

**Performance Management Issues  
in  
Flexible Manufacturing Systems:  
An Analytic Perspective**

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## Abstract

Increased competition has led to pressures for the development of manufacturing systems that recognize the need for flexibility, efficiency and economies of scope and scale. In recent years managers have started to realize that investing money in new automated facilities does not by itself guarantee performance improvement. Managed poorly, these investments may even degrade the plant's performance. This paper focuses on the major issues relevant to performance management of Flexible Manufacturing Systems (FMS). The paper highlights the distinctive nature of these modern manufacturing systems and describes their emerging role in support of the overall corporate strategy. This new role results in a more volatile workload and in an increased versatility of the required production mix. It also challenges production managers who need to quantify and monitor the effective productive capacity at their FMSs. Moreover, it is shown here why some operational decisions, which are relatively simple to model and to comprehend in a conventional manufacturing context, become more involved - and less intuitive - when carried out in the typical FMS context. All this leads to the development of a new performance management paradigm for FMSs. That new paradigm consists of the following modules: *Physical FMS Attributes*, *Operating Policies*, and *Order Profiles*. A critical research overview of several analytical decision models formulated recently is developed here. This overview examines the characteristic decisions within each one of the modules of the proposed performance management paradigm. The paper further evaluates the changing role of FMSs in the finished products' life cycle and identifies major research opportunities.

## 1. Introduction

The pace of introduction of new technologies in manufacturing has been increasing. Increased competition has led to pressures for the development of manufacturing systems that recognize the need for flexible, efficient and economies of scope and scale. Shorter product life cycles combined with rapidly changing production economies tend to make the design and redesign of manufacturing systems more frequent. What is more, production systems should follow the products as they go through their life cycle (Buffa (1984)). The appropriate interface between the production system and the products is a matter for careful strategic choice. This interface affects the choice among competing strategies that vary in terms of costs, availability, innovation, quality, or flexibility. As a result of all these problems there is an increasing need for performance evaluation and management techniques, and modeling or analytical tools, that assist in the design, evaluation, and effective management of such industrial systems. In this study, we focus on the special issues relevant to performance management of Flexible Manufacturing Systems (FMS) and on some of the analytical tools developed to help deal with them.

In general, analytic models of manufacturing systems are developed to provide users with rapid and accurate answers to problems involving cost and performance tradeoffs in four major areas:

- \* *Manufacturing system design:* including the determination of the number of machines or pallets, choice of facility layout, and design of material handling systems.
- \* *Purchase:* the evaluation problems faced in the choice of a turn-key system from the available alternatives proposed by an external vendor.
- \* *Continued improvements:* the identification and analysis of performance problems in existing systems and of the necessary modifications that result in reduced in-process inventories and lead times.
- \* *Capacity management:* the prediction of when current capacity will prove insufficient; the determination of production mix, routing priorities, volume and lead time relationships.

The desired outcome of the performance management effort is a cost-effective balance among the following major criteria:

- Production workloads
- Service level
- Manufacturing equipment
- Cycle(lead) times
- Costs.

Many of the criteria and approaches to performance management are prevalent for various types of automated production systems or job shops. However, recognizing the unique features of the FMS environment will help us appreciate the complexities of the managerial problems and the

effectiveness of the various decision support approaches that have been developed over the years. The first type of distinct features has to do with the 'service' characteristic of many FMS today. They are required to perform and respond to random customer calls within short lead times. Due to the highly variable mix of jobs and product attributes, there are no stocks of finished goods to draw on. Another noteworthy feature is the large number of alternate production planning and control decisions, which are a direct result of the increased routing flexibility and tooling commonality. FMS are tightly coupled systems: decisions made regarding one resource have an immediate impact on the utilization level of several other resources. Parts require multiple tasks by several simultaneous resources such as tools, fixtures, machines and pallets. The high price tags of the modern machining centers, and of the automated guided vehicle systems which serve them, result in minimal slack capacity for most critical resources. Long lead times for all kinds of customized production tools exacerbate these problems. Automated processing of customer orders, along with relatively short production runs, provides for minimal learning opportunities. Hence, automated processing implies that many of the production control decisions must be developed beforehand, and they must be verified and implemented by the system software. During production runs, the human operators are used primarily for exception handling and supervisory control tasks. Finally, the third set of unique features, increasing variety of job characteristics, is the cause of the need for even longer term planning activities regarding raw material and tools requirements planning, lead times estimates and incremental capacity expansions.

The task of defining, measuring, and monitoring production capacity is typically straightforward in conventional manufacturing facilities. Capacity management in conventional facilities is based on tracking the cycle times per part, or on the number of processing hours available at the facility per unit time. That task gets more involved in the flexible environment as a result of two primary sets of issues. The first set of issues is the impact of volatile, and transient production mix. In such a case, the lead time per order is affected by contentions and externalities caused by the other part types being processed simultaneously. Other factors confounding the capacity control tasks include pallet mix, jobs priorities, loading policies, part routing, choices of tools and processing rates, or machine grouping patterns and tool availability considerations. All these factors have direct bearing on the issue of performance monitoring. For example, having a stationary benchmark for anticipated on-time delivery performance is mandatory for implementing a financial incentive scheme that rewards on-time performance. Developing a reliable and mutually acceptable benchmark, however, can become a challenge in such an environment. The other set of issues has to do with determining the optimal way to stretch the existing productive capacity. Given the nature of the dynamic market, and the complex interplay among the various resources, the optimal capacity expansion decision must be based upon careful quantitative analysis which integrates as many of these concerns as possible (Brown( 1988)).

The complexities of these FMS environments support the conclusion that FMS capacity management should be based upon a vector of performance measures. Based upon a survey of the research literature in operations management, and based upon numerous case studies conducted by the author, a set of common measures can be identified:

- \* *Number of parts produced.* This includes both good and scrapped parts.
- \* *Machine utilization.* This includes measures by machine type and the contribution from each product type. Such metrics also indicate the time proportions dedicated for set up, processing and maintenance activities.
- \* *Flow times per item.* These are segmented by product type as well as by operation. The relative time proportions of net processing, queueing delays, transportation, load/unload and set up time are also important in this context.
- \* *Work in process (WIP) and queues.* This also includes the distribution of queues ahead of particular machines, equipment groups, or the composition of WIP per product type.
- \* *Due date performance.* The typical measures used in this context include the proportion of late orders and lateness contribution (or progress monitoring) at each work center.

In most cases the first moment (mean values) and some higher moments of the key measures are tracked to control for the tail effects of some undesired trends. These trends may include concerns such as a queue buildup in front of a bottleneck machine, or a highly skewed distribution of lead times for a certain set of part types. Having established and prioritized these measures, one can start manipulating the various system resources to try and improve the system performance as needed. Improving the system performance involves changes in WIP levels, regrouping of machines, priority reallocation and so on. The interesting point in FMS is the fact that some of these decision options, which were relatively simple to model and to follow intuitively in a conventional manufacturing context, become more involved - and less intuitive - when carried out in the typical FMS context. Two of these counter-intuitive points are examined next.

We begin our examination by looking at the impact of changing the number of pallets on the FMS throughput. Doing so we denote by  $TH(\mathbf{K}, \mathbf{C})$  the throughput of a single-class FMS with  $\mathbf{K}$  pallets and a vector  $\mathbf{C}$  describing the allocation of machines to work stations. It can be shown that if the FMS is modeled as a closed network of queues (Seidmann, Schweitzer, and Shalev-Oren (1987), Schweitzer and Seidmann (1992)), then the value of  $TH(\mathbf{K}, \mathbf{C})$  is increasing and concave in  $\mathbf{K}$ . If the FMS has  $R$  types of jobs, with  $\mathbf{K}_r$  dedicated pallets for class  $r$  ( $r=1,2,\dots,R$ ) then the throughput of class  $r$ ,  $TH_r(\mathbf{K}, \mathbf{C})$  is increasing with  $\mathbf{K}_r$ . On the other hand, the throughput of class  $m$ ,  $TH_m(\mathbf{K}, \mathbf{C})$ ,  $m \neq r$ , need not increase with  $\mathbf{K}_r$ . Furthermore, the

aggregate system throughput  $\sum_{r=1}^R TH_r(\mathbf{K}, \mathbf{C})$  need not increase in  $K_r$ , for all  $r$  values. The

implication is that total FMS throughput may not increase when one increases the total number of pallets. This conclusion contradicts our prior expectations from the single part type case.

Buzacott and Shanthikumar (1992)) show that  $TH(\mathbf{K}, \mathbf{C})$  is increasing and concave in the number of machines in work station  $i$ ,  $C_i$  ( $i=1,2,\dots,M$ ). Hence the FMS throughput increases if machines are pooled together to form larger work centers. If the FMS has  $R$  types of jobs, with  $K_r$  dedicated pallets for class  $r$  ( $r=1,2,\dots,R$ ) then the throughput of class  $r$ ,  $TH_r(\mathbf{K}, \mathbf{C})$  need not increase with  $C_i$  ( $i=1,2, \dots,M$ ). Moreover, the aggregate system

throughput  $\sum_{r=1}^R TH_r(\mathbf{K}, \mathbf{C})$  need not increase when more machines are pooled together. In

multiple product FMS the pooling of resources may not result in improved aggregated throughput. These two examples show the subtleties in the performance management of FMS, where certain decisions that are intuitively beneficial may actually result in overall inferior performance. This is due to the unexpected interaction effects among the various part types at certain bottleneck resources. All this motivates the need for developing a more comprehensive set of performance management models to improve our intuition about system response and to provide some guidance for key resource allocation decisions.

## 2. Research on Major FMS Performance Issues

### 2.1. The FMS Performance Paradigm

Corporate strategy determines the competitive posture of a company with respect to propositions such as development of core competency in certain manufacturing technologies, order lead times, production costs, quality assurance, degree of innovation and the rate of new product introduction, support for existing products, and the scope of products. The FMS Performance Paradigm presented in Figure 1 depicts the overall perspective for dealing with that subject. As shown in Figure 1, the major factors affecting a system's performance are: the *physical FMS attributes* (machines, layout, pallets, tools, etc.), the *operating policy* (part routing and dispatching, batching, tool allocation to machines, etc.), and the *profile of the orders* (due date

assignment policies, master production schedule, release control priorities, etc.). The performance management function uses these three sets of inputs along with the corporate strategy guidelines to provide two types of outputs. The first output is a set of feasibility indicators. These simply signal whether certain objectives, such as on-time deliveries of particular customer orders, can be met at all. The second is an overall assessment of the performance measures and their trends. The next section provides an overview of analytical research efforts dealing with each one of the three major factors affecting system performance. Due to space limitations this overview is not an exhaustive one. It is presented primarily to provide an overall structure within a single integrated framework. This approach should enable one to value the relative contribution and role of analytical studies addressing these issues, as well as to identify promising research directions.

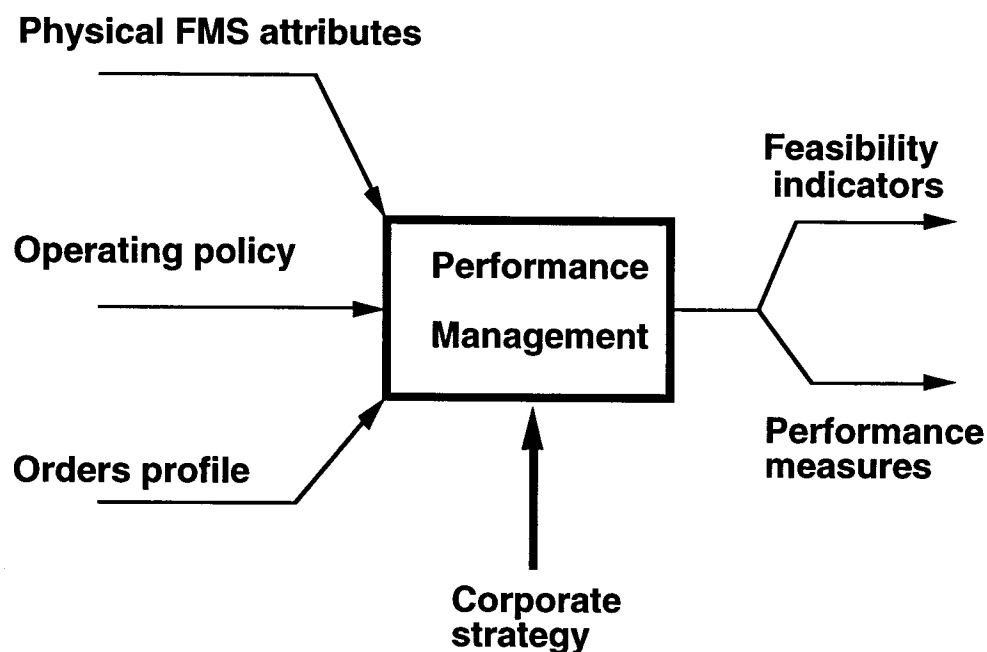


Figure 1. The FMS performance paradigm

## 2.2. Physical Attributes

Capacity has become a general term with multiple interpretations in FMS research. A variety of issues are associated with planning the physical capacity attributes in FMS. These include choices in determining *processing rates*, the *number of machines*, *material handling robots*, or the *number of pallets* to be used. Representative studies of these major choices are discussed below. We begin with two recent studies treating the problem of allocating the total production capacity among the various machines in a FMS. Wein (1989) considers the capacity allocation problem for a generalized Jackson network. That network has general interarrival times

and a general service time distribution, the system throughput is TH parts/unit - time, and the visit ratio for machine  $i$  ( $i=1,2, \dots,M$ ) is  $V_i$ . The problem he considers is the determination of the variable processing rate at each machine ( $1/S_i$ ,  $i=1,2, \dots,M$ ), subject to an overall budget constraint of  $\$D$ . A linear unit capacity cost of  $C_i/S_i$  is assumed. Heavy traffic Brownian motion approximation is used for deriving the optimal result:

$$\frac{1}{S_i} = TH V_i + \frac{\sqrt{c_i \sigma_i^2}}{\sum_{j=1}^M \sqrt{c_j \sigma_j^2}} \left( \frac{D - TH \sum_{j=1}^M c_j V_j}{c_i} \right)$$

The  $\sigma_i^2$  values indirectly measure the variability of the queue length and of the workload at machine  $i$ . This result suggests that each machine is allocated the minimal production capacity required to satisfy its effective arrival rate, plus an added amount which is proportional to the square root of the variability parameter  $\sigma_i^2$ . This assures that machines associated with greater variability will be allocated a greater share of the available capacity.

The study by Schweitzer and Seidmann (1991) presents an optimization methodology for minimizing the variable capacity investment in FMS given the throughput target TH, the WIP level K, the part routes, transporter delays, and the variable production cost function. That study focused on the tooling costs and assumed a general cost function typical for metal cutting applications. The FMS dynamics are modeled by extending the Mean Value Analysis queueing network approximation of Schweitzer (1979). In the case of linear costs, it is shown by Schweitzer and Seidmann (1991) that the optimal capacity allocation is given by:

$$\frac{1}{S_i} = TH V_i \left( 1 + \frac{\sum_{j=1}^M V_j \sqrt{C_j}}{V_i \sqrt{C_i} K y_0} - \frac{1}{K} \right)$$

The  $y_0$  measures the capacity loss due to transporter delays. This result generalizes the classical square root capacity allocation rule (Kleinrock 1964) for dealing with closed queueing network models of FMS's with transporter delays. The main insight gained here is that the optimal processing rate at machine  $i$  equals the minimal capacity  $THV_i$ , needed at this machine in order to meet the throughput goal, plus an added nonnegative increment: the percentage increment in this machine capacity is inversely proportional to the product of the visit ratio multiplied by the square root of the marginal capacity cost-rate parameter and is inversely proportional to the transporter

delays in the FMS ( $y_0$ ). This result also indicates that it is not optimal to set equal utilization in all machines.

Facilitating the manufacturing positioning of the firm, one has to consider the basic trade-offs among the various performance measures such as lead times, WIP, routing flexibility, variable operating costs, quality, and investments in capacity increments. The capacity targeting problem discussed by Bitran and Tirupati (1989) deals with an open multi-product queueing network with single machine stations and general arrival and process time probability distributions. The objective is to determine a least-cost schedule of capacity additions to achieve a target performance measure such as an average WIP level. In their model, capacity denotes resource availability, and a one-to-one correspondence is shown between the processing rate and capacity of each machine. Several powerful heuristics are presented for solving the resulting nonlinear program. Bitran and Tirupati (1989) also describe a balancing problem in which the objective is to minimize the system WIP, subject to a total capacity constraint. Similarly, Boxma, et. al (1990) and Vliet and Rinnooy Kan (1991) aim at minimizing the total system WIP (or leadtimes) subject to Boxma, et. al constraints on the total number of machines.

Several other studies have also dealt with the impact of physical FMS attributes on system performance. The model developed by Shanthikumar and Yao (1988) allocates a given number of identical machines among  $M$  production cells within an FMS. The objective is to maximize the throughput for a given number of machines and pallets. This model was later extended by Shanthikumar and Yao (1987) to handle the case of nonidentical servers. It is assumed here that the production cells are not necessarily identical in terms of machine cost and profit margins. The objective is to maximize the net difference between an increasing concave revenue function and a convex cost function for the number of machines allocated to each cell. In other cases the FMS is composed of several machine types where each group of machine types is further partitioned into a subnetwork. These subnetworks are required as a result of space or tooling constraints. Such a case is studied by Dallery and Stecke (1990). They show that for any machine type for which the group sizes are prescribed and equal for the different groups, the overall FMS throughput is maximized when the allocated workload is balanced. Overall, in these three studies, the FMS is modeled as a product form closed network of queues with one pallet type and a central server that represents the potential transportation delays. These studies identify and investigate some fundamental structural properties that facilitate the development of efficient optimization algorithms for the machine allocation problems.

A design optimization problem concerning the number of pallets of each type circulating in an FMS with several pallet types is considered by Solot (1990). The design objective is to maximize the throughput rate of a given product mix, subject to limiting constraints on the total investment in pallets and on the maximal turnaround times per pallet type. The heuristic solution

algorithm starts with an initial set having one pallet per part type. This set is incrementally modified yielding the maximal increase of the objective function at each step. Other authors also consider design optimization problems in which the costs of pallets and machines must be minimized while achieving a given throughput rate. For example, Vinod and Solberg (1985) and Dallery and Frein (1986) combine a heuristic search with an enumeration algorithm to solve that problem. All these studies assume that each pallet type can not support more than one part type, and closed queueing network models are used for computing the system throughput as a function of the proposed resource set. However, the issues of part refixturing or the need to use more than one pallet type per part type are typically ignored.

In the FMS technology, increasing benefits are offered as the system integrates more elements of the plant operations. Implementation and acquisition decisions leading to the realization of its overall value take into account complex technical, operational and corporate policy concerns. In doing so, managers have to deal with multiple objectives and difficult to quantify factors. Typical concerns relate to machining capabilities, operational integrity, cost reduction, quality assurance, lead time, vendor's reputation, and so on.

The multitude of issues relevant to these decision problems are addressed by the performance evaluation model developed by Arbel and Seidmann (1984). Their performance evaluation approach, which is carried out using the analytic hierarchy process (AHP), handles both tangible and intangible decision factors. For a number of reasons their performance evaluation approach has proved to be quite useful in the industrial applications conducted by the authors and by subsequent researchers (Canada and Sullivan (1989), Bijayananda and Chakravarty (1991)). First, it allowed the incorporation of various levels of expertise into an integrated framework. Thus, upper level management and engineering experts could contribute in their respective areas of knowledge and responsibility. This assured that all important concerns were properly addressed in the process. Second, the approach is based on combining different modules into an assessment hierarchy. This modularity property permits great flexibility in addressing different decision issues that reflect the idiosyncrasy of the particular organization. Finally, the complete process proved to be very useful in communicating ideas among the participating decision makers who identified with the focus and details of the study and the competing vendors. These external vendors were briefed on their relative proposal status and were given a chance to respond with better understanding of their customers' needs. In practice, that effort usually leads to impressive improvements in the overall cost effectiveness of the system performance.

### **2.3. Operating Policy**

We begin this section with the key observation that individual part movements are practical in FMS because of the automated material handling system. In addition, having the ability to change the machine program from one part type to another within short time intervals enables rapid capacity distribution changes among the various part types. These changes may be required as a result of varying demand patterns for the end products or as a result of machine failures. Machine failures have an immediate impact on the effective capacity and on the delivered production mix. The managerial decision options for policy selection implemented by various FMS managers vary depending on the nature of the production technology being used and on the characteristics of the major performance evaluation criteria. These decision options include *part loading, job routing, workload assignment to machines, priority scheduling, processing rates, tools set ups, shifts, overtime and batching*. Representative studies of these major choices are discussed below.

The recent study by Schweitzer, Seidmann, and Goes (1991) shows that the ability to adjust system behavior by changing operating conditions may lead to some unexpected responses: 1) increasing WIP saves money, 2) increasing capacity increases machine utilization, and 3) having unbalanced machine utilization can be beneficial. For the case reported in that paper, the authors show that the major cost savings, in order of decreasing importance, are:

- 1) Tool speed selection
- 2) Part rerouting and assignment of tasks to machines
- 3) Tool type selection
- 4) Setting multiperiod throughput goals
- 5) Adjusting the number of pallets.

The interaction among these decision options demonstrates the need for using comprehensive reevaluation models for performance analysis when system tuning is allowed. A critical evaluation of many conventional conclusions is also warranted.

The three level hierarchical production scheduling policy developed and implemented by Akella, Choong, and Gershwin (1984) uses available status information, past performance trends, and system flexibility to anticipate and to react to disruptive events. The hierarchical policy is designed to keep the difference between the total number of parts of type  $r$  and the total number of parts required as close as possible to zero for all  $r=1, 2, \dots, R$ . The concept of capacity is a crucial component of that scheduling policy as the FMS capacity at any instant depends on the operational status of the machines. This status changes as machines fail, or are repaired. If parts are loaded into the FMS at a rate that violates the capacity constraints, material accumulates in buffers or in the material handling system. This results in congestion and poor performance. The status of the machines is given by the vector  $\alpha$ , where  $\alpha_i = 1$  or  $0$  ( $i=1, 2, \dots, M$ ) if machine  $i$  is up or down, respectively. The *top level* of the hierarchy computes (off-line) two key decision parameters: the number of machines that type  $r$  parts visit,  $A_r(\alpha)$ , and the hedging point for type  $r$  part,  $H_r$ . The

hedging point determines the dynamic amount of safety stock deployed to compensate for capacity shortfalls as a result of machine breakdowns. The proposed hedging point  $H_r(\alpha)$  for part type  $r$  is:

$$H_r(\alpha) = \frac{T_r d_r (b \rho_r - a d_r) - T_f a b (\rho_r - d_r)}{(a+b) \rho_r}$$

where  $d_r$  is the demand rate for type  $r$ ,  $T_r$  is the MTTR for all machines used by  $r$ ,  $T_f$  is the MTBF for all machines used by  $r$ , and  $\rho_r$  is the average utilization of all machines used by  $r$ . The values of  $a$  and  $b$  represent the costs of having a surplus or a shortage of parts. As expected, the optimal hedging point increases with the MTTR and with the machine utilization, and it is inversely proportional to the machine reliability. The *middle level* of the hierarchy computes on-line the short-term production rates for each part type for each machine rate. The local objective is to compute the production rates such that the safety stock level per part type approaches and remains equal to the proposed hedging point  $H_r(\alpha)$ . The *lower level* of the hierarchy dispatches parts into the manufacturing system with the aim of maintaining the part-loading rate equal to the computed production rate. Extensive simulations, and an industrial application for an automated card assembly line, show that this approach can be very effective in handling capacity disturbances. It facilitates high output rates with low WIP and is robust for a wide range of policy parameters.

In contrast with the approach taken by Schweitzer, Seidmann, and Goes (1991), or by Akella, Choong, and Gershwin (1984), it is not likely that job routing in the FMS always follows a fixed route independent of the state of the system. The study by Yao and Buzacott (1985) is an early attempt at developing a state-dependent part-routing scheme which also possesses a tractable analytic structure. They consider the probabilistic shortest queue discipline (PSQ) which routes parts with the highest probability to the station which has the largest number of empty spaces, or alternatively, to the shortest input queue. In their model, part routing is defined for the part flows to the machines not for individual parts. Whenever a routing decision is to be made, an appropriate machine is identified and then a certain part is picked from the central storage area and is delivered to that machine. This scheme is essentially a randomized version of the deterministic shortest queue policy. Yao and Buzacott (1985) prove that PSQ routing leads to a time reversible process which has a product form equilibrium probability distribution.

The study by Seidmann and Tenenbaum (1991) develops two optimal routing policies and three closed-loop heuristic routing schemes for FMS similar to those studied by Yao and Buzacott (1985). One of the optimal routing policies is based on a new initiated suspension part-routing strategy. This strategy results in a reduced load on the material handling system while increasing the expected throughput (or revenue generation) rates of the machines.

Maximizing the weighted throughput rate means that the resulting queueing network model has a state-dependent arrival process and product form solutions do not hold. The alternative modeling approach developed by Seidmann and Tenenbaum (1991) is based on extending the earlier semi-Markov framework of Seidmann and Schweitzer (1984). The study by Schweitzer, Seidmann, and Goes (1991) introduces optimal static part routing procedures an FMS that is modelled as a closed network of queues. The objective of that study is to maximize the upper bound of the system capacity and to reduce the variable operating costs. The optimal routing is determined using the constrained derivatives developed for the appropriate performance measures. Significant reductions in the unit production cost are demonstrated as a result of routing jobs from heavily utilized machines to a more lightly utilized machine which is also capable of performing the same set of operations. This conclusion expects to hold for adaptive routing as well.

In many industrial applications there is a need for some job-related priority scheduling scheme in order to balance the load among the machines and to provide a preferential service to specific job classes. This scheme is relevant for capacity planning and for the operational control of existing facilities. Relevant managerial issues are, for example, the impact of the total work load and of the priority assignment policy on the relative difference between the queueing times of the high-priority and low-priority jobs, or the relationship between the priority assignment policy, the machine utilization and the product mix. The study by Shalev-Oren, Seidmann, and Schweitzer (1985) develops an analytic model of closed networks of queues with multiple product types, various non-preemptive priority service disciplines, and parallel machine stations. It incorporates the characteristic features of FMS such as robot carriers and local conveyor belts. The model was installed in a computer program named PMVA (Priority Mean Value Analysis) that was extensively tested and implemented by the authors (e.g., Seidmann, Schweitzer, and Shalev-Oren (1987)) and others. Utilizing PMVA in several operating FMS shows that throughput and flow times can be quite sensitive to the choice of priorities at the heavily loaded machines.

Schedules are sometimes implemented while assuming a given processing time for each operation on a part type using a particular machine tool. Once a throughput target is set, however, the processing times can be manipulated to reduce costs and increase tool lives (as well as to improve surface qualities) at no expense to system throughput. This interaction between machining conditions and the overall system throughput suggests that improved scheduling performance can be based on a production rate/tool wear tradeoff.

Hitomi (1976, 1977) tackles the joint problems of determining the optimal machining speeds and optimal cycle time in a deterministic multi-stage flow line. Unlimited buffer space is assumed between machines. Cost savings are obtained by slowing down noncritical machines until their cycle times match that of the bottleneck machine. McCartney and Hinds (1982) introduce a procedure to review the machining rates of parts which are first scheduled using

maximum production rates. Their procedure will slow some machining rates to reduce production costs (on machines which are not on the critical path) while maintaining due-date performance. Their policy is similar to classical PERT/CPM heuristics (see for example, Whitehouse (1973)). Determining buffer capacity along with optimal cutting speed and tool replacement policy in a two-machine system is discussed by Koulamas, Lambert, and Smith (1987). A penalty cost is imposed for tool failures during production. They show that the tool replacement policies determined independently for each operation do not change when these two operations are coupled, and that the buffer size is sensitive to the tool change times.

Optimizing the process rates and determining changes in bottlenecks and queue lengths as the processing rates are altered is particularly intricate due to the problem of shifting bottlenecks. Schweitzer and Seidmann (1988, 1991) present several nonlinear queueing network optimization methodologies which determine the minimum cost processing rates given the FMS throughput target, the work-in-process level, part routes, transporter delays, and tool cost functions. Using industrial sample data, they show that a slight acceleration of the processing rates at a few economic bottleneck machines allows for significant rate reductions in others. Their studies provide for substantial gains in tool lives compared with conventional one-machine process planning models. Their results also prove that it is not optimal to: balance utilization of all machines, to balance waiting times at all machines, nor to manipulate processing times to compensate for local transporter delays.

Watanabe and Fujii (1988) find that when adaptive control systems adjust machine feedrates and cutting speeds due to changes in workpiece hardness and tool dullness, predetermined schedules are often violated. They propose a heuristic control model which links the operation speed to the order tardiness. This model is believed to result in major operational improvement. Given the heavy computational demands of this control scheme, however, its applicability to full scale, real-time adaptive control is currently unclear.

The total number of tools required to process a set of parts on a flexible machine is usually larger than the available magazine storage capacity. As a result, a required tool may be absent from the magazine and a tool change must occur before that operation can begin. Tang and Denardo (1988a, 1988b) explore this issue for a single machine with a limited tool magazine, assuming that production requirements are known in advance. The decisions are: (1) how to sequence the parts and (2) which tools to change on the machine prior to processing each part. Their objectives are to minimize the number of group tool change instances, or to minimize the number of individual tools changed. The former is appropriate only when the changing time is roughly constant regardless of the number of tools changed. These studies assume that there is a deterministic change time and that all changes are due to part mix, ignoring tool changes due to normal wear or breakage. Bard and Feo (1989) address the problem of minimizing the total setup, tool replacement and machining

times for individual batches subject to tool magazine capacity constraints and metal volume removal requirements. This approach requires that all feasible tool paths be generated manually before being considered by the optimization algorithm.

Capacity selection decisions and the degree of heterogeneity or similarity of the jobs to be processed affect the utilization of the productive resources. These attributes have a major impact on the formation of queues with the resulting delays in the flow of jobs. Dobson, Karmarkar, and Rummel (1987) distinguish between two types of flow times for a part on the machine: *item-flow*, when a part can be delivered immediately after the machining on it is complete, and *batch-flow*, when a part must wait at the machine until the rest of the parts in its batch are completed. Queuing delays constitute the major part of manufacturing lead times, and hence also affect the flexibility and output mix. In addition, batching, shift and overtime policies have a significant impact on the processing capacity and the WIP characteristics. Karmarkar (1987) and Zipkin (1986) have examined the impact of set up times and lot sizes on manufacturing lead times and on WIP and the accumulation of safety stocks. They show that the optimal lot sizes - used for production planning with stochastic job arrival patterns - are different from those of the conventional EOQ models, which use set up costs as a device to enforce capacity constraints. These studies were later extended by Karmarkar, Kekre and Kekre (1985) to handle multiple-item, multiple-machine shops. Their results explain why shop performance is especially sensitive to undersized lots. In a more recent work, Karmarkar, Kekre and Kekre (1987) describe the analysis of capacity equipment levels in a manufacturing cell that considers equipment levels, multiple shifts, over-time, and batching policy. That paper demonstrates that excess equipment capacity may be economically preferable to multiple shifts.

## **2.4. Orders' Profile**

The effective use of critical manufacturing resources is achieved by carefully planning the mix of jobs and product types to be processed at any point in time. The profiles of orders and jobs have a significant impact on the overall system performance. These include decisions about the *order acceptance process, due date assignment procedures, generation of the master production schedule using rough-cut capacity planning, order release control policies, and the selection of parts and machines to be used at each planning period*. Several of the studies are presented below acknowledge the fact that in a flexible build (or produce ) to order environment, the order acceptance process is the most important interface between the manufacturer and its customers. The order acceptance process requires the estimation of waiting times at each machine, since the ability of the manufacturing manager to negotiate accurate lead times is vital to customer satisfaction. If the marketing group sets the due dates oblivious to plant capabilities, then the result

is often an overloaded facility with a large volume of WIP and many jobs past due. Thus, it is very important for due dates to be based on the status and capabilities of the plant, or on the urgency and relative importance of the various jobs. The decision model discussed by Luss and Rosenwein (1990) is particularly well suited for flexible flow lines that process numerous product types. They assume that one can generate a set  $h_i$  ( $i=1,2, \dots,n$ ) of alternative schedules for each one of the  $n$  available orders. These alternative schedules specify the potential path and timing of tasks performed on each order. The completion date of order  $i$  in schedule  $j \in h_i$  is  $c_{ij}$ . The due date requested by the customer for order  $i$  is  $d_i$ , and the weight assigned to that order is  $w_i$ . The objective is to minimize the total weighted tardiness of the existing orders:

$$\min \left\{ \sum_{i=1}^n \sum_{j \in h_i} [w_i x_{ij} \max\{0, c_{ij} - d_i\}] \right\},$$

where  $x_{ij}=1$  if order  $i$  is assigned to schedule  $j \in h_i$ ; zero, otherwise. One alternative schedule is selected per order, subject to capacity constraints for all resources. The results presented by the authors exploit the flexibility of the manufacturing facility and indicate significant reduction in order tardiness. These improvements are achieved by simultaneously considering a batch of jobs, thus facilitating better utilization of the most flexible bottleneck resources.

The advent of JIT has drawn attention to policies and models in which earliness, as well as tardiness, is discouraged. Seidmann and Smith (1981) introduced the due-date assignment problem for systems having randomly distributed processing times. The aggregate cost function used includes: 1) a cost that increases with lead times, 2) a cost for tardiness, and 3) an earliness cost. Several extensions of that work to a general shop operation are given by Shanthikumar and Sumita (1988). The deterministic version of the common due-date assignment problem studied by Panwalkar, Smith, and Seidmann (1982) further incorporates a flow time penalty into the cost function described above. They show that for any specified sequence, there exists an optimal value of the common due date that coincides with the completion time of one of the jobs in that sequence. Baker and Scudder (1990) provide a comprehensive review of the due-date assignment and deterministic sequencing literature. Their paper proposes some unifications and extensions to the current work in the field. Wein (1991) looks at two problems of simultaneous due-date setting and priority scheduling in a multiclass M/G/1 queueing system. Several policies for due-date and priority sequencing are studied. The objective is to minimize the weighted due-date allowance, subject to an upper bound constraint on the number of tardy jobs or on the average job tardiness. In most of the simulations presented, the due-date selection policy has a more significant impact than the priority sequencing scheme. Glassey and Resende (1988), and Wein (1988) show that

due-date setting and input release controls can both be thought of as *tactical design decisions*, that should be made at a *higher level* than priority sequencing and scheduling decisions.

Parts inputs and machine selection policies for FMS were studied extensively in the context of FMS operations (Gray, Seidmann, and Stecke (1990)). Stecke and Solberg (1981) present six alternative objectives for FMS loading and control. Stecke (1983) defines five FMS production management problems: the part-type selection problem, the machine grouping problem, the production ratio problem, the resource allocation problem, and the loading problem. She notes that the principal objective of the FMS is to maximize expected production rates and that surrogate criteria are typically used in order to achieve this overall objective. Mazzola, Neebe, and Dunn (1989) propose a hierarchical structure that integrates FMS production planning into a closed-loop MRP system. This structure gives rise to the FMS/MRP rough-cut capacity planning problem and the FMS/MRP grouping and loading problem. They present mathematical programming formulation for these problems, and show that using the idea of planning batches the rough-cut planning problem can be modeled as a generalized assignment problem. The problem formulation accounts for the fact that often two or more different part operations on the same machine will require a common subset of tools. These tools need not be allocated twice to the same tool magazine. They also address modifications that arise from additional factors such as dependent-demand-related part types within the FMS. Other studies dealing with aggregate multi-stage capacitated scheduling of FMS are discussed by Toczyłowski and Hindi (1991).

The problems of determining the part types to be processed in an FMS and the selection of machines and tools are very large indeed. The algorithms available to solve them are necessarily suboptimal. Two such algorithms are proposed by Whitney and Suri (1985). One algorithm is a high-level decision tool. It selects both the machines and the part types to be processed. Detailed information about tooling and process requirements is assumed unavailable at that stage. The other algorithm is an operational tool which selects parts for a given set of machines. These algorithms can be used together to define the most financially attractive set of parts to produce, and to ensure the feasibility of the selected set of parts with regard to tool constraints, both system-wide and at individual machines. Stecke and Kim (1988) compare seven approaches from the literature dealing with the selection of part types for short-term production planning. Many other integer linear programming models have been proposed to solve this problem, but not all of them take tools into account. Those that do not consider tooling are quite unrealistic, especially when set up times are important with respect to processing times. Werra and Widmer (1991) developed a few integer programming models for part loading. Their formulation considers machine, tooling, magazine capacity and timing constraints. The objective functions proposed include makespan minimization, minimization of the number of tool changes, and minimization of the total processing time.

### **3. The Changing Nature of the Performance Management Function in FMS**

The initial role of FMS was to fill the gap between high-production transfer lines and low-production job shops with numerical control machines. The volume in which complex metal products are being manufactured ranges from individual units to hundreds of thousands per order. The production mode of these products depends largely upon the volume, whether it is small, medium, or large batch production, or a mass production transfer line. The FMS was originally designed to handle medium production volume with greater flexibility and parts variety than transfer lines, and to facilitate lower variable production costs than those encountered in job shops. Such designs are in high demand, as over 50% of all complex metal parts are produced in batches of less than 50 units (Cook (1975)). The 'ideal' FMS would combine the flexibility of general purpose machine tools with the high productivity of a transfer line. This was the motive for introducing the Sundstrand line in the late sixties. It was one of the first facilities to integrate machining centers with a material handling system delivering parts and tools. It consists of eight 5-axis machining centers with two automatic multispindle drills, an automated material handling system and centralized supervisory computer control. It is capable of producing about seventy different types of housings for the speed control gears of aircraft generators. This line replaced a conventional shop that required approximately 100 conventional machine tools; the number of operators was reduced from 125 to 25; WIP was decreased by 40%. That successful concept has served as a prototype for many of the FMS that were built later. More advanced systems were designed not only for machining operations but also for welding, forming, cutting, and variety of assembly tasks. On the other hand, the idea of building unmanned factories, or of running second and third shifts unmanned, has turned out to be somewhat elusive due to the lack of sufficient exception handling capabilities in the control software and machine reliability falling short of expectations.

In recent years managers have started to realize that a manufacturing advantage that can stand up to international competition must be built upon high performance factories. These should provide rapid on-time delivery, high quality, and low delivered costs. Investing money in new automated facilities is not by itself a guarantee for performance improvement. Managed poorly, these investments can reduce the plant's performance (Hayes, Wheelwright, and Clark(1988)). Of greater significance than the new machinery is the way in which it is managed and the impact it has on the process of continued improvements in the company. For example, the author has observed several cases where FMSs are being used to support two strategic objectives: 1) reduction of time to market for new product introductions; and 2) reduction of spare parts inventories. In some automotive plants they are used by design teams to quickly produce working prototypes to be test

driven and licensed. This approach has a significant impact on reducing time-to-market for new product's introductions. Similarly, in certain aerospace applications, rather than producing the anticipated demand for spares before hand, companies try and produce some of the more complex spares upon demand from their customers. Figure 2 illustrates this new role of the FMS in the product's life cycle; the next step may be expanding the role of FMS manufacturing from the 'tails to the center' to increase scope and responsiveness. It is still unclear, however, whether the present technology is sufficiently reliable and cost-effective to meet these challenges, and what is the best way to manage that transition process.

The typical FMS is involved in producing subassemblies, or components that are later incorporated with other units at the final assembly line prior to being shipped to the customers. Many of these final assembly lines are moving towards JIT production and their master production schedules no longer call for deliveries of fixed batch sizes. To meet their erratic JIT assembly schedules, these internal 'customers' want ancillary delivery contracts with some kind of upper, and maybe lower, supply bands. Such contracts demand that the FMS facility manager produce upon request any amount of parts between the previously agreed upon lower and upper bands. Having such contracts with several final assembly lines presents a difficult challenge for the corporate and the facility managers. They have to provide good estimates of the capacity needed to handle 'peak loads' with a variety of future part mixes. These estimates affect the number of machines, tools, jigs, fixtures and pallets to be purchased. Other unresolved problems include issues of volume sensitive pricing, priority incentives, and joint production opportunities.

Another dilemma observed in industry is the aging of existing facilities. Maturing systems installed during the seventies and early eighties are coping with expansion and technological upgrade issues. It is clear that installing the latest technological systems may have many advantages. On the other hand, mixing old and new machines within the same cells will reduce compatibility (and flexibility) across all the plant resources. Finally, using a FMS eliminates major upfront investments in dedicated facilities when launching a new product to the market. For small- to mid-volume production, the variable production costs are also relatively low in FMSs. As a result, the author has observed several cases where the Strategic Business Unit manager, or the products' managers, were trying to keep and use the shared corporate FMS for relatively high production volumes. This is typically done during the ramp-up period in order to defer as much as possible the need (and the burden) for building a dedicated facility that would handle the anticipated increase in volume. In these circumstances, when one order captures a significant portion of the systems' capacity, other users face excessive leadtimes and delays. This underscores the fact that understanding the exact nature of the externalities imposed by the users is a necessary condition for achieving satisfactory performance levels in these complex and highly capable facilities.

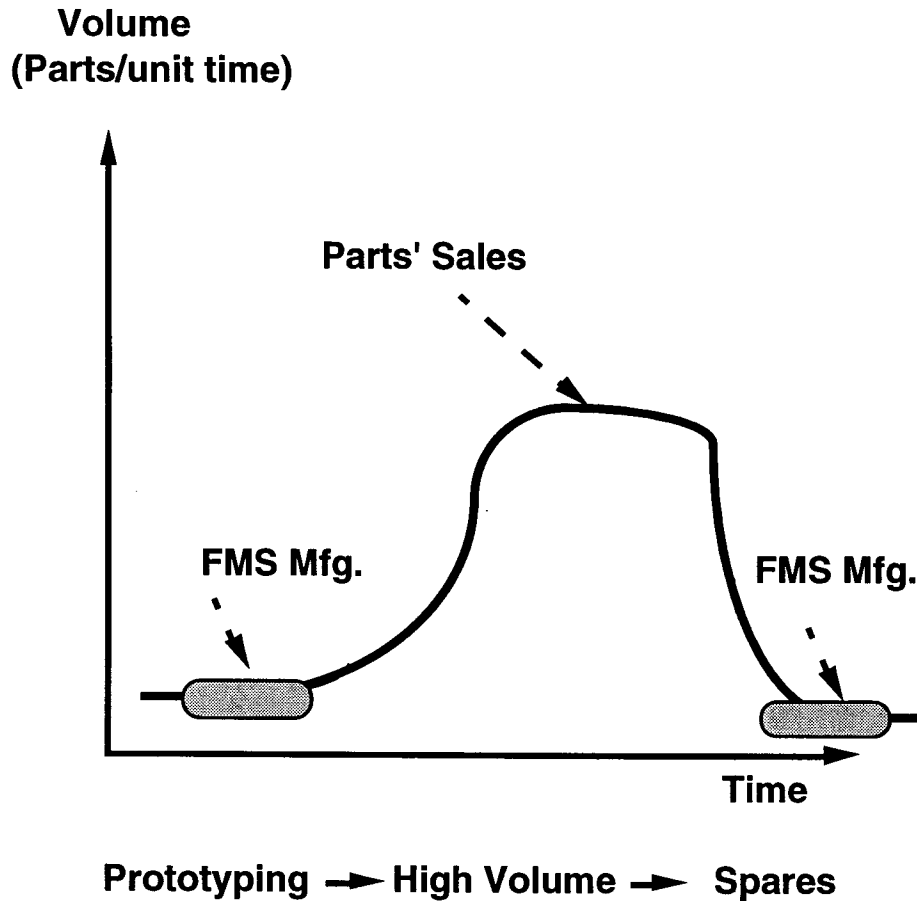


Figure 2. The FMS role in the product's life cycle.

Our analysis of the various performance issues identifies four substantial research opportunities. First, there is a growing need for richer analytical (queuing) models for dealing with the impact of special FMS performance issues: simultaneous resources, machine interference, partial machine grouping, and state-dependent part-release protocols. Second, little progress has been made so far regarding the analysis of the transient FMS behavior. Such a transient behavior will manifest itself during ramp-up production runs, adjustments in production mix, or when using dynamic routing. Compensating for lost throughput due to yield, tool shortages, and machine breakdowns can also lead to transient FMS behavior. Third, there is a need to develop underlying theories supporting the generation of adequate master production scheduling systems. This is a key component in coordinating the FMS performance with the rest of the company. These systems should handle multiperiod operations with stochastic, dynamic demand patterns and with variable operating parameters, such as the mix of special tools, jigs or pallets, variable processing rates, and customized quality requirements. Fourth, there is a need to develop better

ways to integrate conceptually the ‘product design/process selection/production planning’ decision phases with the key economic drivers of the manufacturing firm, rather than to squeeze them between marketing and design engineering requirements.

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