Winter 1989), 17–23.

——, *Manufacturing: The Formidable Competitive Weapon*, John Wiley, New York, 1985.

Slack, Nigel, "Manufacturing Systems Flexibility-An Assessment Procedure," *Computer-Integrated Manufacturing Systems*, 1, 1 (February 1988), 25–31.

——, "Flexibility as a Manufacturing Objective," *International J. Oper. and Prod. Management*, 3, 3 (1983), 4–13.

Son, Y. K. and C. S. Park, "Economic Measures of Productivity, Quality, and Flexibility in Advanced Manufacturing Systems," *J. Manufacturing Systems*, 6, 3 (1987), 193–206.

Stalk, George Jr. and Thomas M. Hout, *Competing Against Time*, The Free Press, New York, 1990.

Srinivasan, K., S. Kekre and T. Mukhopadhyay, "Impact of Supplier Material Flow Complexity and Information Technology Support on JIT Performance: An Empirical Investigation," Graduate School of Industrial Administration, Carnegie Mellon University, Pittsburgh, PA, 1991.

Suarez, Fernando F., Michael A. Cusumano and Charles H. Fine, "Flexibility and Performance: A Literature Critique and Strategic Framework," Sloan School, MIT, Cambridge, MA, 1991.

Swamidass, Paul M., *Manufacturing Flexibility*, Operations Management Association Monograph No. 2, The Schneider Group, Waco, TX, January 1988.

—— and William T. Newell, "Manufacturing Strategy, Environmental Uncertainty, and Performance: A Path Analytic Model," *Management Sci.*, 33, 4 (April 1987), 509–524.

Tombak, Mihkel and Arnoud DeMeyer, "Flexibility and FMS: An Empirical Analysis," *IEEE Trans. Engineering Management*, 35, 2 (May 1988), 101–107.

Ulrich, Karl, D. Sartorius, S. Pearson and M. Jakiela, "A Framework for Including the Value of Time in Design-for-Manufacturing Decision Making," Sloan School, MIT, Cambridge, MA, 1991.

Von Hippel, Eric, *The Sources of Innovation*, Oxford University Press, Oxford, England, 1988.

Wharton, T. J. and E. M. White, "Flexibility and Automation: Patterns of Evolution," *Oper. Management Review*, 6, 3 and 4 (Spring and Summer 1988), 1–8.

Whitney, Daniel E., "Real Robots Do Need Jigs," *Harvard Business Review*, May-June (1986), 110–116.

Accepted by Richard M. Burton; received September 1991. This paper has been with the author for 2 revisions.

Copyright 1993, by INFORMS, all rights reserved. Copyright of Management Science is the property of INFORMS: Institute for Operations Research and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.