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FMS PLANNING DECISIONS, OPERATING FLEXIBILITIES AND SYSTEM PERFORMANCE

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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 performance needs to be better understood in order to evaluate the desirability of flexible automation for any company.

This paper considers the role of system planning in determining operating flexibility and system performance. We argue that while the overall flexibility of any system is constrained by the decisions made at the system design stage, the realized short-term flexibility depends significantly upon the planning decisions made during pre-production setup. Different planning objectives lead to different system configurations, and simultaneously yield varying levels of process-oriented flexibility. We also present a scheme for classifying the different types of flexibilities, and use this scheme to also present an illustrative comparison of conventional and flexible manufacturing methods for the two extremes of high volume/low variety and low volume/high variety manufacture. We observe that the inverse relationship that exists between flexibility and productivity for conventional manufacturing systems does not necessarily carry over to FMSs.

1. Introduction

Considerations of improved productivity and production flexibility have assumed major importance in the design and operation of manufacturing systems. While global competition has clearly underlined the need for enhanced productivity, shorter product life cycles and greater product proliferation and market fragmentation indicate that manufacturing flexibility is essential 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. However, investigations of flexible manufacturing systems (FMSs) highlight the need to address the process-oriented flexibility as well. Indeed, the interdependence of product- and process-oriented flexibilities is well recognized now, as is the need to address these two aspects of manufacturing flexibility along multiple dimensions (see, for example, Gerwin 1987). 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.

While previous research has addressed the role of system hardware and the supporting computer architecture (Sethi and Sethi 1990), as well as the need for a human infrastructure to support the flexible manufacturing processes (Gerwin 1982), this paper considers the role of system planning in determining operating flexibility and system performance. In the short term, manufacturing flexibility is required to maintain continuity in operations in the face of unforeseen events, such as machine breakdowns, unexpected demand surge, etc. While the overall flexibility of any system is constrained by the decisions made at the system design stage, the realized short-term flexibility depends significantly upon the pre-production setup decisions. By considering different planning objectives, the same physical system can be reconfigured to optimize different measures of performance, and simultaneously yield varying levels of different dimensions of process-oriented flexibility. In order to facilitate this discussion, we first present a scheme for classifying the different types of flexibilities. We use this scheme to also present an illustrative comparison of conventional and flexible manufacturing methods for the two extremes of high volume/low variety and low volume/high variety manufacture.

The paper is organized as follows. Section 2 reviews the hierarchy of decisions that need to be made in an FMS, and in particular, presents the various FMS planning problems. In Section 3, we present a taxonomy of the various flexibilities available in a manufacturing system. Section 4 discusses how planning decisions determine the short-term flexibilities of a system, and also how these flexibilities relate to three important measures of system performance. In so doing, we also discuss the tradeoffs among the various flexibilities that are made at the system planning stage. Section 5 compares two sets of conventional and flexible manufacturing systems with respect to the various types of flexibilities as well as the relevant manufacturing decisions. We conclude in Section 6 with suggestions for future research. Throughout this paper, a *product* refers to the finished workpiece. A product is an assembly of several *parts*. Parts with the same physical and performance characteristics belong to the same *part type*.

2. FMS Production Problems

In this section, we address the various manufacturing issues faced by an FMS. Following Stecke (1985), these issues can be considered within a hierarchical framework comprising: (i) the design problems, (ii) the planning problems, and (iii) the scheduling and control problems.

FMS *design* problems include the selection of part types and part families that will be processed within the FMS, the selection and layout of machine tools and the material handling system, the design of buffers, and the computer control architecture. These decisions typically have long-term implications, and are consequently made only periodically. While faster technological obsolescence and shorter product life cycles tend to reduce the interval between successive decision points, this trend is somewhat negated by the increasing emphasis on greater part standardization and the increasing use of a common platform for introducing a generation of new products (Clark and Wheelwright 1993).

For the given design decisions, FMS *planning* problems address resource allocation in the medium term. Stecke (1985) identifies five FMS planning problems; in this paper, we focus on three of these problems, namely: (i) the part type selection problem, (ii) the machine grouping problem, and iii) the machine loading problem. The *part type selection* problem requires determining the subset of part types that should be taken up for imminent manufacture from among the set of all part types that the system is capable of producing. The *machine grouping* problem partitions the available machines into groups of identically tooled machines; machines within the same group provide parallel processing capabilities. The *machine loading* problem allocates the various operations within each part and the cutting tools to individual machine groups subject to the system's technological and capacity constraints. The FMS planning decisions form a part of the pre-production system setup.

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. It is useful to distinguish scheduling decisions that are made off-line, such as part input sequence determination, from dispatching decisions that are made in real time. Similar to the FMS planning decisions, off-line schedule generation forms a part of the pre-production system setup.

3. Dimensions of Manufacturing Flexibility

Several taxonomies for classifying manufacturing flexibility are available in the current literature (see, for example, Buzacott 1982, Mandelbaum and Buzacott 1986, Zelenovic 1982, Browne et al. 1984, Carter 1986, Kumar 1987, Son and Park 1987, Swamidass 1988, Chandra and Tombak 1990, Sethi and Sethi 1990, Gerwin and Kolodny 1992, and Rachamadugu, Nandkeolyar and Schriber 1994). In this paper, we use the framework proposed by Sethi and Sethi (1990) with some modifications especially in regard to short-term flexibilities. Before presenting this framework, we make three observations below.

First, any type of flexibility needs to be considered along the dimensions of both range and time (Slack 1983). Greater flexibility implies a wider range of alternatives and/or more rapid access to a given set of alternatives. In many cases, it is more meaningful to consider the interaction between these two dimensions. This can be done, for example, through the use of range-response curves (Slack 1988) that graph the time taken to achieve each alternative in the set of feasible alternatives.

Second, the appropriateness of the metric used for measuring any flexibility depends upon whether the purpose of studying that flexibility is to understand its impact on overall system performance or to evaluate that flexibility across several systems (or at various points in time). In the former case, it is important to emphasize how changes in individual flexibilities can bring about changes in system performance; hence, it is more meaningful to express them in terms of parameters that can be determined *a priori*, i.e., before actual production takes place. While *a posteriori* measures based on realized parameter values can better evaluate the flexibility of a system, they tend to obscure the proactive aspect of flexibility (also see Gerwin and Kolodny 1992). For example, by defining process flexibility as the set of parts currently manufactured by the system, it is possible to study the impact of this flexibility on order turnaround times. On the other hand, it is unclear how process flexibility, defined as the ratio of the dollar value of total output to the waiting cost of parts (Son and Park 1987) based on values observed over a period of time, can be used to affect changes in the system.

Third, it is difficult to measure any flexibility with a single metric. Each type of flexibility allows for multiple (although mutually consistent) definitions; the appropriateness of any definition is likely to be situation dependent. Consequently, the definition of any type of flexibility used in this paper is not meant to cover all its aspects; it does, however, bring out its relationship with other flexibilities as well as the manufacturing decisions.

Similar to Sethi and Sethi (1990), we identify three levels of manufacturing flexibility. The first level comprises *basic flexibilities,* and includes machine flexibility, material handling flexibility and operation flexibility. *Machine flexibility* relates to the ease with which the machine can process various operations. It is meaningful to consider machine flexibility in terms of the range-response curve that relates the number of different operations that can be processed at the machine and the corresponding changeover times. *Material handling flexibility* is a measure of the ease with which different part types can be transported and properly positioned at the various machine tools in the system. This could be expressed, for example, by the degree to which the various machines in the system are directly connected (Chatterjee et al. 1984), as well as the average travel time between machines. Stecke and Browne (1985) rank various material handling devices according to their flexibilities. The *operation flexibility* of a part type measures the ease with which alternative operation sequences can be used for processing it. While the range aspect of operation flexibility is determined primarily by the part design, the time taken to implement the alternative operations sequences is determined by the system layout, the material handling system, and the computer control architecture. Note that the level of material handling flexibility required in a system depends upon the available machine flexibility, as well as the range component of operation flexibility. For example, if the machines are dedicated to specific tasks and there is a dominant operation sequence, then the material handling system need not be very flexible. In its turn, material handling flexibility impacts the time aspect of operation flexibility.

The second level consists of *system flexibilities* that are a result of the basic flexibilities. These flexibilities include volume flexibility, expansion flexibility, process flexibility, product flexibility, and routing flexibility. *Volume flexibility* is a measure of the system's capability to be operated profitably at different volumes of the existing part types. High volume flexibility in essence implies a low break-even point. *Expansion flexibility* relates to the system's capability of being 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 is the expansion flexibility. Similar to the basic flexibilities discussed earlier, volume and expansion flexibilities comprise both range and time components (see Gerwin and Kolodny 1992).

The *routing flexibility* of a part is a measure of the alternative paths that it can effectively follow through the system for a given process plan. Thus, routing flexibility not only allows failed machines to be bypassed, it can also alleviate congestion when it provides parallel servers. It is important to distinguish between *potential* and *actual* routing flexibility. Metrics such as the number of alternative paths that a part can follow through the system (Chatterjee et al. 1984, Chung and Chen 1989) measure the potential routing flexibility of that part. This is an overestimate of the available routing flexibility in that it ignores the impact of unreliable and heavily utilized machines. Clearly, even if there are several alternative machines available for processing an operation, the probability that any of them will be available immediately for processing the operation is small if they are all heavily utilized or they are unreliable.

Let n be the number of operations in an arbitrary part j. The range component of routing flexibility of j is given by $\{a_1, ..., a_n\}$, where $a_i \in \{0,1\}$ measures whether there is at least one machine on which operation i within part j can be processed immediately. Note that this measure considers each operation within a given part. The *real-time* routing flexibility changes continuously as machines are engaged and freed up. However, from a system planning perspective, it may be more meaningful to consider the *steady state* routing flexibility in which a_i, $0 < a_i < 1$, denotes the steady state probability that operation i can be processed immediately. In any system, a_i depends on several parameters such as the number of alternatives machines on which i can be processed, and their utilization levels and failure patterns; the functional form of this dependence is determined by the system configuration. a_i tends to zero if, for example, machine utilization levels increase and/or machines are increasingly prone to failures. (Kumar 1987 develops a related concept of flexibility that is based on the transitional probabilities in a Markov chain.) Incorporating the time aspect yields the expression $\{w_1, ..., w_n\}$ for routing flexibility, where w_i is the *minimum* expected waiting time for operation i after considering all available alternative machines on which it can be processed; clearly, lower values of w_i are indicative of higher flexibility. It is interesting to note that routing flexibility can be increased by deliberate underutilization of machines.

Process flexibility is a measure of the volume of the set S_1 of part types that the system can produce *without incurring any setup*. It is constrained by the machine flexibilities of the various machines in the system, the versatility of the material handling system, and the extent of automated control of operations. Process flexibility changes whenever the machines in the system are reconfigured for a different set of part types. Thus, like routing flexibility, it is a measure of the short-term flexibility of the system although it does not change as dynamically. Note, however, that routing and process flexibilities place antithetical requirements on the system. In a typical FMS, the total number of *distinct* operations that can be processed simultaneously is limited by the total number of slots available at the tool magazines at various machines. Consequently, the planner has to choose between increasing the number of distinct part types that can be produced simultaneously (thereby increasing process flexibility), and increasing the number of alternative machines available for producing the same part type (thereby increasing routing flexibility).

Product flexibility refers to the volume of the set of part types S_2 that can be manufactured at the FMS with *minor* setup. Because the magnitude of the changeover required depends upon the part types that can currently be produced in the system, S_2 strongly depends upon S_1, and $S_2 \supseteq S_1$. Note that S_1 and S_2 differ only in the amount of time required to change the setup among the various parts in a given set. As part program downloading times decrease and automated tool interchanging capabilities of a system increase, its process flexibility increases to equal its product flexibility.

The third level comprises *aggregate flexibilities*, and it includes program flexibility, production flexibility, and market flexibility. *Program flexibility* is the ability of the system to run for reasonably long periods without external intervention. High program flexibility needs the system to be self-corrective in the face of disruptions, and to make part sequencing decisions. This typically requires high routing flexibility, and in many cases, high process flexibility as well. Clearly, high program flexibility, for example, results in greater system utilization. *Production flexibility* is the set S_3 of part types that the system can produce without major investment in capital equipment. Thus, production flexibility includes those parts that need major setup as well. Clearly, $S_1 \subseteq S_2 \subseteq S_3$, and process, product, and production flexibilities can be seen to differ only in the magnitude of the required setup time. In the limiting case, if part program downloading and tool interchanges can be affected immediately, these three flexibilities are equal.

Market flexibility is the ability of the system to efficiently adapt to changing market conditions. The *short term* market flexibility measures the time and effort required to deal with changes in customer orders, while the *long term* market flexibility addresses the system's ability to cope with changes in customer needs, short product life cycles, and changes in product technology. Clearly, aggregate flexibilities are the most visible measures of a manufacturing systems' overall flexibility since they impact parameters that are immediately measurable, such as machine utilization, range of products manufactured, customer order turnaround time, and new product introduction frequency.

Manufacturing flexibility requirements vary with 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. Consequently, the dependent flexibilities that are relevant in the short term are operation flexibility, routing flexibility, process flexibility, product flexibility, short-term market flexibility and program flexibility.

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 production- and volume-flexible as well. 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 long-term market-flexible, a firm needs to be expansion-flexible as well at this level. Carter (1986) proposes a similar time-frame based taxonomy of flexibility.

4. Impact of FMS Production Decisions

In the context of the flexibility framework described above, it can be seen that basic flexibilities are determined primarily by the design decisions. Material handling flexibility is clearly determined by the system hardware selected, as is machine flexibility. 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. It is, however, defined within the envelope of the part types produced by the system which is itself a design decision. If these part types belong to the same family (through similarity in material, configuration, geometry, etc.), then machine flexibility increases. Expansion flexibility is also determined by the design decisions in that it relates to the ability to add to the machines, the material handling system, and the computer architecture modularly. To a large extent, design decisions also impact the fixed investment in the system, and therefore, its volume flexibility as well. Design decisions also affect production flexibility. This flexibility, however, changes continuously as new parts are added.

Of greater interest to us, however, is the impact of planning decisions on the process and routing flexibilities, and on the overall system performance. The performance criteria that we consider are *production rate* and *part flow time* - two measures that play important roles in the justification of flexible manufacturing systems. In the short term, production rate is strongly correlated with the total factor productivity (Hayes, Clark, and Wheelwright 1988) of the system, and therefore, is indicative of system profitability because resource levels essentially remain the same. Part flow time is the major component of the lead time required for order execution. While the magnitude of its immediate impact on profitability is usually difficult to measure (it is a first-order intangible in the sense of Gerwin and Kolodny 1992), it is clearly an important determinant of a company's competitiveness (see, for example, Meredith and Suresh 1986).

We include a third criterion, namely, the ease of real-time scheduling, to evaluate *planning robustness*. Real-time scheduling decisions are often based on local, as opposed to systemwide, considerations. The complexity of these decisions and the frequency with which they need to be considered implies that most scheduling problems can only be solved heuristically without any guarantee of optimality. However, if alternative processing modes are available (through operation or routing flexibility, for example), then the difference in system performance under optimal and heuristic solutions diminishes (also see Conway, Maxwell, and Miller 1967 for a related discussion). Thus, the degree to which the actual system performance is insensitive to the quality of the real-time scheduling decisions is a measure of the robustness of the planning decisions. This criterion is a second-order intangible in the classification of Gerwin and Kolodny (1992). The various planning problems are now discussed.

1. *Part type selection problem*: In most FMSs, because of different part due dates, and technological and tool magazine constraints, the planner needs to select a subset of part types for immediate and concurrent manufacture from the set of all part types that the system is capable of manufacturing. Selecting few part types clearly reduces the system's process flexibility; however, it leads to a higher routing flexibility since the available machines and material handling devices are shared among fewer part types. In the short run, there is also a tradeoff between the range and time aspects of market flexibility. While the number of different products for which demand can be met is limited, the time taken for producing the parts within this range can be small.

Producing fewer part types simultaneously (having low process flexibility) tends to simplify the scheduling decisions because it is then easier to establish priorities among parts of the same type. This results in strong precedence relationships among part types, which in turn, simplifies the off-line scheduling process, and also the dispatching decision to be made in real time. It follows from basic queueing theory that greater routing flexibility also leads to a reduction in the flow time of part types being produced currently. Low process flexibility also increases the production rate, especially if the various part types are being manufactured in the appropriate ratios (Stecke 1992). On the other hand, low process flexibility may lead to higher flow times for part types that are not being produced currently. If order sizes are small, it may also result in a lower production rate and a possible loss of productive capacity because of more frequent (although shorter) setups. Overall, planning for low process flexibility is likely to be preferable in the presence of unreliable machines, large order sizes, and small setup times.

It may be best to allow the FMS to adapt its process flexibility in response to order arrivals and the changes in the system status such as machine breakdowns. Stecke and Kim (1991) develop such a flexible approach to part type selection. Their procedure alters the mix of part types being produced dynamically, by suitably changing their production ratios, in order to allocate and balance appropriate workloads to the various machines in the system. A large-scale FMS comprising over 60 machines being installed currently by a major automobile manufacturing company is likely to adopt such a flexible part type selection policy.

2. *Machine grouping problems*: Machine grouping provides alternative machines for processing a part type; this results in higher routing flexibility. Conway, Maxwell, and Miller (1967) observe that increased routing flexibility leads to simpler scheduling. Following Stecke and Raman (1994), it is possible to distinguish three levels of grouping - *no grouping*, in which each operation is assigned to exactly one machine, *partial grouping*, in which an operation is assigned to multiple machines but no two machines are tooled identically, and *total grouping*, which consists of one or more groups of identically-tooled machines. Stecke and Solberg (1985) note that total grouping

results in higher production rate. They also find that production rate increases when the group sizes are unequal, and the workload per machine should be higher for machines in the larger groups.

Stecke and Raman (1994) find that unequal machine groups and unbalanced workloads are more effective as the coefficient of variation of product processing times (CVOPT) increases, and as the system is more heavily utilized. Note that higher part type variety leads to higher CVOPT; thus, unequal groups favor greater process and product flexibilities. Overall, Stecke and Raman find that partial grouping performs the best in terms of reducing average product lead time, as well as sensitivity to the schedule quality.

3. *Machine loading problems*: Stecke (1983) suggests several machine loading objectives pertaining to the various grouping configurations. These are shown in Table 1.

TABLE 1: FMS Grouping and Loading Objectives

Grouping Objectives	*Loading Objectives*
No Pooling	Minimize number of part movements
	Balance machine workloads
Partial Pooling	Minimize number of part movements
	Balance machine workloads
Total Pooling	Minimize number of part movements
	Balance workload per machine group
	Unbalance workload per machine group

The objective of minimizing movements is applicable across all three levels of machine pooling. This objective leads to greater aggregation of operations, and therefore, tends to decrease routing flexibility. However, it results in higher production rate, especially in the absence of equipment and tool breakdowns (Stecke and Solberg 1981). Stecke and Solberg also find that under this loading objective, the output rate is largely invariant with the various scheduling rules used. When machines are pooled, either partially or totally, and the alternative routes are used effectively, both of these benefits are further enhanced. Stecke and Raman find that this loading objective is effective also for minimizing mean part flow time, especially for large values of CVOPT.

Stecke and Raman (1994) find that balancing machine workloads is the best loading objective at low CVOPT values and when there is no machine pooling. Maximizing the weighted sum of operation duplications provides routing flexibility. The latter objective could yield higher productivity and flexibility if the operation weights are selected judiciously. Stecke and Raman (1994) 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.

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 production rate (Stecke and Solberg 1985), and small flow time values, especially at high CVOPT and utilization levels (Stecke and Raman 1994). However, Dallery and Stecke (1990) show that balanced workloads are optimal for equal-sized groups; Stecke and Raman (1994) find that balanced workloads with equal-sized groups leads to higher routing flexibility and the performance is less sensitive to the scheduling rule used (also see Stecke and Solberg 1981, and Lin and Solberg 1991).

Finally, we note that planning decisions can help provide certain flexibilites in order to (partially) compensate for the lack of some other kind of flexibility. 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. 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, and therefore, part flow time as well. 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, and using both flexibilities simultaneously can be best. Wayson's and Neimeier's studies also found that, with greater operation and routing flexibility, the manufacturing time of a given part was found to be less sensitive to the dispatching rules used.

The above discussion indicates that while the decisions made at the design stage provide an upper bound on the levels of flexibilities achievable, the realized levels depend substantially on the planning decisions as well. These levels can be affected to some extent by the off-line scheduling decisions as well; for example, introducing idle times at various points in the schedule can lead to higher real-time routing flexibility. However, real-time scheduling decisions do not contribute to system flexibility. On the contrary, as argued earlier, the robustness of these decisions is determined by the short-term flexibility available in the system.

5. Illustrative Paradigms of Flexible Manufacture

In this section, we consider two contrasting operational environments relating to high volume/low variety and low volume/high variety manufacture. We discuss how the various production decisions impact the levels of flexibilities available under both conventional and flexible manufacturing situations within each environment.

High Volume/Low Variety Manufacture

High volume/low variety operations require efficient production of a few part types that have stable designs and demand requirements. Under both conventional and flexible manufacture, 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; the parts, therefore, have low operation flexibility. Continuous monitoring of quality problems and breakdowns is essential for ensuring minimal deviations from targeted production levels. Safety stocks of finished goods are carried to decouple production from actual demand to minimize variations in production volumes.

The appropriate manufacturing system is a transfer line under conventional manufacture, and a flexible transfer line (FTL) under flexible automation. Examples of FTLs 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. Table 2 compares the levels of individual flexibilities available in conventional and flexible transfer lines, and Table 3 presents the various manufacturing decisions that need to be made in each of these systems. The use of more versatile, general-purpose computer numerically controlled (CNC) machines, together with the ability of downloading part programs quickly, provides greater machine flexibility in an FTL. This facilitates quick removal of broken tools, minimal part fixturing and setup time, and rapid changeover between different part types.

Under normal conditions, parts follow a fixed route in both FTLs and transfer lines. However, greater machine versatility and flexible material handling capabilities provide higher routing flexibility in an FTL so that in the event of a breakdown, parts can be rerouted. It is easier to bypass an unnecessary machine in an FTL without having to move through it. FTLs also allow easier pooling of parallel machines; a part needs to visit only one of the pooled machines. However, in order to achieve the higher level of routing flexibility, an FTL requires solving the machine grouping and loading problems periodically.

Because of its greater capability of switching among operations, an FTL is better positioned to handle mixed-model manufacture. This requires the part type selection decision to be made periodically to determine the mix of products to be manufactured concurrently. Furthermore, the production rate and part flow times obtained in an FTL depend also on how well the off-line part type input sequence problem has been solved although, as argued earlier, the real time scheduling problem is simplified in the presence of alternative routes available through machine pooling. In general, however, the number of different parts made simultaneously in an FTL - its process flexibility, is usually small because the major emphasis in such systems is on providing higher routing flexibility.

On the other hand, it is also generally true that FTLs can be reconfigured with relatively small setup times in order to produce several variants of existing products - possibly belonging to the same family. This results in a higher product flexibility for FTLs. 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, however, both conventional and flexible transfer lines tend to be volume-inflexible in that their profitability can be susceptible to variations in production volumes because of large capital investments. Both FTLs and conventional transfer lines generally are expansion-inflexible as well because of the use of the tightly coupled stages with minimal in-process inventories. However, because an FTL employs more general-purpose equipment, smaller capacity increases are sometimes possible.

TABLE 2: Levels of Available Flexibilities

Type of Flexibility	*Conven. Transfer Line*	*Flexible Transfer Line*	*Job Shop*	*Type II FMS*
Machine	Low	Low - medium	Medium - high	High
Material handling	Low	Low - medium	High	Medium - high
Operation	Low	Low	High	High
Process	Low	Low - medium	Low	Medium - high
Product	Low	Medium	Low - medium	High
Routing	Low	Medium	Low	Medium - high
Volume	Low	Low, situation dependent	Low - medium	Medium
Expansion	Low	Low, situation dependent	High	Medium - high
Program	Low	Medium - high	None	Medium
Production	Low	Low - medium	High	Medium - high
Market				
- short run	High	High	Low	Medium
- long run	Low	Low - medium	High	High

Typically, conventional transfer lines do not have control policies that provide alternative approaches to follow in case of unanticipated problems such as tool failure or raw material quality problems (other than possibly shutting the line down). On the other hand, FTLs permit the necessary corrective actions required under such conditions to be preprogrammed, and the routing flexibility available in these systems may allow parts to be rerouted without external intervention. This results in greater program flexibility and higher system utilization.

The versatility of machines in an FTL also results in higher production flexibility relative to the conventional transfer line. Typically both systems are insulated from short run changes in the market demand through finished goods inventory. However, the higher machine and process flexibilities of an FTL leads to smaller batch sizes and lower finished goods inventories.

TABLE 3: Production Issues: High Volume/Low Variety Manufacture

Manufacturing Issues	*Conventional Transfer Line*	*Flexible Transfer Line*
DESIGN ISSUES:		
Types of machine tools	Dedicated	Programmable
Material handling system	Conveyor	Conveyor or AGVs
Size of buffers	Small	Small
PLANNING ISSUES:		
Part type selection	No	Selects a few part types at a time with medium requirements
Machine grouping	No	Sometimes (can have pools of machines)
Machine loading	Once, during design	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

Both systems generally tend to respond poorly to changes in product design; this leads to low long-run market flexibility. However, the use of more general-purpose equipment in an FTL permits minor changes in part design to be accommodated more readily. Note that conventional transfer lines are likely to yield higher productivity, under normal circumstances, because of the use of dedicated special-purpose machines by making use of its program flexibility. However, as Jaikumar (1986) argues, this difference can be reduced by permitting longer hours of unmanned operations with the FTLs.

Low Volume/High Variety Manufacture

Low volume/high variety manufacturing systems usually produce to order. The key manufacturing considerations are meeting order due dates with short lead times, and the ability to produce a large variety of products in varying, but usually small, order quantities. Typically there are no dominant operation sequences, which implies that the parts could have high operation flexibilities. These systems make extensive use of general-purpose equipment. Also, the CNCs or the material handling system in an FMS may have volume and weight restrictions. The most appropriate manufacturing system under conventional manufacture is a job shop, and under flexible manufacture is a Type II FMS that comprises multiple machining centers which are linked by one or more AGVs (see, for example, Browne et al. 1984). Some such systems are the Cincinnati Milacron FMS at LTV Vought Aerospace in Dallas, Texas, and at Okuma in Nagoya, Japan. The levels of various flexibilities achieved under these two systems are shown in Table 2, while Table 4 compares the manufacturing decisions required in these systems.

TABLE 4: Production Issues: Low Volume/High Variety Manufacture

Manufacturing Issues	*Job Shop*	*Type II FMS*
DESIGN ISSUES:		
Types of machine tools	Manual, partially	Flexible, versatile
Material handling system	Manual, pallets	AGVs
Size of buffers	Large	Small or ASRS
PLANNING ISSUES:		
Part type selection	Yes, during machine scheduling	Yes
Machine grouping	Usually no	Yes
Machine loading	Yes, during machine scheduling	Often
SCHEDULING ISSUES:		
Part input sequence	No	Yes
Machine scheduling	Yes, critical	Yes
Control policies to handle breakdowns	Yes, involves rescheduling	Yes

The greater versatility and the larger tool magazines available in a CNC machine provides a Type II FMS with higher machine flexibility than the general-purpose equipment available in a typical job shop. In addition, the use of AGVs in a Type II FMS leads to higher material handling flexibility (Stecke and Browne 1985). This implies that these systems have higher process, routing, and program flexibilities as well. However, efficient use of these flexibilities is predicated upon how well the various planning decisions are made. The large variety of part types, greater machine versatility, and small order sizes result in increasing the complexity and the frequency with which the part type selection decision has to be taken in an FMS. The large number of distinct operations tend to make the machine grouping and loading, and the off-line scheduling decisions complex as well.

While some 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, because of little or no 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. The part type selection and machine loading decisions in a job shop are usually integrated with machine scheduling. In the absence of pooling, the machine grouping decision is usually not required.

Because of short setup times, a Type II FMS has the potential to provide higher product flexibility; however, the general-purpose nature of the equipment implies that both job shops and Type II FMSs are highly production-flexible. Because the operations at the various stages are usually decoupled in both systems, they can be expanded modularly. The higher routing flexibility available in a Type II FMS can provide additional short-term capacity to act as a buffer against demand and supply uncertainties (Schmitt 1984), as well as greater ability to turn around customer orders rapidly; both of these capabilities lead to higher short term marketing flexibility. Both systems can incorporate product design changes. However, a Type II FMS may be somewhat less long-term market-flexible because it requires pre-production part programming and in many cases, part type-specific fixture design as well. For small order sizes, these activities could easily constitute the bulk of the product cost and manufacturing lead time. Hence, a Type II FMS may be less suitable for manufacturing a large number of part types in very low volumes.

Greater routing flexibility insures that real time scheduling decisions are simpler in Type II FMSs. Control decisions in these systems usually require specifying the part rerouting policies. Sometimes, these decisions may also involve match-up scheduling (Bean and Birge 1986) that attempts to compensate for disruptions, and if possible, regain the off-line schedule determined initially. Control decisions in a job shop are made manually and they typically involve schedule regeneration.

We note here that, while the design and scheduling level decisions need to be made in both conventional and flexible manufacturing systems, the planning level problems (as described in Section 2) are explicitly addressed only in the latter. In a conventional system, the system setup issues addressed at the planning stage in an FMS are considered either at the design level itself, as in the case of a high volume flow line, or at the scheduling stage, as in a job shop.

6. FUTURE RESEARCH SUGGESTIONS

This study indicates several directions for future research. The analysis of short-term flexibility shows that operation and routing flexibilities can significantly reduce manufacturing lead times. For a given set of part types with the available operation flexibilities, an important planning problem is to find the best allocation of appropriate routing flexibilites to these part types in order to optimize system performance. This requires developing quantifiable tradeoffs between these two flexibilities, as well as the process and the product flexibilities for the given system.

A second problem deals with the location and use of an FMS within a multi-product, multi-echelon production system operating under, say, an MRP system. While manufacturing flexibility is an alternative to other means, such as carrying safety stocks, for mitigating demand and supply uncertainties, the realized flexibility of a system is constrained by the flexibility of its raw material suppliers. If the set of upstream workstations are considered to be the suppliers and the set of downstream workstations are treated as customers, what would be an appropriate location for an FMS within a factory? How will it impact the mix of other buffering alternatives such as safety stocks, safety lead times, and extra capacity?

From the perspective of long-term market responsiveness, an important question to address is the impact of production flexibility on product line design. The bulk of new product introduction decisions have considered these two decisions sequentially. The research on integrating product design and process selection decisions is of relatively recent origin (Dobson and Kalish 1988, 1993; Chhajed and Raman 1992, Dobson and Yano 1993). An interesting line of inquiry is the impact of manufacturing flexibility on the range and mix, as well as the profitability of the products introduced.

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