Division of Research
Grdauate School of Business Administration
The University of Michigan

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PRODUCTION FLEXIBILITIES AND THEIR IMPACT ON MANUFACTURING STRATEGY

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Kathryn E. Stecke
Narayan Raman

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.

This paper analyzes the complex relationships between flexibility and productivity for both conventional and flexible manufacturing systems. Also, from a long-term strategic perspective, the impact of production flexibility on product-process interdependence is investigated. Achieving manufacturing focus with flexible automation requires consideration of the dimensions of flexibility in addition to the dimensions 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) (see, for example, Browne et al. [1984], Carter [1986], Chatterjee et al. [1984], Falkner [1986], Gerwin [1982], and Jaikumar [1984]) indicate that there are other, process-oriented dimensions of production flexibility as well. The differences in the relative efficiencies of conventional and flexible manufacturing methods could be largely attributed to the differences in their process flexibilities. However, this does not imply that, for any system, the product- and process-oriented dimensions of flexibility are independent of each other. On the contrary, the limitations of process flexibility determine the maximum achievable product-oriented flexibility for a given system. Falkner [1986] underscores this point by noting that researchers who have ignored the processing limitations of any system tend to over-emphasize 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, etc. While, for a given system, this flexibility is dependent in part upon its design, we show that the realized short-term flexibility is determined to a large extent by pre-production setup as well. We suggest guidelines for the measurement of short-term flexibility. Subsequently, we investigate the impact of short-term flexibility on system productivity and present a comparison of conventional and flexible manufacturing methods for the two extremes of high volume/low variety and low volume/ high variety manufacture.

From a long-term perspective, we 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 manufacture, 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 different types of flexibilities that are potentially available in a manufacturing system, and the FMS planning problems. Section 3 discusses the operational implications of production flexibility. In Section 4, we study the impact of flexibility on the productivity of any system. We also compare conventional and flexible manufacturing methods with respect to the various types of flexibilities as well as several manufacturing issues. We discuss the implications of any particular objective, selected to be used in formulating the FMS production planning problems, for the short-term flexibility of the system. 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 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 we subsequently discuss.

2.1 Classification of Production Flexibilities

Several researchers have proposed different, but somewhat similar, schemes 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*: 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 which 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*: 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*: is the ability of the system to maintain its efficiency in the face of 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 (see Stecke [1983]).

4. *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*: 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*: represents the ability of the given manufacturing system to changeover efficiently from a particular set of part types to a different set. Product flexibility requires, in addition to machine flexibility, efficient and automated planning and control procedures.

7. *Expansion Flexibility*: relates to the manufacturing system's capability to be built and expanded modularly. It is a function of 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*: is the cumulative result of the seven previous flexibilities. It is a measure of the system's efficiency in manufacturing its universe of part types.

Production flexibility is required for some particular systems that can have either high or low production volumes, and for high and low varieties of products. The demands for individual products occur in varying volumes for the majority of manufacturing firms. For example, an automobile manufacturer faces high volume demands for vehicles (however, the required volumes for each model/color/option combination may be quite small), while spare parts are sometimes required in smaller volumes. For the firm to be production flexible, it should be able to meet both types of requirements efficiently. Production efficiency implies low (competitive) manufacturing cost and high service levels, measured in terms of product quality and short manufacturing lead times.

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 face of increasing product demand. Carter [1986] has proposed 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. Stecke defines five palling problems – i) Part Type Selection Problem, 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 Problem, which involves partitioning machines into groups, each group comprised of identically tooled machines; iii) Production Ratio Problem, which requires determining the ratio in which different part types will be manufactured concurrently; iv) Resource Allocation Problem, which assigns resources such as pallets, fixtures, etc. to the various part types; and v) Machine Loading Problem, which allocates operations and the cutting tools to individual machine groups subject to the systems'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 can be an assembly of several *parts*. Parts with the same physical and performance characteristics belong to the same *part type*.

3. COMPONENTS OF SHORT-TERM FLEXIBILITY

In the short term, production flexibility implies the ability to resolve operational uncertainties efficiently, many of which arise in real time at the scheduling and control level. For a given set of part types and a given manufacturing system, the interdependence between a part type and its associated process provides two approaches to determining the actual short-term flexibility available in the system.

The part type-oriented approach measures short-term flexibility in terms of the part types by considering the sequence of operations required to fabricate them. The system hardware, which consists of the machine tools as well as the material transport system and the computer architecture, specifies the constraints which can limit this flexibility. According to this approach, short-term flexibility can be expressed in terms of the *operation* and *routing flexibilities* of the different part types.

An alternative process-oriented approach measures short-term flexibility in terms of the system hardware, given the operations required for manufacturing a particular set of part types. Short-term flexibility can then be expressed in terms of the *machine* and *process flexibilities*.

Between the two approaches, the process-oriented approach facilitates easier understanding of the machining limitations and, therefore, highlights those aspects of the system hardware which need to be modified for increasing short-term flexibility. However, the part type-oriented approach is amenable to a more convenient measurement. In addition, as we shall see later, it provides an easier understanding of how the part type design and the solutions to the FMS planning problems impact the availability of short-term flexibility. Therefore, in most of the remainder we shall follow the part-oriented approach to measuring actual short-term flexibility available in a system with the understanding that, in the short term, specifying *machine* and *process flexibilities* specifies *operation* and *routing flexibilities*, and vice-versa. However, *machine* and *process flexibilities* have implications for the medium and long terms as well, since they impact *product*, *volume*, and *expansion flexibilities* too.

In a manner analogous to that followed by Chatterjee et al. [1984], each part type can be represented by an operation graph, which depicts the precedence relationships among the operations required for manufacturing that part type. Figure 1 provides an example of such a part type operation graph.

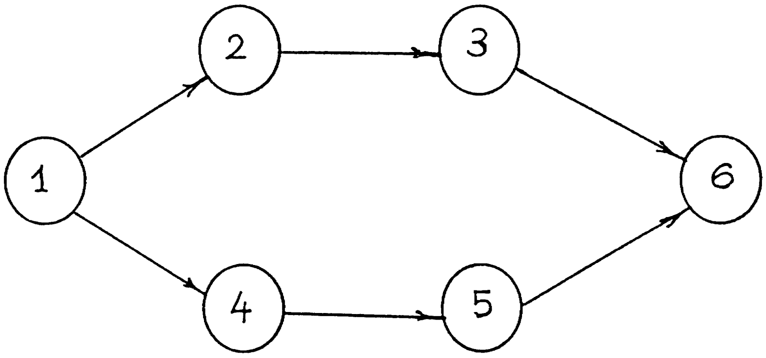

Figure 1 : Example of a Part Type Operation Graph

The design of a part type specifies the upper bound on its *operation flexibility*, which can be expressed in terms of the number of alternative operation sequences which can be followed for manufacturing that part type. Denoting this upper bound for a given part type *i* by its potential operation flexibility POF_i, we note that POF_i is independent of the manufacturing system. For the example given in Figure 1, POF_i is 6.

The *operation flexibility* OF_i of part type i measures the extent to which POF_i can be realized in a given system. Alternative operation sequences usually follow different sequences of material removal, and consequently, have different processing times. In practice, considerations of efficient material removal determine the dominant operation sequence, which has the shortest total processing time among all of the alternative operation sequences.

For achieving high *operation flexibility*,

1) the number of alternative operation sequences realizable in a given system should be high, and
2) the total processing times of the alternative operation sequences should be comparable to that of the dominant operation sequence.

To illustrate this point, consider two manufacturing systems, A and B. System A provides four alternative operation sequences, which yield total processing times of 10, 12, 14, and 16 minutes, respectively. System B provides two alternative sequences which have total processing times of 10 and 12 minutes, respectively. Clearly system A is more *operation* *flexible* than system B. Instead, if system B provided four sequences with processing times of 10, 12, 24, and 30 minutes, respectively, system A would still be more *operation flexible* because of the greater efficiencies of system A's alternative operation sequences.

The *operation flexibility* of a given part type *i* can therefore be expressed in the following functional form:

$$OF_i = f\left(N_i * tp_i \Big/ \sum_{j=1}^{N_i} tp_{ij} \right)$$

where,

N_i = *the number of alternative operation sequences possible in the given system,*

tp_{ij} = *total manufacturing time (including processing, setup, and travel times) for operation sequence j, and*

tp_i = $min_j\ [tp_{ij}]$.

The *routing flexibility* RF_i of part type *i* for a given operation sequence is a measure of the number of alternative machine visitation routes possible in a given system. Unlike OF_i, RF_i is independent of the part type design. RF_i is determined at the system design stage, through the selection of machines, etc., and at the planning stage, by the assignment of operations to different machines. For a given system configuration, which includes the machines, the material handling system, and the operation assignments to machines, and for a given operation sequence, RF_i is a function of:

1. the number of possible alternative routes, and
2. the efficiency of each route (as measured in terms of the total processing time), and the utilization level and the reliability of each machine along that route.

Clearly, to achieve high values of RF_i, it is not enough merely to have a large number of alternative routes. If the alternative routes require much larger processing times (with respect to the most efficient route), it can be argued that they are no longer desirable and, therefore, do not contribute to system flexibility. Similarly, if the alternative routes require the use of machines which are heavily utilized or which are highly unreliable, the likelihood that any part would be dispatched through them in real time is considerably reduced.

Both OF_i and RF_i are influenced by decisions made at the system design level, such as the number and types of machines and the selected material handling system. General-purpose machines of comparable efficiencies and a variable-route transport system would favor higher values of OF_i and RF_i. Also, the shorter the response time to detect the need and arrange for rerouting, the greater is the realized short-term flexibility. However, resource limitations, such as the machine tool magazine capacities and numbers of fixtures of different types, for example, require tradeoffs among the *routing flexibilities* that can be provided to different part types. If the *operation flexibilities* are constrained because of inherent design limitations for certain parts, it is necessary to augment them by providing *routing flexibilities.* (However, this does not imply that these two flexibilities are totally interchangeable or that they are equally efficient.) The decisions made at the planning level (such as the aggregation of operations into operation sets, assignment of operation sets to machines, machine pooling, and duplication of operations) reflect these tradeoffs and help to determine the realized system flexibility. These issues are discussed in greater detail in Section 4.

4. THE IMPACT OF SHORT-TERM FLEXIBILITY

The manufacturing system's ability to cope with unforeseen events in the short term, and therefore, 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, its productivity, measured in terms of the output rate, is lower, in particular, when it is using its flexibility to cope with random events. Although such an inverse relationship between flexibility and productivity may be generally true for conventional manufacturing methods, it does not usually carry over to flexible manufacture.

For a better understanding of how the choice of flexibility affects productivity in an FMS, in Section 4.1 we identify those factors which contribute to the flexibility of an FMS, and subsequently, study how these factors impact system productivity. It turns out that the FMS planning decisions play a major role in determining the choice of short-term flexibility and productivity. In Section 4.2, we compare conventional and flexible manufacturing methods for both high volume/low variety and low volume/high variety manufacture. Finally, in Section 4.3, we investigate how flexible manufacture impacts the several alternative ways of providing buffers against supply and demand uncertainties in a multi-echelon production system with dependent demand.

4.1 Impact of Flexibility on Productivity

To judge 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

PRODUCTIVITY AS A FUNCTION OF FLEXIBILITY

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

1. Duplication of machines and/or operations: *routing flexibility* is achieved by providing alternative routes either through machine pooling (see 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 if

they are used actively 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 2 minutes using only one route while system D provides two routes simultaneously, each with a processing time of 4 minutes. Though the two routes in system D are individually less efficient than the route in system C, the overall productivity of system D is the same as that of system C. In addition, it is more robust in the event of breakdowns. However, this reasoning is valid only if the batch size of each part type 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. In the limiting case of unit batch sizes, the flexibility provided by alternative routes clearly 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 are usually greater than those for fixed-route transporters, such as conveyors (see Stecke and Browne [1985]), part in-process times are correspondingly increased. On the other hand, with the more flexible material handling system, a part may travel directly to its next machine, rather than potentially traversing the entire length of the conveyor, to increase productivity.

3. Use of general-purpose machines: if the system is run in a fixed manner for the repetitive production of few parts with known and constant requirements, special-purpose machines can be dedicated to specific tasks to reduce machining times. Such machines are also likely to be less expensive for high production volumes. In addition, the use of dedicated special-purpose equipment usually simplifies the 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 "scattering" and 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 simultaneously (see Stecke and Solberg [1981]). However, *operation flexibility* provides a capability which should be used only when needed to increase the productivity.

5. Ease of real-time scheduling: while having the provision of flexibility complicates solution procedures for the *production planning problems*, the scheduling of operations 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, in the presence of *operation and routing flexibilities*, system performance is not overly sensitive to the quality of the scheduling rule used. 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: we had shown in Section 3 that one of the ways to increase routing flexibility is to deliberately underutilize machines. When machine utilizations are low, parts can be re-assigned 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, the long-term productivity is adversely affected.

Productivity gains in FMSs are also obtained through a greater number of hours of unmanned operation and through often 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 up-to-the-minute information.

This discussion indicates that it may be 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. As mentioned earlier, the loss in productivity can be mitigated if the batch sizes 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 (see Stecke and Kim [1986]).

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 also 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 sizes. 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.

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 →|

FLEXIBILITY ⟶

The first 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. 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 (see

TABLE 3

IMPACT OF GROUPING AND LOADING OBJECTIVES ON PRODUCTIVITY

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

PRODUCTIVITY ———→

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.

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 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 (see 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.

Duplicating operations, and to a lesser extent filling tool magazines, provide the possibility of allocating *routing flexibilities* selectively to individual part types. For those part types which are constrained by their designs to have low *operation flexibilities*, additional *routing flexibility* can be provided through the duplication of operations.

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 as a corollary that maximum *routing flexibility* should be provided for operations that are part of the dominant operation sequence.)

The above discussions indicate 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.

We shall now investigate how design and planning issues impact the productivity and flexibility considerations in both conventional and flexible manufacturing.

4.2 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 first 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.

4.2.1 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. 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 or 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 movement 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.

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 would 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 few 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 accomodated more readily. Also, the lead time for the manufacture of new part types is substantially reduced.

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 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	High or medium
Ability to Handle Market Uncertainty	None	Little
Deliverability:		
Response Time for Existing Part Types	Quick	Quick
Lead Time for New Part Types	Slow: months	Medium: weeks
Mixes	No	Sometimes or no
Capacity Needs	Fixed	Relatively variable
Nature of Demand	Fixed	Fluctuating

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.

4.2.2 Low Volume/High Variety Manufacture

Low volume/high variety manufacturing systems usually produce to order. 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

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
Buffers	None	Small
PLANNING ISSUES:		
Part Type Selection	No	Selects one part at a time in medium batches (10–100)
Machine Grouping/ Operation Duplication	No	No
Determination of Production Ratios	No	No
Loading Problems	Once, during design	Easy, and at every changeover
SCHEDULING ISSUES:		
Part Input Sequence	No	Identical to part type selection
Machine Scheduling	No	No
Control Policies to Handle Breakdowns	No	Yes

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.

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 in 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. 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	TYPE II FMS
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 Market Uncertainty	High	Somewhat less
Deliverability:		
Response Time for Existing Part Types	Slow	Medium
Lead Time for New Part Types	Medium: weeks	Medium: weeks
Mixes	Medium	Medium
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	TYPE II FMS
DESIGN ISSUES:		
Types of Machine Tools	Manual	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	Very often
SCHEDULING ISSUES:		
Part Input Sequence	Yes	Yes
Machine Scheduling	Yes	Yes
Control Policies to Handle Breakdowns	Yes	Yes

TABLE 8

LEVELS OF AVAILABLE FLEXIBILITIES

TYPE OF FLEXIBILITY	CONVENTIONAL MANUFACTURE		FLEXIBLE MANUFACTURE	
	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	System dependent (can be medium-high)
PRODUCT	Low	High	Low	Medium
EXPANSION	Low	Medium	Somewhat low	Medium

4.3 Alternative Means of Controlling External Uncertainties

The flexibility comparisons of Table 8 motivates us to investigate how flexible manufacturing methods impact the various means of facing external uncertainties in conventional manufacture. For clarity in presentation, we focus on systems in which the majority of manufactured parts have dependent demands.

Whybark and Williams [1976] categorize external uncertainties into product demand and raw material supply uncertainties. Each of these are further classified into quantity and timing uncertainties. They discuss the alternative buffering mechanisms of either providing safety stocks or safety lead times. Schmitt [1984] suggests two other methods – providing surplus capacity and replanning (in a manner similar to net change material requirement planning systems). Whybark and Williams's study indicates that safety stocks are preferable for smoothing quantity uncertainties, while safety lead times are more efficient for meeting timing uncertainties. Schmitt's study shows the superiority of surplus capacity in achieving a given service level with minimum inventory.

As discussed in Section 4.2, the greater *machine* and *process flexibilities* available in FMSs translate into much shorter manufacturing lead times, which implies that productive resources can be committed at a later point in time, when the uncertainties are reduced. Therefore, the levels of safety lead times can be reduced. For the same demand uncertainty, shorter manufacturing lead times also imply lower finished goods and WIP safety stock levels. The magnitude of dollar savings would depend upon the commonality in the processing requirements of various parts and the degree to which *machine* and *process flexibilities* are achieved in the system.

However, flexible manufacture cannot do much to mitigate supply uncertainties. On the contrary, system performance can be even more susceptible to these uncertainties. It is important to note that the flexibility of an FMS (and the consequent reduction in lead times) can be realized only when the raw material deliveries are reliable. The available options to improve delivery are: i) increasing the number of suppliers; ii) having larger safety stocks and/or safety lead times; iii) closer control of suppliers' operations (a strategy followed by Toyota); and iv) greater raw material standardization. However, since carrying raw materials is cheaper than carrying WIP and finished goods, the overall inventory holding costs are likely to be much lower in flexible manufacture.

Surplus capacity can be provided in FMSs through the duplication of operations and machine pooling. Increases in demand requirements can be accomodated by dispatching parts through alternative routes. Note that even without machine pooling, the versatility of machines and their larger tool magazine capacities can be used for duplicating operations. Therefore, the capacity of the system with respect to different part types can be used interchangeably. The provision of similar redundancies in conventional systems is much less useful and/or efficient for the reasons described in Section 4.2.

Schmitt's study found contingent replanning to be the least efficient alternative because of its inherent nervousness. The impact of nervousness in flexible manufacture could be even more disruptive, because of the significance and the complexity of the FMS planning problems. Besides, retooling the system can sometimes be time-consuming. However, retooling cannot be avoided because tools wear and break and because FMSs are operated in an integrated and tightly-controlled manner. Changes made in any one machine are likely to affect the productivity and flexibility of the other machines as well.

On balance, we agree with Carter (1986) that flexible manufacturing alone would not resolve uncertainties totally. Safety stocks, safety lead times, provision of surplus capacity, and contingent replanning would still be useful or necessary. However, the mix of these alternatives can be altered, thereby leading to savings in the cost of holding unutilized assets.

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 only a few 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 W. Germany, Jaikumar [1984] notes that substantial differences exist in the modes of operation and in the underlying expectations from these systems. He attributes the slow acceptance of flexible manufacture in the U.S. to managerial, rather than technical, reasons. Rosenthal's [1984] survey supports this view.

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] argue 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 a positioning along the diagonal of this matrix.

Hayes and Wheelwright's studies were, however, based on conventional manufacturing methods. The discussions here indicate that, for a given set of part types, a firm 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 add a *third dimension of flexibility* to the product-process matrix as shown in Figure 2.

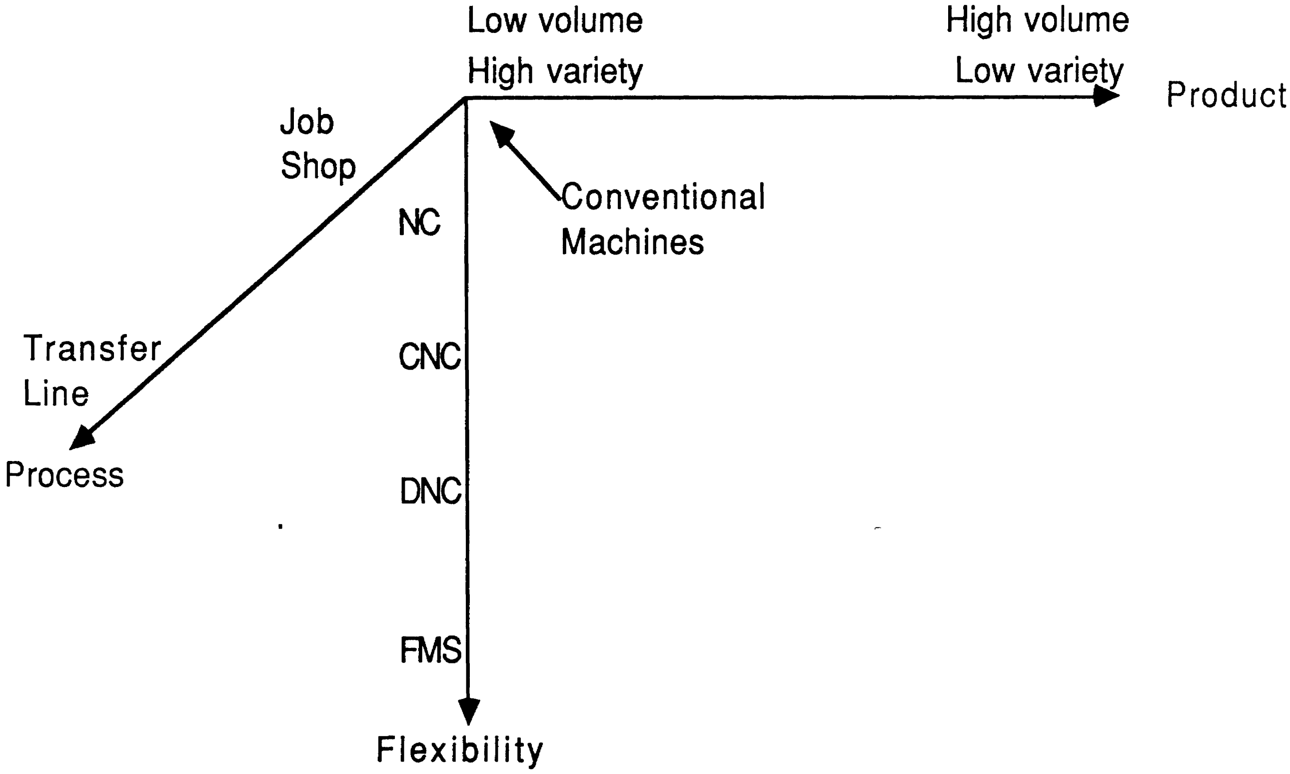

Figure 2 : Product-Process-Flexibility Matrix

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 operations come under direct computer control. An FMS, in which the machines as well as the movement of parts are centrally controlled, defines the maximum level of flexibility (of certain types) attainable.

As the technological evolution progresses, the extent of achievable flexibility is likely to increase further. For example, two major constraints of most existing FMSs are the lack of flexible tool delivery and part fixturing systems. 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. However, development work is being undertaken for ensuring automated tool supply (see, for example, Tomek and Zeleny [1984]), and in designing universal fixtures (see Yingchao et al. [1983]) that can accomodate 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.

The investigations of Ettlie [1984], Jaikumar [1984], and Rosenthal [1984] indicate that, 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 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 3.

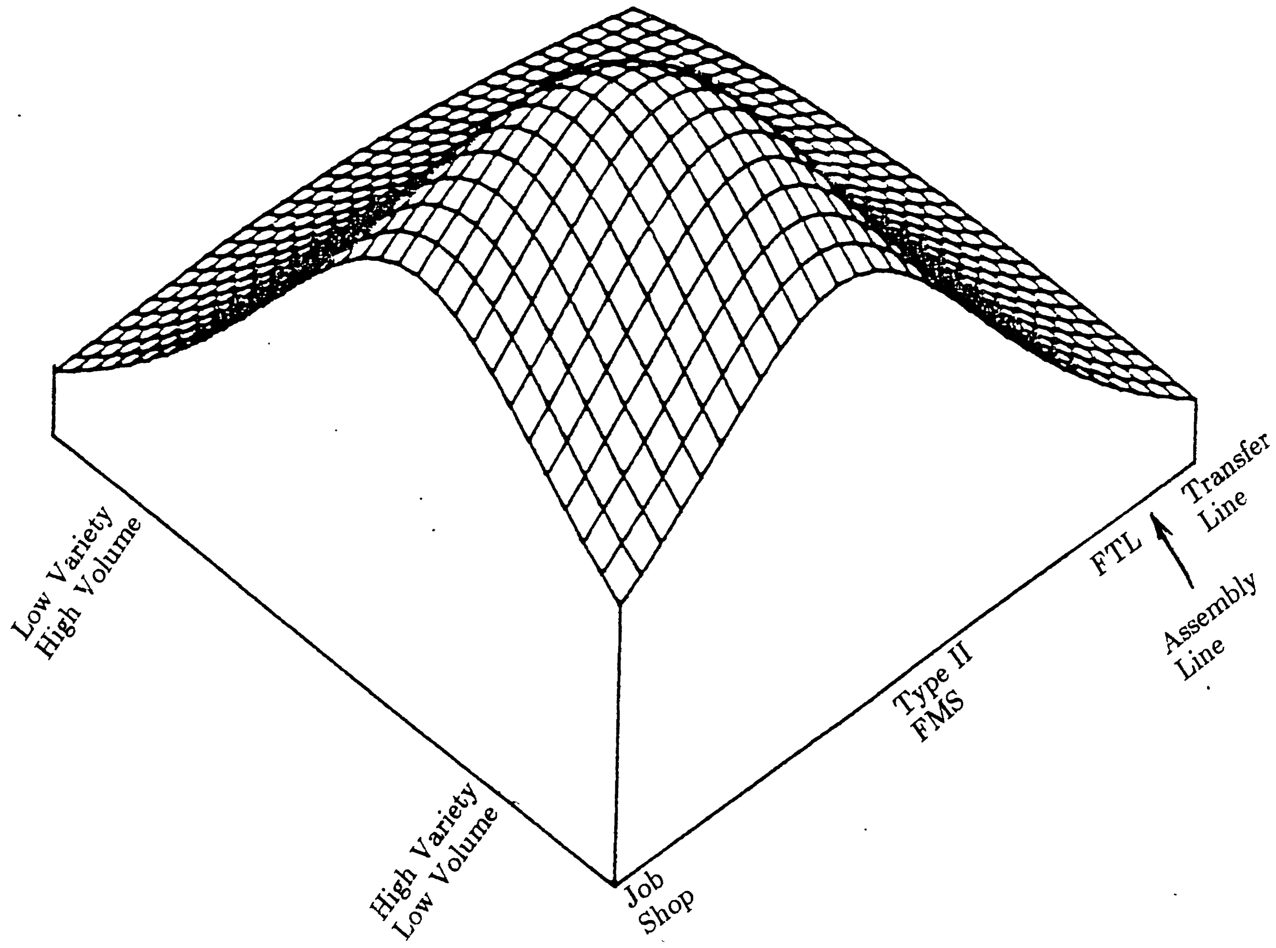

Figure 3 : Process Dependence of Production Flexibility

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 fewer products, there is a reduction in *operation, routing, process* and *expansion flexibilities* which results in the lower *production flexibility* 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 The Interdependence of Product and Process

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 involves 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 may be 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 accomodate 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. Because of this consideration, some of Skinner's (1974) arguments (which are based on conventional manufacture) may need to be reconsidered. Skinner states that it is inappropriate to combine 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. With an increase in ***production flexibility***, the distinction between these extremes is diminished. 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 times 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 dimension 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 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 hence 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. Two 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 of an FMS within a multi-product, multi-echelon production system. In Section 4.3, we showed that 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 quite 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 constantly against the threats this may pose.

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