Division of Research
School of Business Administration
The University of Michigan

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Impact of Production Flexibilities on Manufacturing Decisions

Kathryn E. Stecke
The University of Michigan

and

Narayan Raman
University of Illinois at Urbana-Champaign

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ABSTRACT

The flexibility of manufacturing systems has been conventionally associated with their ability to manufacture a variety of part types. However, flexible automation has introduced several process-oriented dimensions to flexibility. The impact of these dimensions on system productivity should be better understood in order to evaluate the desirability of flexible automation for any company.

This paper analyzes the relationships between flexibility and productivity in a flexible manufacturing system (FMS) from both short- and long-term perspectives. In the short-term, system flexibility is strongly influenced by the FMS planning decisions such as part type selection, machine grouping, and machine loading. We examine the implications of the various planning objectives for the different types of flexibilities, and evaluate their impact on system productivity. We observe that the inverse relationship that exists between flexibility and productivity for conventional manufacturing systems does not necessarily carry over to FMSs.

From a long-term perspective, we investigate the possible impact of production flexibility on the product-process matrix and the existing models on product and process innovations. Achieving manufacturing focus with flexible automation requires consideration of the additional dimension of flexibility as well as those of product and process.

1 INTRODUCTION

Considerations of improved productivity and production flexibility have assumed major importance in the design and operation of manufacturing systems. The overseas competition has clearly underlined the need for greater manufacturing effectiveness. On the other hand, shorter product life cycles, and greater product proliferation and market fragmentation indicate that, in addition to enhanced productivity, manufacturing flexibility should be considered for the long-term viability of many firms. Kindel (1984) notes a shift towards a "workshop economy" in which the consumers increasingly seek differentiation, even in generic products. Flexible manufacturing methods with computer-controlled and versatile machining and assembly capabilities, promise an efficient solution to the simultaneous requirements of productivity and flexibility in addition to providing superior quality.

Much of the existing literature pertaining to conventional manufacturing systems has associated manufacturing flexibility with the ability to produce a variety of part types. A job shop is more flexible than a transfer line because of the greater ease with which it can be reconfigured to change over to produce a different set of part types. However, recent investigations into the flexibility of flexible manufacturing systems (FMSs) (Gerwin 1982, Browne et al. 1984, Chatterjee et al. 1984, Falkner 1986, Carter 1986, Jaikumar 1986, Kumar 1987, Gupta and Goyal 1989, Chandra and Tombak 1990, Sethi and Sethi 1990, Rachamadugu, Nandkeolyar and Schriber 1993) indicate that there are other, process-oriented dimensions of production flexibility as well. Much of the differences in the relative efficiencies of conventional and flexible manufacturing methods can be attributed to the differences in their process flexibilities. However, it must be recognized that, for any system, the product- and process-oriented dimensions of flexibility are dependent on each other. The maximum achievable product flexibility of any system is limited by its process flexibility. Falkner (1986) underscores this point by noting that researchers who ignore the processing limitations of any system tend to overemphasize its capabilities with respect to product-oriented flexibility.

This paper analyzes the impact of the individual components of flexibility on a manufacturing system from both short-term and long-term perspectives. In the short term, production flexibility enables the system to maintain its production in the face of unforeseen events, such as machine breakdowns, unexpected demand surge, etc. We argue that while the production flexibility of any system is partly determined at the system design stage, the realized short-term flexibility depends upon the pre-production setup as well. We investigate the impact of production planning decisions on short-term flexibility and productivity of the system.

From a long-term perspective, we present a comparison of conventional and flexible manufacturing methods for the two extremes of high volume/low variety and low volume/high variety manufacture. We also study the implications of flexible manufacture for some of the existing models relating to the evolution and interdependence of product and process life cycles. We argue that, while one-to-one correspondence between the respective stages of the product and process life cycles could possibly be established for conventional manufactures, flexible automation tends to delink the product from the process. Consequently, achieving focus in flexible manufacture also requires selecting the appropriate level of production flexibility, in addition to ensuring that the product(s) and the process(es) are consistent with one another.

The paper is organized as follows. Section 2 reviews the taxonomies relating to the different types of flexibilities potentially available in a manufacturing system, as well as the FMS planning problems. In Section 3, we study the impact of flexibility on the short-term productivity of any system in the context of the operating decisions made at the production planning stage. We discuss the implications of the various FMS production planning objectives for the short- term flexibility of the system. Section 4 presents a comparison between conventional and flexible manufacturing methods with respect to the various types of flexibilities as well as several other relevant manufacturing decisions. Section 5 investigates the impact of flexible manufacture on some existing models relating to product-process interdependence. Section 6 concludes with suggestions for future research in determining the appropriate mix of flexibilities.

2 PRODUCTION FLEXIBILITY AND FMS PLANNING PROBLEMS

This section provides frameworks for analyzing the relationships between production flexibility and the various manufacturing issues in an FMS. In Section 2.1, we review the individual components of production flexibility, and discuss how the contributions from these components vary depending upon the time-frame considered. Section 2.2 presents the hierarchy of FMS production problems and highlights five major planning problems which form the basis of subsequent discussion.

2.1 Classification of Production Flexibilities

Several somewhat similar schemes are available in the current literature for classifying flexibility. In this paper, we adopt the taxonomy proposed by Browne et al. (1984), who define eight types of flexibility for a manufacturing system. Five of these – *machine, process, operation, routing*, and *volume* flexibilities – relate to a given system and a given set of part types, while the others are applicable more generally. Browne et al.'s classification is briefly reviewed below.

1. *Machine Flexibility*: Machine flexibility is a measure of the ease with which the operations of a given set of part types can be performed at a given machine. It is determined, in part, by the number of different operations that can be carried out at the machine and the efficiency with which the machine can switch from one operation to another. Machine flexibility improves, for example, with increases in machine versatility and tool magazine capacity and reduction in the setup time required to changeover to produce a different part type.

2. *Process Flexibility*: Process flexibility relates to the ability of the manufacturing system as a whole to manufacture a given set of part types in several ways. It is determined by the machine flexibilities of the various machines in the system as well as by the versatility of the material handling system and the extent of automated control of the operations.

3. *Routing Flexibility*: Routing flexibility is the ability of the system to maintain its efficiency in the face of congestions and breakdowns by providing alternative machine visitation routes during the manufacture of the given part types. It is increased by pooling machines to form machine groups as well as by duplicating selected operations (Stecke 1983).

4. *Operation Flexibility*: Operation flexibility measures the ease with which the sequence of operations for each of the given part types can be interchanged. It aims at increasing system efficiency by providing more options with regards to the schedulability of operations in real time.

5. *Volume Flexibility*: Volume flexibility is indicative of the system's capability to be operated profitably at different volumes of the existing part types. High volume flexibility implies a low break-even point.

6. *Product Flexibility*: Product flexibility represents the ability of the given manufacturing system to change over efficiently from a particular set of part types to a different set. Product

flexibility requires efficient and automated planning and control procedures in addition to machine flexibility.

7. *Expansion Flexibility*: Expansion flexibility relates to the manufacturing system's capability to be built and expanded modularly. It depends upon the magnitude of the incremental capital outlay required for providing additional capacity: the smaller the marginal investment, the greater the expansion flexibility. It is also determined by the ease with which capacity can be added to the existing system without adversely affecting its ongoing operations and its productivity.

8. *Production Flexibility*: Production flexibility is the cumulative result of the seven flexibilities listed above. It is a measure of the system's efficiency in manufacturing its universe of part types. Production efficiency implies competitive manufacturing cost and high service levels, measured in terms of product quality and short manufacturing lead times. Demands for individual products occur in varying volumes for the majority of manufacturing firms. For example, while an automobile manufacturer faces high volume demands for vehicles, the spare parts are usually required in smaller volumes. For the firm to be production flexible, it should be able to meet both types of requirements efficiently.

Production flexibility requirements vary, depending upon the time-frame considered. In the short term, the product portfolio and the manufacturing processes are fixed. Product demands may be stable and design changes are few and minor. Short-term flexibility enables the firm to maintain its production in the face of uncertainties arising on account of factors such as machine breakdowns, minor design changes, unreliable raw material supplies,and demand variations. Since short-term flexibility is related to a particular system and a given set of products with known demand, it is determined by *machine, process, operation*, and *routing* flexibilities.

In the medium term, major product design and production volume changes are possible while the manufacturing system remains essentially the same. Medium-term flexibility allows the efficient use of the existing facilities, while coping with a new set of products with a possibly different demand structure. These uncertainties require the firm to be *volume- and product- flexible.*

In the long term, changes could be made in the manufacturing system as well, possibly in response to the introduction of new products and major shifts in product demand. Flexibility in the long term is required in order to alter the scale of production without major disruptions in ongoing operations and with minimal incremental investment. In addition to being *volume- and product-flexible*, a firm needs to be *expansion-flexible* at this level, especially in the fact of increasing product demand. Carter (1986) proposes a similar time-frame based taxonomy of flexibility.

2.2 FMS Production Problems

For greater clarity in understanding short-term flexibility, we need to first understand the manufacturing issues faced by an FMS. Following Stecke (1985), these issues can be decomposed into: (i) design problems, (ii) planning problems, and (iii) scheduling and control problems.

FMS *Design* Problems include the selection of part types that will be processed, the selection and layout of machine tools and the material handling system, the design of buffers, and the computer control architecture. FMS *Planning* Problems comprise resource allocation decisions. The five planning problems are: (i) *Part Type Selection*, which requires selecting the subset of part types for imminent manufacture from among the set of all part types having current production orders; (ii) *Machine Grouping*, which involves partitioning machines into groups of identically tooled machines; (iii) *Production Ratio*, which requires determining the ratios in which the different part types will be manufactured concurrently; (iv) *Resource Allocation*, which assigns resources such as pallets, fixtures, etc. to the various part types; and (v) *Machine Loading*, which allocates the operations and the cutting tools to individual machine groups subject to the system's technological and capacity constraints. FMS *Scheduling and Control* Problems relate to the execution of orders and include determining the part input sequence, the part processing sequence at each machine, and monitoring the actual system performance and taking the necessary corrective actions.

For expositional clarity, we define some terms used in the remainder of the paper. A *product* refers to the finished workpiece. In general, a product is an assembly of several *parts*. Parts with the same physical and performance characteristics belong to the same *part type*.

3 THE IMPACT OF SHORT-TERM FLEXIBILITY

The manufacturing system's ability to cope with unforeseen events in the short term – its short-term flexibility, has been conventionally associated with a corresponding loss in its productivity. For example, while a job shop is quite robust in the face of machine breakdowns and changes in product mix, it has low productivity, in particular, when it is using its flexibility to cope with random events. Similarly, while a transfer line is quite efficient, it is susceptible to breakdowns and yield variations. Although such an inverse relationship between flexibility and productivity may be generally true for conventional manufacturing methods, it may not carry over to flexible manufacture.

In order to assess the impact of flexibility on productivity, we identify some of the factors which contribute to the increased flexibility of a manufacturing system. These are outlined in Table 1. The impact of these factors on system productivity is discussed subsequently.

TABLE 1

THE IMPACT OF SOME PRODUCTION FACTORS ON FLEXIBILITY AND PRODUCTIVITY

	Impact on Productivity	
Factors that Affect Flexibility	*Favorable*	*Unfavorable*
1. Duplication of machines and/or operation assignments	XX	X
2. Flexibility of the material handling system	XX	X
3. Use of general-purpose machines	XX	X
4. Less aggregation of operations	XX	X
5. Ease of real-time scheduling	XX	
6. Underutilization of machines		XX

1. *Duplication of machines and/or operations*: Routing flexibility is achieved by providing alternative routes either through machine pooling (Stecke 1983) or by duplicating machine assignments for one or more operations. This may lead to a loss in productivity since the machines and the tool slots that provide the redundancies could otherwise have been used for processing other part types. On the other hand, productivity of the subset of part types being produced would be increased by allowing alternative routes since they are used to process parts of the same (or similar) part type. For example, consider two systems C and D. System C processes a given part in p time units using only one route while system D provides two routes simultaneously, each with a processing time of $2p$ time units. Though the two routes in system D are individually half as efficient as the route in system C, the overall productivity of system D can be more than that of system C because of the

pooling effect. It is also more robust in the event of breakdowns. However, providing alternative routes for any part type is advantageous only if its production quantity is large enough to take advantage of the alternative routes or if substantial commonality of operations exists among the various part types being manufactured simultaneously (Stecke 1983). In the extreme case of having part types with unit production requirements, the flexibility provided by alternative routes usually implies a loss in productivity.

2. *Material handling system*: Operation and routing flexibilities can be increased by the use of variable-route material handling systems, such as automated guided vehicles (AGVs). Since the travel times for such transporters can be greater than those for fixed-route transporters, such as conveyors (Stecke and Browne 1985), part in-process times may be correspondingly increased. On the other hand, with a more flexible material handling system, a part may travel directly to its next machine, rather than potentially traversing the entire length of the conveyor, with a consequent increase in productivity. Also, if there is at least one input buffer at each machine, or if it is scheduled properly, an AGV may get a part to a machine "on time", with no loss of machine utilization.

3. *Use of general-purpose machines*: If the system is run in a fixed manner for the repetitive production of few part types with known and stable requirements, special-purpose machines can be dedicated to specific operations in order to reduce machining times. Such machines are also likely to yield lower manufacturing cost for high production volumes. In addition, the use of dedicated special-purpose equipment usually simplifies production planning and real time scheduling of operations, since the scope for alternative operation assignments to machines is limited. On the other hand, the potential for alternative routing available from the general-purpose machines can increase productivity.

4. *Less aggregation of operations*: Operation flexibility is increased by duplicating the operations of any given part type among the machines. The implementation of operation flexibility requires that operations of a part type should occasionally be assigned to different machines, even if some of them could be done on the same machine. However, this implies that a part may visit a larger number of machines with commensurate increases in the queueing and travel times. Considerations of greater productivity would, on the other hand, require that the operations which could be performed on the same machine (without violating precedence feasibility) be grouped together and performed consecutively (Stecke and Solberg 1981).

In their study of a general FMS, Stecke and Raman (1992) find that operation aggregation has a mixed impact on part mean flow time. In particular, for high coefficient of variation of the operation processing times (CVOPT), aggregating operations leads to lower flow time values. However, at low CVOPT, its impact is also effected by the machine grouping configuration. In general, operation aggregation is desirable in the presence of machine groups comprising two or more machines.

5. *Ease of real-time scheduling*: While the provision of routing and operation flexibility complicates solution procedures for the production planning problems, the operation scheduling can be simplified and can be carried out in real time based on the current states of individual machines. Even in the absence of stochastic events, such as breakdowns, sequencing operations on individual machines optimally is a hard combinatorial problem. Analytical studies (see, for example, Buzacott 1982) and simulation-based studies (see, for example, Russo 1965) have shown that real-time scheduling is more efficient in increasing system throughput. Also, as shown in Stecke and Raman's (1992) study, system performance is not overly sensitive to the quality of the scheduling rule used in the presence of operation and routing flexibilities. Clearly, delaying the decision on selecting the next operation or the next machine until the time they are ready for processing is meaningful only when alternative routes and operation sequences are available.

6. *Underutilization of machines*: One way to increase routing flexibility is to deliberately underutilize machines. When machine utilizations are low, parts can be reassigned to alternative routes in real time with greater ease. While the routing flexibility provided in this manner is desirable for maintaining the production of part types currently in the system, this approach clearly affects the long-term productivity of the system.

Productivity gains in FMSs are also obtained through a greater number of hours of unmanned operation and better control over the quality of output resulting in higher yields. Closer monitoring of operations and machine states implies that parts can be routed in real time based on the up-to-the-minute information.

This discussion indicates that it is sometimes possible to increase both flexibility and productivity simultaneously. In general, the relationship between flexibility and productivity is complex and, for a given system, depends largely on the decisions made at the planning stage. The impact of these production planning problems on flexibility and productivity is now discussed.

1. *Part type selection problem*: Given the set of part types with production requirements, the planner can opt for selecting a large number of part types for immediate manufacture to try to maximize machine utilization and, therefore, productivity as well. This approach would obviously limit the number of alternative routes available for any given part type. Also, the startup and the finishing period for the large batches would be less productive. Alternatively, (s)he may choose to manufacture a smaller subset of part types and hence provide more operation and routing flexibilities to each. The larger number of subsets formed in the second approach may result in a drop in productivity because of more frequent (however, much shorter) setups and a possible loss of productive capacity (for creating operation redundancies). On the other hand, producing fewer part types and allowing operation and routing flexibility can increase productivity (Stecke 1992). As mentioned earlier, the loss in productivity can be mitigated if the production requirements are large. In addition, a flexible approach to selecting only a few part types to be produced simultaneously can be used to increase productivity while decreasing the overall setup and loading time (Stecke and Kim 1991).

2. *Machine grouping and loading problems*: Machine grouping leads to an increase in routing flexibility and a possible drop in productivity unless the alternative routes are utilized effectively in the manners described above. Then production can increase. Stecke (1983) suggests six possible loading objectives, which are: (a) balancing the assigned machine processing times; (b) minimizing the number of movements from machine to machine; (c) filling tool magazines as densely as possible; (d) maximizing the weighted sum of operation duplications; (e) unbalancing the workload per machine group for groups; and (f) balancing the workload per machine group for groups of equal size. The likely impact of these objectives on system *flexibility* and *productivity* is shown in Tables 2 and 3, respectively. These tables *qualitatively* indicate the lower and upper bounds of system flexibility and productivity achievable under these objectives for varying levels of machine pooling. The upper bound is of primary interest to us since it reflects the potential of a given objective.

The first balancing objective is applicable to systems with no pooling or with partial pooling of machines. This objective provides no operation and routing flexibilities when there is no pooling. Also, as shown in Table 3, other objectives are likely to perform better with regard to the system productivity.

TABLE 2

IMPACT OF GROUPING AND LOADING OBJECTIVES ON **FLEXIBILITY**

GROUPING OBJECTIVES	*LOADING OBJECTIVES*
No Pooling	|← *Minimize number of movements* →| |← *Balance machine workloads* →|
Partial Pooling	|← *Minimize number of movements* →| |← *Balance machine workloads* →| |← *Fill tool magazines* →| |← *Maximize sum of operation duplications* →|
Total Pooling	|← *Minimize number of movements* →| |← *Fill tool magazines* →| |← *Maximize sum of operation duplications* →| |← *Unbalance workload per group* →| |← *Balance workload per group* →|

The objective of minimizing movements is applicable across all levels of machine pooling. This objective leads to greater aggregation of operations, and therefore, tends to decrease flexibility. However, productivity is likely to be higher (Stecke and Solberg 1981), especially in the absence of equipment and tool breakdowns. When machines are pooled and the alternative routes are used effectively, productivity can be further improved. For the case of total pooling, forming machine groups of unequal sizes and unbalancing the workloads allocated to these groups has been shown to yield high productivity (Stecke and Solberg 1985). However, the flexibility provided by this objective could sometimes be lower than that available under the objective of balanced group workloads for equal-sized groups.

Filling tool magazines and maximizing the weighted sum of operation duplications provide both operation and routing flexibilities. The latter objective could yield higher productivity and flexibility if the operation weights are selected judiciously. For example, for those part types that are constrained by their designs to have low operation flexibilities, additional routing flexibility can be provided through the duplication of operations. Stecke and Raman (1992) find that in systems with high CVOPT, it is desirable to provide alternative routes to as large a number of operations as possible. However, in systems with low CVOPT, it is preferable to duplicate operations with longer processing times.

TABLE 3

IMPACT OF GROUPING AND LOADING OBJECTIVES ON PRODUCTIVITY

<table>
<tr><th><i>GROUPING OBJECTIVES</i></th><th><i>LOADING OBJECTIVES</i></th></tr>
<tr><td><i>No Pooling</i></td><td>|<——— <i>Balance machine workloads</i> —>|
|<—<i>Minimize number of movements</i>—>|</td></tr>
<tr><td><i>Partial Pooling</i></td><td>|<—— <i>Balance machine workloads</i> ——>|
|<——— <i>Fill tool magazines</i> ———>|
|<—<i>Maximize sum of operation duplications</i> —>|
|<—— <i>Minimize number of movements</i> ——>|</td></tr>
<tr><td><i>Total Pooling</i></td><td>|<——————— <i>Fill tool magazines</i> ———————>|
|<————<i>Maximize sum of operation duplications</i> ———>|
|<—————— <i>Balance workload per group</i> ——————>|
|<————— <i>Minimize number of movements</i> —————>|
|<—————— <i>Unbalance workload per group</i> ——————>|</td></tr>
</table>

It may be desirable, even otherwise, to provide these redundancies for critical operations. Job shop studies conducted by Wayson (1965) and Neimeier (1967) indicate that routing flexibility is more efficient than operation flexibility for reducing system congestion. As noted by Conway et al. (1967), this is because providing alternative means of performing the same operation allows a busy (or inoperative) machine to be bypassed altogether, while altering the sequence of operations merely postpones the requirements of that machine. However, in both cases system performance improves relative to the system in which no such flexibility is available. Of course, using both flexibilities simultaneously can be best. Another important outcome of Wayson's and Neimeier's studies was that, with greater flexibility, the manufacturing time of a given job was found to be less sensitive to the dispatching rules used. Also, note that routing flexibility provides close adherence to the dominant operation sequence. It follows that maximum routing flexibility should be provided for operations that are part of the dominant operation sequence.

The above discussion indicates that while the decisions made at the design stage provide an upper bound on the levels of flexibilities achievable through an aggregate tradeoff between productivity and flexibility, they are affected substantially by the planning decisions as well. For these reasons, we disagree with Falkner's (1986) contention that once a manufacturing system is designed, its flexibility is completely specified.

4 COMPARISON OF CONVENTIONAL AND FLEXIBLE MANUFACTURING METHODS

Comparisons between conventional and flexible manufacture are difficult for two reasons. First, it is difficult to define a flexible system which is equivalent to a particular conventional system. Second, an FMS's flexibility depends upon how it is operated; for example, a system with many general-purpose machines can be very rigid, if the material transporters have to follow a fixed route or if the computer control does not permit real-time rerouting of parts. Therefore, comparisons are made here only at an aggregate level with respect to the potential flexibilities achievable under the two manufacturing methods.

For simplicity, it is convenient to consider the two extremes of high volume/low variety and low volume/high variety manufacture. In conventional manufacture, the former is associated with transfer lines and the latter with job shops. The classification proposed by Browne et al. (1984) provides four generic FMS types. For comparison purpose, we restrict consideration to a flexible transfer line (FTL) and a Type II FMS, which are "flexible" equivalents of a conventional transfer line and a job shop, respectively.

4.1 High Volume/Low Variety Manufacture

High volume/low variety manufacture requires low cost and efficient production of a few part types which have stable designs and demand requirements. Such systems include a Sundstrand FMS at the Caterpillar Inc. plant in Peoria, Illinois and the SCAMP system of the Colchester Lathe Company in Colchester, United Kingdom. The management of operations is made simple by following a dedicated mode of operation and by simplifying the planning and scheduling procedures through line balancing. Productivity considerations require that the dominant operation sequence be followed closely. Continuous monitoring of quality problems and breakdowns is essential for ensuring minimal deviations from the targeted production levels. These systems normally produce to stock. Safety stocks of finished goods are carried to decouple production from the actual demand to minimize variations in the production volumes.

Such systems would find high machine and routing flexibilities useful to augment their productivity. Machine flexibility facilitates a quick removal of broken tools, minimal part fixturing time, and rapid changeover between different part types on their variants. Routing flexibility is required to decrease the impact of machine breakdowns. An FTL meets these requirements much more efficiently than a transfer line. A greater use of general-purpose computer numerically controlled (CNC) machines, with the ability to download part programs quickly, enhances machine flexibility. Under a normal mode of operation, material movements in both FTLs and transfer lines follow a fixed route. However, in the event of a breakdown, parts can be rerouted in an FTL to bypass the inoperative machine. Also, in an FTL, it is easier to bypass an unnecessary machine without having to move through it. FTLs can also more easily allow pools of parallel machines, where a part may need to visit only one machine in the pool.

From medium- and long-term perspectives, these systems would find volume and expansion flexibilities useful. Since these systems entail large capital investments, their profitability can be susceptible to variations in production volumes. This is because it is also desirable to keep the cost of incremental investments as low as possible. Both FTLs and conventional transfer lines are expansion-inflexible. However, the use of more general-purpose equipment in an FTL may facilitate smaller capacity increases. No definitive statement can be made regarding the relative values of their volume flexibilities; they need to be evaluated on a case by case basis, since specific details of the part types and the equipment need to be considered. In general, they tend to be volume-inflexible.

Table 4 depicts the differences in the operating flexibility of the two systems. While, in general, both systems are designed for manufacturing new part types, the higher machine and process flexibilities of an FTL leads to a reduction in batch sizes. Minor changes in part type demands can therefore be accommodated more readily. Also, the lead time for the manufacture of new part types is substantially reduced.

TABLE 4

SYSTEM OPERATING FLEXIBILITY:

HIGH VOLUME/LOW VARIETY MANUFACTURE

PARAMETERS	*CONVENTIONAL TRANSFER LINE*	*FLEXIBLE TRANSFER LINE*
Number of Part Types	One or few	Few
Number of options	Few	Some
Components and spare parts market	No	Some
Production Volume	High	Medium to high
Ability to handle demand uncertainties	None	Little
Deliverability:		
Response time for existing part types	Quick	Quick
Lead time for new part types	Slow: months	Medium: weeks
Product mixes	No	Sometimes
Capacity needs	Fixed	Relatively variable
Nature of demand	Fixed	Fluctuating

Conventional transfer lines are likely to yield higher productivity, under normal circumstances, because of the use of dedicated special-purpose machines. However, the difference can be reduced by permitting longer hours of unmanned operations with the FTLs. Also, frequent runs of the various products in smaller batch sizes implies that finished goods inventories can be lower relative to the conventional transfer lines.

Table 5 presents the manufacturing issues for these two systems. Greater machine and process flexibilities of an FTL imply that more planning and scheduling issues need to be resolved in such systems. In particular, efficient control policies to handle breakdowns and reroute parts in real time are essential for effective unmanned operation.

TABLE 5

DESIGN, PLANNING AND SCHEDULING ISSUES:

HIGH VOLUME/LOW VARIETY MANUFACTURE

MANUFACTURING ISSUES	*CONVENTIONAL TRANSFER LINE*	*FLEXIBLE TRANSFER LINE*
DESIGN ISSUES:		
Types of machine tools	Dedicated	Automated
Material handling system	Conveyor	Conveyor or AGVs
Buffers	Small	Small
PLANNING ISSUES:		
Part type selection	No	Selects few part types at a time with medium requirements (10-100)
Machine grouping/ Operation duplication	No	Sometimes (can have pools of machines)
Determination of production ratios	No	Sometimes for mixed-model production
Loading problems	Once, during design	Easy, and at each changeover
SCHEDULING ISSUES:		
Part input sequence	No	Yes, identical to part type selection
Machine scheduling	No	No
Control policies to handle breakdowns	No	Yes

4.2 Low Volume/High Variety Manufacture

Low volume/high variety manufacturing systems usually produce to order. Some such systems are the Cincinnati Milacron FMS at LTV Vought Aerospace in Dallas, Texas, and Okuma in Nagoya, Japan. The key manufacturing considerations are meeting customer due dates with short lead times, and the ability to produce a large variety of products in varying, but small, order quantities. Productivity is not of critical importance, especially when the order quantities are extremely small. There are usually no dominant operation sequences, which implies extensive use of general-purpose equipment. Also, the CNCs or the MHS in an FMS may have volume and weight restrictions.

Since the economic viability of these systems is dependent in part upon their ability to manufacture a large variety of part types, achieving product flexibility is a major consideration in their design and operation. In comparison to a job shop, a Type II FMS possesses somewhat lower product flexibility because of the pre-production part programming and fixture design requirements. (However, process plans and fixturing methods for new part types have to be developed in a job shop as well.) For very small product requirements, these constitute a major portion of the manufacturing cost and lead time. However, much higher operation and routing flexibilities can be achieved in a Type II FMS because of the computer control of operations and the greater machine flexibility of the CNC machines owing to larger tool magazines and the ability to perform multiple operations with negligible changeover between operations. While limited routing flexibility can be achieved in a job shop through total or partial pooling of machines, it is wasteful, since by doing so, only a few operations can be duplicated. (One reason for not duplicating operations in a job shop is the large set-up time between consecutive operations and lack of machine versatility. Flow time for a batch may decrease, but machine utilization would also usually decrease, which would decrease other part types' production.) Also, in the absence of computer control, the ability of a job shop to adjust to the current state of the machines and reroute the parts automatically is low. An attempt to reroute parts manually could lead to future problems and bottlenecks.

In a Type II FMS, manufacturing lead times are reduced because of faster setups and the consequent reduction in waiting times. Therefore, work-in-process inventories are also lower. In addition, the higher routing and operation flexibilities available in a Type II FMS can provide additional short-term capacity to act as a buffer against demand and supply uncertainties (Schmitt 1984). Taken together, these factors may outweigh the reduced product flexibility of a Type II

FMS, especially if the part types are required in relatively large volumes.

Table 6 summarizes the impact of the differences in the *flexibilities* of the two systems on some key operating parameters. The greater product flexibility available in a job shop makes it more suitable for manufacturing very low volumes of a large number of part types. On the other hand, if the part types are required in medium volumes, a Type II FMS is likely to be more efficient.

TABLE 6

SYSTEM OPERATING FLEXIBILITY:

LOW VOLUME/HIGH VARIETY MANUFACTURE

PARAMETERS	*JOB SHOP*	*FMS TYPE II*
Number of Part Types	Maximum	Medium
Number of options	Several	Several
Components and spare parts market	Yes	Yes
Production Volume	Low	Medium
Ability to handle demand uncertainties	High	Somewhat less
Deliverability:		
Response time for existing part types	Slow	Medium
Lead time for new part types	Medium: weeks	Medium: weeks
Product mixes	High	Medium to high
Capacity needs	Unknown	Variable
Nature of demand	Variable	Fluctuating

A comparison of the manufacturing issues for these two systems is shown in Table 7. Since the machines in a Type II FMS are more versatile and more expensive, design stage decisions are more complex in this system. Greater machine versatility usually provides greater flexibility in assigning operations to machines, and, therefore, makes the loading problem much more complex.

Efficient and frequent resolution of this problem is a critical issue in a Type II FMS. Qualitative comparisons of the different types of flexibilities available under the conventional and flexible modes of manufacture are summarized in Table 8.

TABLE 7

DESIGN, PLANNING AND SCHEDULING ISSUES:
LOW VOLUME/HIGH VARIETY MANUFACTURE

MANUFACTURING ISSUES	*JOB SHOP*	*FMS TYPE II*
DESIGN ISSUES:		
Types of machine tools	Manual, partially automated	Automated
Material handling system	Manual, pallets	AGVs
Buffers	Large	Small or ASRS
PLANNING ISSUES:		
Part type selection	Yes	Yes
Machine grouping/ Operation duplication	Usually no	Yes
Determination of production ratios	No	Yes
Loading problems	No	Often
SCHEDULING ISSUES:		
Part input sequence	No	Yes
Machine scheduling	Yes	Yes
Control policies to handle breakdowns	Yes	Yes

5 STRATEGIC IMPLICATIONS OF FLEXIBLE MANUFACTURE

While the operational aspects, and economic planning and justification of flexible manufacture are attracting increasing attention, little is understood about how the medium- and long-term flexibilities of these systems impact the interdependence of product and process and their implications for the competitive stance of any firm. This technology is still evolving and, in general, only large companies have installed FMSs to date. Related to this issue is the lack of consensus among users on how they should be managed. In his study of FMSs operating in U.S., Japan, and Germany, Jaikumar (1986) notes that substantial differences exist in the modes of operation and in the underlying expectations from these systems. He attributes the earlier slow acceptance of flexible manufacture in the U.S. to managerial, rather than technical, reasons. Rosenthal (1984) and Ettlie and Reza (1992) support this view. We believe that the state of the economy was a significant factor; FMSs are expensive and there was a recession at that time.

TABLE 8

LEVELS OF AVAILABLE FLEXIBILITIES

	CONVENTIONAL MANUFACTURE		*FLEXIBLE MANUFACTURE*	
TYPE OF FLEXIBILITY	*TRANSFER LINE*	*JOB SHOP*	*FLEXIBLE TRANSFER LINE*	*TYPE II FMS*
Machine	Low	Low	High	High
Process	Low	Medium	Medium	High
Operation	Low	Medium	Low	High
Routing	Low	Medium	Low, as needed	High
Volume	Low	Low	System dependent: higher	System dependent: lower
Product	Low	High	Low	Medium
Expansion	Low	Medium	Somewhat low	Medium

In this section, we examine how flexible manufacturing impacts and changes the product-process matrix developed by Hayes and Wheelwright (1979a, 1979b) as well as the model of product and process innovations presented by Utterback and Abernathy (1975).

5.1 The Product-Process Matrix Reviewed

Hayes and Wheelwright (1979a, 1979b) showed that, just as a product traverses its life cycle through the initial stage of low volumes and less standardization to the final stage of high volume and high standardization, the process also evolves through the types of flow characterized as jumbled, batch, assembly line, and continuous. Therefore, a product-process matrix has been defined, in which the different stages of the product and process life cycles are plotted along two axes. A balanced manufacturing strategy requires positioning along the diagonal of this matrix.

Hayes and Wheelwright's studies and insights were, however, based on conventional manufacturing methods. The discussions here indicate that, for a given set of part types, a firm sometimes has a choice between conventional and flexible modes of manufacture. For a given level of flexibility, it is possible to map conventional manufacturing methods into their "flexible" counterparts. To capture the impact of flexible manufacture, it is useful to include a third dimension of flexibility to the product-process matrix as shown in Figure 1.

INSERT FIGURE 1 HERE

The use of special-purpose conventional machines without computer control provides the lowest level of flexibility, while general-purpose conventional machines represent the next higher level of flexibility. Stand-alone numerically controlled (NC) machines represent a subsequent stage in which greater flexibility is achieved through paper tape part programming and greater machine versatility. CNC and direct numerically controlled (DNC) machines represent stages of increasing process flexibility as more hardware comes under computer control. An FMS, in which the machines well as the movement of parts are centrally controlled, defines the maximum level of flexibility attainable.

As the technological evolution progresses, the extent of achievable flexibility is likely to increase further. For example, three major constraints of most existing FMSs are the lack of flexible tool delivery, part fixturing systems, and flexible planning and scheduling software. The variety of part types which can be manufactured simultaneously is limited by the capacities of tool magazines and the need for dedicated fixtures for individual part types. While some automatic tool delivery systems exist today (for example, Yamazaki Mazak in Japan offers tool magazine delivery systems although this option is rarely purchased), there is a need for more development work in this area (Tomek and Zeleny 1984). Similarly, there is ongoing work in designing universal fixtures (Yingchao et al. 1983) that can accommodate different part geometries. If these developments yield the expected results, substantial increases in product flexibility can be affected. This dimension highlights the fact that flexibility decisions are not all or nothing; varying degrees of flexibilities are available.

In a manner similar to the dimensions of product and process, a learning curve can be associated with the dimension of flexibility as well. While this learning is only marginal at the machine level since they are under programmed control, the above studies indicate that significant learning is involved for part programmers and software programmers, maintenance personnel, production schedulers, and shop supervisors. Also, this learning is not a function only of the cumulative output of any one product; it is also dependent upon the number of different products manufactured and the total time the system has been operational. It is also a function of the degrees of automation and the extent to which automation is a new experience for the firm.

If we superimpose the third dimension of flexibility on the process dimension, we can qualitatively represent the impact of flexible automation on the production flexibility achieved by a given system, as shown in Figure 2. This figure shows the increase in the overall production flexibility as we move from a job shop that is suitable for low volume, high variety manufacture to a Type II FMS that is more appropriate for medium volume, medium variety production. However, production flexibility drops continuously as we move towards FTLs and subsequently towards assembly and transfer lines that are geared towards high volume, low variety manufacture.

INSERT FIGURE 2 HERE

The production flexibility of a job shop with conventional machines is mainly attributable to its high product flexibility. As the job shop progressively incorporates NC, CNC, and DNC machines, its production flexibility increases because of greater machine, process, operation and routing flexibilities. A Type II FMS represents the highest level of production flexibility achievable under current technology. With the increasing use of predetermined operation sequences and fixed-route material handling devices for few products, there is a reduction in operation, routing, process and expansion flexibilities which results in the lower production facility of an FTL. A transfer line, in which the machines are also dedicated to a given set of products, yields the lowest level of production flexibility.

5.2 Interdependence of Product and Process Innovations

Investigations of Utterback and Abernathy (1975) led to models of product and process innovations. In response to changing competitive conditions, a product evolves through stages of performance maximization, sales maximization, and finally cost minimization. In a related manner, a process progresses through three stages which Utterback and Abernathy call uncoordinated, segmental, and mechanistic.

Therefore, a meaningful analysis of a manufacturing system can involve addressing a "productive unit," which comprises a product (or a set of products) and the associated manufacturing process (see also Kantrow 1980). Skinner's (1974) emphasis on the necessity to focus the manufacturing operations of a firm on the needs of a specific set of products and market can be seen to be a generalization of this concept.

However, the definition of a productive unit implies strong interrelationships between product and process, especially in the later stages of development. While this is valid for conventional manufacture, flexible manufacture tends to undermine this interdependence. Higher flexibility levels require the use of general-purpose equipment, and only the part program distinguishes one part type from another. The desire towards increasing volume and product flexibilities can be interpreted as an attempt to standardize the process (comprising the machines, the material handling system, and the computer architecture) so that the same system can be used to accommodate greater volume and product variations. A firm now has the option of controlling the product-process interdependence through a specific choice of flexibility.

In view of the above arguments, providing a proper focus to a plant's operations implies determining the required flexibility as well. In his seminal work, Skinner (1974) argues the need for distinguishing between general- and special-purpose equipment, long- and short-run operations, high and low tolerances, new and old products, stable and changing designs, products with long and short lead times, and jobs with high and low skills. Production flexibility tends to blur this distinction. Programmability and versatility of machines can make special-purpose machines redundant. Increasing part type variety could render long-run operations expensive, while low setup times and setup costs obviate the need for the special-purpose machines. Shorter runs imply a reduction in lead time as well. In an environment of rapidly changing consumer preferences and requirements, the distinction between stable and changing designs as well as between old and new products can be merely marginal. Improved capabilities should reduce the need to distinguish machines on the basis of their ability to maintain dimensional tolerances (although technology in advanced metal-cutting is not developed enough to allow this). And finally, increased flexible automation leads to low requirements of operational skills and high "knowledge" skills such as part programming and maintenance that are relatively independent of the part types being manufactured.

However, higher levels of flexibility may not be desirable for a firm if the impact on productivity is unfavorable or if the requirement of strict control on raw material supplies is untenable. For a multi-product firm, it may be advantageous to operate different manufacturing sections at varying levels of flexibility. Flexible manufacture expands the set of available alternatives. It also makes the problem of achieving proper manufacturing focus considerably more complex.

6 DISCUSSION AND FUTURE RESEARCH SUGGESTIONS

The arguments presented in this study have major implications for the justification and operation of flexible manufacturing systems. First, FMS planning decisions are important. Since the objectives used in the production planning problems significantly impact system flexibility and productivity, the output depends not only on the system hardware but on the planning decisions as well. The same system can be operated in different modes to yield different output levels. Second, as product flexibility increases, there is less interdependence between product and process and it becomes harder to translate capacity into measurable output quantities. While these two characteristics exist to a limited extent in a job shop too, they are less significant because of the smaller investment magnitudes involved.

This study poses several research problems. Three are described below. The analysis of short-term flexibility indicates that operation and routing flexibilities can significantly reduce manufacturing lead times. For a given system and a given set of part types, how should these potential flexibilities be allocated among individual part types to minimize the total lead time? The solution to this problem requires the development of quantifiable tradeoffs between the routing and operation flexibilities provided for the individual part types. These tradeoffs need to consider the potential operation flexibilities of the part types, the operation processing times, the total number of operations, and the tool magazine capacities.

A second problem deals with the location and uses of an FMS within a multi- product, multi-echelon production system. Manufacturing flexibility is an alternative to other means, such as carrying safety stocks, for mitigating demand uncertainties. However, it requires tight control over raw material supplies. If we redefine suppliers as the set of upstream machining centers and buyers as the set of downstream machining centers, how can the arguments presented in this study be used to define and locate an FMS within a factory-wide manufacturing system? How will it impact the mix of other manufacturing alternatives? The solutions to these problems will help to facilitate the introduction of FMSs considerably.

The impact of flexible manufacture on the competitive position of a firm also requires further investigation. Greater product flexibility vis-a-vis conventional mass production manufacturing methods indicates that scale economies may be reduced. While, in itself, this would tend to lower entry barriers, requirements of high initial investment and appropriate managerial skills may prove to be major deterrents to entry. Those firms which have invested heavily in developing the necessary manufacturing skills and computer expertise may have already created strong entry barriers. Since this technology is recent, future developments will be substantially affected by the requirements of the initial users. Therefore, first-mover advantages are likely to exist. However, as there are at least two sources of this technology, namely, machine tool and computer industries, greater discontinuity in its evolution is possible. The FMS users need to guard themselves against the threat this may pose.

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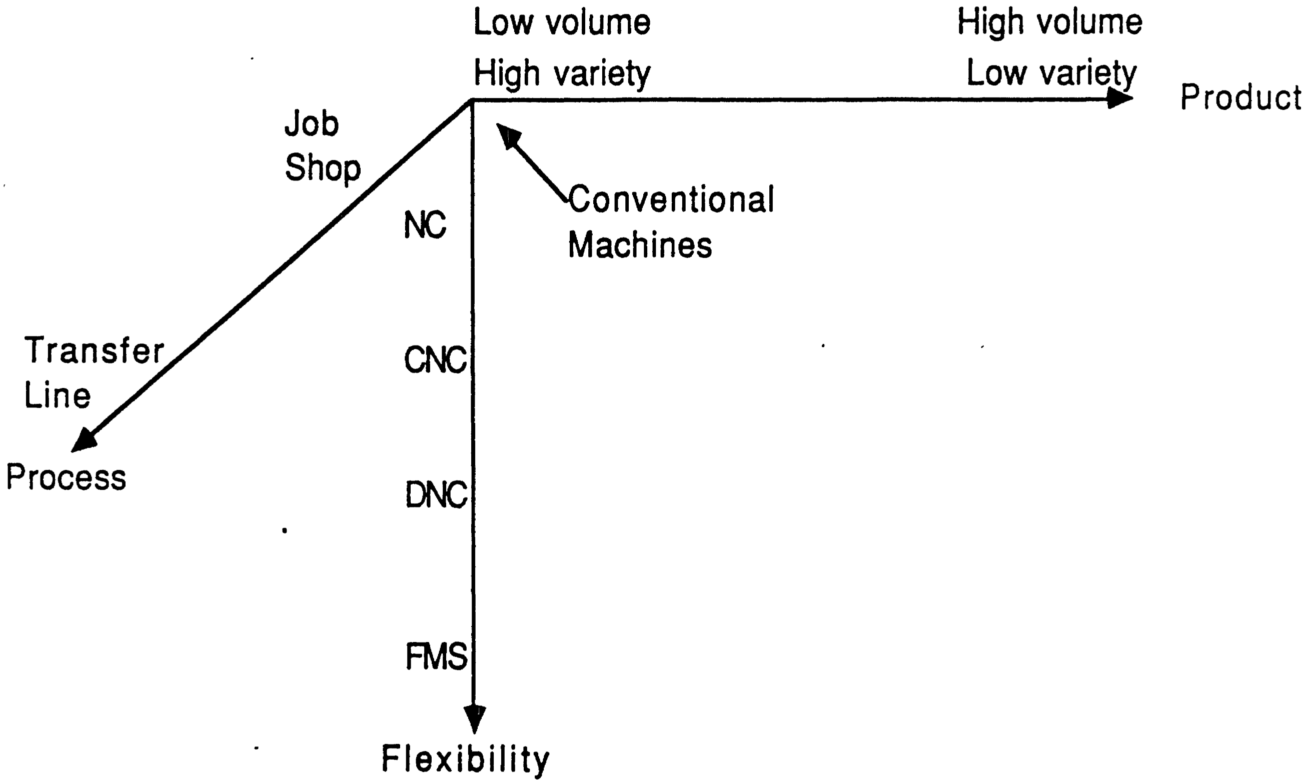

Figure 1: Product–Process–Flexibility Matrix

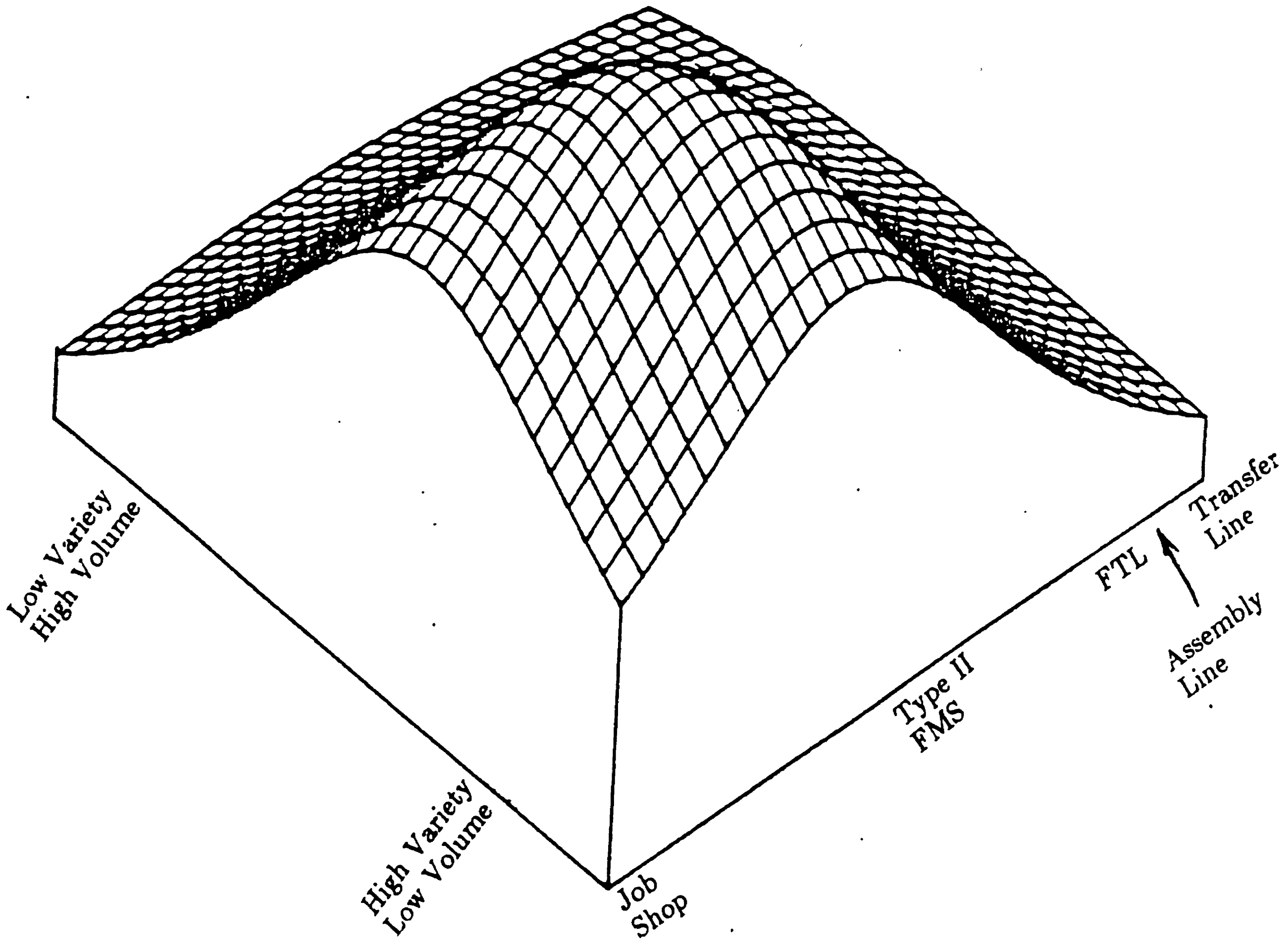

Figure 2: Process Dependence of Production Flexibility