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USEFUL MODELS TO ADDRESS FMS OPERATING PROBLEMS

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Both a good design and the efficient operation of flexible manufacturing systems (FMSs) involve some intricate operations research problems. These systems consist of several computer numerically controlled (CNC) machine tools, integrated via an automated material handling system, all under the control of one or more computers. An FMS is capable of the concurrent manufacture of diverse part types in unit batch sizes.

Many mathematical models that can or have been used in the design, planning, scheduling, and control of these systems will be discussed. These models have been used in the *design* of an FMS to determine, for example, the appropriate number of machine tools of each type, the capacity of the material handling system, or the size of buffers. They have also been used in the *planning*, or set up, of an FMS to determine which part types should be simultaneously machined over some upcoming time period, the optimal partition of machine tools into groups, allocations of pallets and fixtures to part types, and the assignment of operations to machine tools and associated cutting tools of each operation among the limited-capacity tool magazines of the machine tools. Mathematical models have been used in the *scheduling* of an FMS to determine the optimal input sequence of parts and an optimal sequence at each machine tool given the current part mix. *FMS control* means the real-time monitoring, to be sure that the system is performing as well as you think it is and that the production expected has been achieved.

This paper overviews many of the models that are useful in solving such problems. An extensive bibliography provides additional information on much of the research that has been done to address these problems.

1. INTRODUCTION

A flexible manufacturing system (FMS) is an integrated system of CNC machine tools that are linked by automated material handling. Because of the versatility of the machine tools and the very quick (seconds) cutting tool interchange capability, these systems are quite flexible with respect to the number of part types that can be produced simultaneously and in very low (sometimes unit) batch sizes. These systems can be almost as flexible as, and more complex than, a job shop, while having the ability to attain the efficiency of a well-balanced assembly line. Some existing systems are described in Stecke [1977], Stecke and Solberg [1981], Barash [1982], Cavaillé et al. [1981], and Rathmill et al. [1983]. Most FMSs are devoted to the fabrication of metal parts.

Models are useful to analyze and sometimes solve many of the problems associated with the design, planning, and operation of these highly automated systems. This paper begins by briefly overviewing these FMS problems that have to be addressed in §2. Then, various models that can and have been used to investigate various aspects of these problems are presented and described in §3. Much of the current research addressing these problems is described. Finally, the scope of application of each model is discussed in §4.

2. OVERVIEW OF FMS DESIGN, PLANNING, AND OPERATING PROBLEMS

In this section, we briefly list the many decisions that have to be made during the design, implementation, and operation of an FMS. Additional details and descriptions of these problems can be found in Stecke [1985a].

Assuming that management has decided that flexible manufacturing is the chosen means of production, perhaps to increase capacity in a certain department producing changing products or for new families of products, the following design problems have to be addressed. The decision is made based on both economic comparisons and strategic considerations.

2.1 FMS Design Problems

An initial consideration is to determine the families of part types that will be manufactured and/or assembled on the FMS. Then the process plans for the part types have to be developed. This information helps to provide the capacity and functional requirements from the system, which in turn suggests various combinations of machine tools and cutting tools that can take care of all of the operations that have to be performed as well as meet expected production requirements. Group technology-like concepts and methods can help with these decisions. One difference with traditional group technology applications is that it is desirable to have many identical machines that can perform the same operations. Another difference is the higher diversity of parts that the FMS will produce. This diversity in turn requires additional flexibility from the system.

The amount of flexibility that is needed or desired has to be decided and this helps to determine the degree of automation and the type of FMS that is designed. Impacting this latter decision is the type of automated material handling system (MHS) that will move the workpieces from machine to machine. See Buzacott [1982b], Browne et al. [1984], and Stecke and Browne [1985] for information on a spectrum of flexibility options. The required capacity of the MHS also has to be determined, in the case of tow-line carts or wire-guided vehicles. The type, and then size, of buffer (to hold in-process inventory) has to be determined. The control structure hierarchy among the computers controlling machines, the MHS, and each other has to be designed and built. Other equipment and vendors have to be selected. The FMS layout has to be decided, which impacts appropriate operating strategies. The numbers and designs of both pallets and fixtures of different fixture types have to be specified. Planning, scheduling, and control strategies to operate the system have to be created and developed. The many software development tasks need to be specified, developed, and implemented, perhaps within a project management setting.

There is a lot of iteration among all of these *FMS design problems* as candidate solutions are suggested and then often determined to be infeasible when other factors are considered. Design specifications and needs change. These mandate that initial FMS designs vary widely. Efficient and accurate mathematical models are required to help narrow in on the appropriate FMS design.

Following the development and subsequent implementation of the FMS design, models will then also be useful to help set up and schedule production through the system.

2.2 FMS Planning Problems

Because of the quick automated cutting tool capability, there is negligible set-up time associated with a machine tool in between consecutive operations as long as all of the cutting tools required for that next operation have previously been placed into the machine tool's limited capacity tool magazine. However, determining which cutting tools should be placed in which tool magazine and then loading the tools into the magazine does take some "planning and system set-up" time. We call those set-up decisions that have to be made and implemented before the system can begin to manufacture parts, *FMS planning problems*. When the system has been set-up and can begin production, the problems are those of *FMS scheduling*.

The first *FMS planning problem* is to decide which, of the part types that have production requirements (either forecasted demand or customer orders), should be those manufactured at the same time over some upcoming time period. This information can be used to help determine the amount of pooling among the identical machine tools that can occur. Pooling, or identically tooling all machines that are in the same machine group, has many system benefits. For example, alternative routes for parts are allowed and also, machine breakdowns would not cause the system to stop production. This is because all of the machine tools in a particular group can perform the same operations.

Another *FMS planning problem* is to determine the relative ratios at which the selected part types should be on the system, to attain a good utilization, say. The limited numbers of pallets and fixtures of each fixture type impact these production ratios. Also, determining the minimum number of pallets and fixtures that are needed to maintain these production ratios is required. Finally, each operation and its associated cutting tools of the selected set of part types has to be assigned to one or more of the machine tools in an intelligent manner. Different loading objectives to follow are applicable in different situations.

When all of these decisions have been made and the cutting tools loaded into the selected tool magazines, production can begin. Then the following *FMS scheduling problems* have to be addressed.

2.3 FMS Scheduling Problems

The subsequent problems are concerned with the operation of the system after it has been set up during the planning stage. The first problem to address is to determine the appropriate policy to input the parts of the selected part types into the FMS, or, efficient means to determine which parts to input next. In some situations, a periodic input may be sufficient. (See Levèque et al. [1982].) In others, determining the next input to keep producing according to the calculated production ratios is appropriate. Parts have to be input so as to not exceed capacity.

Then, applicable algorithms to schedule the operations of all parts through the system have to be determined. Real-time scheduling is usually more appropriate for these automated systems, as opposed to a fixed schedule. Tool breakage, down machine tools,..., would totally disrupt a fixed schedule. The potential appropriate scheduling methods range from simple dispatching rules to sophisticated algorithms having look-ahead features. Scheduling might be helped by determining priorities among all part types waiting for a particular machine tool and perhaps priorities among the machine tools. Machine breakdowns and the many other system disturbances should be considered when developing scheduling and control procedures. If the system is "set-up" during the planning phase, with sufficient care, the scheduling function will be much easier.

2.4 FMS Control Problems

By *FMS control*, we mean the continuous monitoring of the system to be sure that it's doing what was planned for it to do and is meeting the expectations set up for it.

For example, during the *FMS design* phase, policies have to be determined to handle breakdown situations of many types. However, all breakdown types cannot be anticipated. If a machine tool goes down, what should be done with the present schedule? Is the breakdown expected to be long or short? Should the planned schedule be revised? Should a new schedule be developed. It might be appropriate to determine how to return to the original schedule as soon as possible. In any case, it is desirable to reallocate operations and reload the cutting tools so that the tool changing time is minimized.

System reliability is an issue. Maintenance policies have to be determined. Preventative maintenance should be performed. Perhaps it could be scheduled on a regular basis. The number of repairpersons has to be determined as well as priorities among their many maintenance tasks.

Inspection points (checks for part quality) and the frequency of inspection of in-process and finished parts must be determined. The appropriate equipment has to be selected, interfaced with the existing machine tools, and implemented.

Monitoring procedures for both the processes and cutting tool lives has to be specified as well as methods to collect data of various types (monitoring and breakdown). Tool life estimates should be reviewed and updated often. Reasons for process errors have to be found (i.e., machine or pallet misalignment, cutting tool wear and undetection, swarf problems,...).

Many of these procedures can be devised during the design phase. New control/monitoring/breakdown problems surface during implementation and operation which require immediate attention. Some of these problems couldn't be anticipated earlier, or before their occurrence.

2.5 Hierarchical Approaches

Because all of the planning and scheduling problems are large, complex, and require a lot of data consideration, many of these problems have been framed and subdivided within a hierarchy. The solution of each subproblem provides constraints on problems lower in the hierarchy. The partition of FMS problems into *planning* (before time zero) and *scheduling* (after production begins) is one example of a hierarchy.

The *FMS planning problems* are another hierarchical decomposition of the whole set-up problem. Stecke [1983, 1985b] suggests hierarchical approaches to several of these problems.

The *FMS scheduling problems* have also been addressed in a hierarchical manner. Both the uncertainty in demand as well as machine breakdowns are accounted for. Hildebrant and Suri's [1980] approach determine policies to follow in every possible failure state. Kimemia [1982], Kimemia and Gershwin [1983], and

Akella, Choong, and Gershwin [1984], account for demand during any particular failure state at the higher level of a hierarchy. A lower level control determines which part should be input next and when, also considering breakdowns.

2.6 Appropriate Objective Functions

The appropriate, applicable objective functions are dependent on the particulars of the system. Also, different objectives are desirable during each stage of an FMS's life cycle, from conception and design through to operation and day to day scheduling.

During the design stage, some appropriate goals are to minimize anticipated system and operation cost; or to maximize system flexibility; or to maximize flexibility/cost; or to meet the projected production requirements on time. Again, breakdowns need to be considered.

At the planning and scheduling stages, some appropriate system objectives might be to maximize production or system utilization; or to minimize inventory or tardiness or flowtime. Quality is an important issue here. In most cases many objectives are desired and it has to be determined which are more important.

3. MATHEMATICAL MODELS USEFUL TO ANALYZE FMS PROBLEMS

Models are useful to identify key factors that will affect system performance and to provide insight into how a system behaves and how the system components interact. Models should be applied to help determine the appropriate procedures to design and set up a system or strategies to help run a system efficiently.

In this section, we overview many of the models that can be and/or have been used to analyze the problems mentioned in §2. In §4, we indicate how these models can and have been used and for which problems each model might be applicable to. Relevent research on various approaches to date will be noted. A whole range of different models are required in order to address the hierarchy of various problems to be solved.

Each model approaches problems from a different point of view. Some models aggregate some system information or ignore other information in order to solve a particular problem or focus on some particular features. Models can and have provided both operational and or qualitative insights into how an FMS could be designed and operated, or what procedures to run the system are better than others.

Some of the models that we now describe are simulation, queueing networks, including mean value analysis, perturbation analysis, mathematical programming, Petri nets, and artificial intelligence. We note that Buzacott and Yao [1982] review the early FMS research that used analytic models, mostly queueing network models. Suri [1984] provides a brief review of some models that can be used to evaluate suggested or candidate solutions to the problems described in §2.

3.1 Simulation

Depending on the amount of information that is built into a particular simulation model, simulation has the potential to be the most flexible model, allowing as much detail as desired or necessary to mimic reality. Simulation can also potentially be the most expensive and timeconsuming to both develop, debug, and run. Often many computer runs are required to investigate various possibilities before a decision can be made. Of course, this need not be. With the aid of simulation languages and/or sufficient modeling capability, a person can efficiently and quickly capture the necessary detail in a particular FMS simulation model. Usually, a simulation is tailor-made for the particular application at hand.

FMSs have been modeled using some of the existing general purpose simulation languages, such as SLAM II, GASP IV, GPSS/H, or SIMSCRIPT. Recently, many special purpose (but still general) *manufacturing system* simulation languages have been developed. Most of the following samples of these languages can all be applied on a microcomputer. Many have graphics capabilities of various types.

MicroNET is an interactive network simulation language developed by Joe Talavadge through Pritsker & Associates. MAP/1 is another product offered by Pritsker & Associates. SEE-WHY is another developed by British Leyland Systems, Ltd. SIMAN is another network language developed by Claude D. Pegden at Pennsylvania State University. CAPS/ECSL (Computer-Aided Programming for Simulation/Extended Control Simulation Language) had in part been developed in the U.K. and extended by George Hutchinson at the University of Wisconsin-Milwaukee. SPEED was developed by Jim Gross and John Ippolito of Horizon Software, Inc. MAST was developed by John Lenz, now at the University of Wisconsin-Milwaukee, and is an outgrowth of GCMS, developed at Purdue University by John Lenz and Joe Talavadge. GFMS of Draper Laboratories is another outgrowth of GCMS. We do not attempt to evaluate or compare any of these here. The main purpose to acknowledge their (and others) existence and usefulness in modeling an FMS.

3.2 Queueing Networks

Both open and closed queueing networks (OQN and CQN) have been used to model an FMS at an aggregate level of detail. These models can take into account the interactions and congestion of parts competing for the same machines and the uncertainty and dynamics of an FMS. Most simple queueing networks require as input, certain average values, such as the average processing time of an operation at a particular machine tool and the average frequency of visits to a machine. The outputs that are obtained and useful for evaluating the performance of a suggested system configuration are also average values and include the steady state expected production rate, mean queue lengths, and machine utilizations. These models are very efficient, running in seconds of computer time. They also give adequate estimates of steady state performance measures.

Solberg [1977, 1979, 1980] first suggested the use of a simple, single-class, closed queueing network to model an FMS. His computer program, called CAN-Q, uses Buzen's [1973] efficient algorithm to analyze product form queueing networks. Dubois [1983] describes a variation of this model to mimic the availability of various amounts of in-process inventory.

In an OQN, parts arrive externally according to a Poisson process and leave when completed. OQNs have been used by Shanthikumar and Buzacott [1979], Buzacott and Shanthikumar [1980], and Shanthikumar and Stecke [1984] for FMS performance evaluation insights. CQNs contain a fixed number of parts, with no external arrivals or departures. The congestion due to parts competing for the same limited resources (machines) is captured. The required normalizing constant provides most of the relevant measures that can evaluate the performance of a particular configuration.

Mean value analysis (MVA) is an alternative means to Buzen's [1973] algorithm of providing steady state mean performance measures for product form networks. MVA provides an easier means to analyze multi-class queueing networks. Although they are more time consuming to analyze, they also allow more modeling detail. However, these models are less flexible in that they cannot easily handle multiple servers. Its main extension to CAN-Q is the ability to explicitly model each part type, allocating a fixed number of pallets to each type. The production rates of each part type are then provided. (See Suri and Hildebrant [1984].)

Cavaillé and Dubois [1982] apply MVA to systems that contain no machine groups. Suri and Hildebrant [1984] allow the pooling of machines into machine groups in a package called MVAQ. Suri [1983] had demonstrated the robustness of these CQN models to provide reliable results even when the assumptions are quite different from reality.

3.3 Perturbation Analysis

Perturbation Analysis is a technique developed by Larry Ho and his colleagues at Harvard University. The analysis provides additional information to that normally provided by a simulation's output. (See Ho and Cao [1983] and Suri [1984], for example.)

The analysis proceeds as follows. A discrete-event system of interest is simulated and a sample path of a trajectory is observed. The relevant data is collected. One event is perperturbed. Perhaps another customer enters the system, or the mean service time at a machine is changed. The perturbation is propogated. The consequences of that perturbation and others caused by it are tracked over time along the initial sample path. The perturbations are added, using some superposition rules, to determine the net effect on a chosen performance measure. The net result is to obtain some additional results from only one simulation run, but as if n simulations had been performed. From the observations of only one sample path, a gradient vector of output is estimated. Sensitivity analyses can be performed on a number of parameters.

3.4 Mathematical Programming

Some of the design, planning, and scheduling problems that were mentioned in §2 have been formulated mathematically, some as nonlinear integer programs (Stecke [1983]), others using linear (Kimemia [1982]) or integer programs. Dynamic programming has also been used (Kimemia [1982], Kimemia and Gershwin [1983]). Depending on the problems formulated, some formulations are detailed and tractable (and hence immediately useful). Other formulations are detailed and untractable. (However, heuristic or other algorithms can be or have been developed from the exact formulations to solve the problems.) Some formulations are somewhat aggregate and do not contain all of the details of the problem being modeled.

3.5 Timed Petri Nets

Timed Petri nets are useful to model systems whose behavior can be described as interferences between asynchronous and concurrent processes (i.e., FMSs). They can be useful for analyzing transient, steady-state, and real-time control issues.

For certain subclasses of timed Petri nets, in particular, those that are decision-free, very efficient algebraic techniques have been developed recently to analyze the performance of a Petri net. A decision-free, timed Petri net description is equivalent to linear state equations in a (max, +)-based algebra. Machine utilizations, information on the bottleneck machine, cycle time and hence production rate, length of the transient period, can all be obtained quickly via efficient algorithms, based on graph-theoretic concepts for the analysis of cyclic event graphs. See Cohen et al. [1983].

3.6 Artificial Intelligence

Expert systems are being developed and applied to such diverse areas as medical diagnostics, oil or mineral exploration, computer system configuration, and production control. The usual method of encoding knowledge for expert systems is in the form of rules. Production rules are typically of the form: If (a series of conditions are satisfied), then (a set of consequences can be produced). The implementation process of an expert system consists of various ways of scanning lists of the if parts of rules in order to conclude and match them with the then parts.

Expert systems can possibly be developed to address some of the *FMS scheduling* and *control* problems described in §2.

4. MODEL APPLICABILITY

In this section, we indicate the scope of applicability of each of the models that were described in §3. The usefulness of each model is discussed as well as which problems each model can address. Many references are provided.

4.1 Simulation

Simulation can and has been used for all problem types. It is the most widely used modeling tool. For example, Renault Machines Outiles used a simulation model to help design their FMS in Boutheon, France, and will use the simulation in future similar design problems. VÚOSO is developing a simulation model to help solve some of their tool management problems (planning problems) at their FMSs at Čelákovice and Olomouc, Czechoslovakia. The Vought Aerospace FMS, bought from Cincinnati Milacron, uses their simulation to help schedule and control production.

Some existing flexible manufacturing installations have been simulated using several of the simulation languages mentioned in §3.1. For example, Stecke [1977] and Stecke and Solberg [1981] investigated alternative loading and scheduling strategies (using GASP IV) for the system built by Sundstrand for Caterpillar Tracter Company in Peoria, Illinois. Cavaillé, Forrestier, and Bel [1981] simulated a proposed design for the Renault FMS in Boutheon, France. Rathmill, Greenwood, and Houshmand [1983] describe how simulation (using GASP IV) was used to fine tune the design of the SCAMP system in Colchester, U.K. Schriber [1984] describes how GPSS/H can be used to model various unique aspects of an FMS.

Because of machine breakdown and other random events, the nature of an FMS is stochastic, despite deterministic processing times. Expertise in simulation output analysis, in the design of experiments, and in determining appropriate confidence limits is required.

At an advanced stage of the *FMS design* process, simulation is very useful to get a precise view of the behavior of the system as a function of the various candidate scheduling and operating policies. More detailed questions can be analyzed and answered and system parameters determined. However, simulation is too detailed and expensive to use during initial design considerations.

4.2 Queueing Networks

Queueing networks are useful in providing quantitative answers to some *FMS design problems*, such as: determining the necessary capacity (perhaps in terms of the number of carts) of the material handling system; determining the number of machine tools that are required of each type; and locating the bottleneck process(es). Queueing networks are certainly very useful in narrowing in on appropriate "ballpark," preliminary designs, to suggest several possible configurations. Then models that allow more detail can be used, and take over to fine tune the actual design parameters.

Closed queueing network models have proven useful in providing insight into how system components interact as parts compete for the same limited resources. They have provided qualitative information about some of the *FMS planning problems*, in particular, about machine grouping (see Stecke [1981] and Stecke and Solberg [1985]) and cutting tool loading. Most of the loading results pertain to workload balancing when there is no grouping (see Buzacott and Shanthikumar [1980] (saturated system), Stecke and Morin [1985], Stecke and Shanthikumar [1984], and Yao [1984]). For results on unbalancing workloads for unbalanced grouping, see Stecke and Solberg [1985]. Since the most relevant queue discipline for an FMS (which retains product form solutions) is FCFS, which requires exponential servers, queueing networks are *not* very useful in studying breakdown situations in the scheduling and control problems.

4.3 Perturbation Analysis

Perturbation analysis is a nice tool to help pull out much information from the data of only one simulation run of some discrete event system, such as an FMS. Gradient vectors can be determined and sensitivity analyses performed on various parameters.

Of course, the event perturbed cannot be too large. For example, the addition of a new machine tool cannot be analyzed using these PA techniques. The technique has been applied to queueing networks for which product form is not preserved, for example, to study finite buffer situations to help determine the correct size of the buffers.

4.4 Mathematical Programming

Mathematical programming has been used to both formulate, and sometimes solve, several of the *FMS planning* and *scheduling problems*. For example, the FMS grouping and loading problems have been formulated in all detail as nonlinear integer problems. (See Stecke [1983], 1985].) Branch and bound (Berrada and Stecke [1985]) and implicit enumeration techniques are useful for solving several of these problems. Stecke and Talbot [1984] have suggested some heuristics for the *FMS loading problem*.

Kimemia [1982] and Kimemia and Gershwin [1983] formulated the higher level scheduling problem as a continuous-time dynamic program, considering both the rate of demand and the state of the system with respect to machine failures. Linear programming is used at a middle level to determine a suboptimal, but appropriate, production rate control.

Many of the other models described here are used to evaluate the candidate solutions that are generated by some of these mathematical programming techniques.

4.5 Timed Petri Nets

Timed Petri nets, in conjunction with certain modeling conventions, appear to be a quite general modeling tool. In particular, activities requiring many resources (such as a part, requiring a machine tool, cart, robot, cutting tools,...) can be modeled. Many activities having durations (such as processing times, transportation times, set-up times,...) can also be modeled. See Dubois and Stecke [1983] for a description and some examples of these modeling capabilities.

However, at present, the only tool that is available to *analyze* a general Petri net description is simulation. In such general situations, Petri nets are at least useful in determining a well-defined simulation.

On the other hand, for certain subclasses of timed Petri nets, efficient algebraic techniques have been developed to analyze and evaluate their performance. See Cohen et al. [1983]. Although work is still just beginning, Petri nets appear to be useful to investigate real-time, steady-state, and transient scheduling and control problems, such as the determination of relevant control rules to order operations waiting for each machine tool or the determination of the minimum number of pallets required to maintain the required production ratios. Information that is readily attainable from the analysis of a decision-free Petri net includes: the cycle time and production rate; the period and the order of the period; the bottleneck machine; the utilizations of the bottleneck machine and all other machines; the critical resources; and the duration of the transient period that precedes steady state. This information can be used to address many of the *FMS design* and *scheduling* problems that were described earlier.

5. SUMMARY

A brief overview of the various mathematical models that can be used to examine and solve many of the design and operation problems associated with flexible manufacturing has been provided. Each model is useful under different circumstances and for different types of problems. For some problems, it is useful to use a hierarchy of models to solve them.

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