SIMULATION OF ADVANCED MANUFACTURING SYSTEMS

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ABSTRACT

Flexible manufacturing systems (FMSes) use a variety of direct numerical control machines embedded within unique material handling systems. An FMS is a hybrid between fixed production and job shop facilities. Possible order-of-magnitude decreases are foreseen in unit manufacturing costs through the use of an FMS.

The input-output conversion process of an FMS is so complex that evaluation is most readily accomplished by simulation within experimental designs. A Simscript model is in use to: determine FMS physical configuration; create decision rule sets for online computer controls; and reduce the management uncertainty in considering investment in FMS installations.

I. INTRODUCTION

FMSes are rare as yet. Evidence assembled to date indicates that FMSes may be several orders of magnitude less costly per part produced than are conventional job shop systems. FMSes can produce parts at a saving of 30 to 70 percent relative to numerical control (NC) or direct numerical control (DNC) machines. Under some circumstances FMSes may even compete with transfer lines.

We will describe FMSes, and the opportunity they represent for productivity increases. Then, the problems associated with design and evaluation of FMSes will be surveyed. A simulation-based approach to resolving these problems will be described. Representative results from the use of our Simscript model will be used to illustrate points of discussion.

II. FMS RELATED OPPORTUNITIES

Automated transfer lines, such as those employed in the automotive industry, are proven as a way to deal with high volume, long-run, low variety production requirements. At the other end of the spectrum, DNC machine installations have come into use to deal with low unit volume, highly varied production requirements such as are found in job shops.

An FMS installation is a hybrid between these two extremes. Typically, a number of DNC machines are embedded within an automated material handling system (MHS) to provide the physical basis for an FMS. The FMS concept is completed by placing the DNC machines and the associated MHS under online control of a computer.

In concept, a current production plan for a mix of parts to be produced can be specified to an FMS and the computer controlled process will turn out the desired stream of required products. More typically, the mix of parts to be produced will fluctuate from day-to-day. This occurs because of dynamic customer demand in the simple case. A more complex, and similarly stochastic situation occurs when one FMS is producing sets of parts to supply the needs of several assembly lines.

The opportunities made available by an FMS are diverse. Given appropriate FMS operating rules:

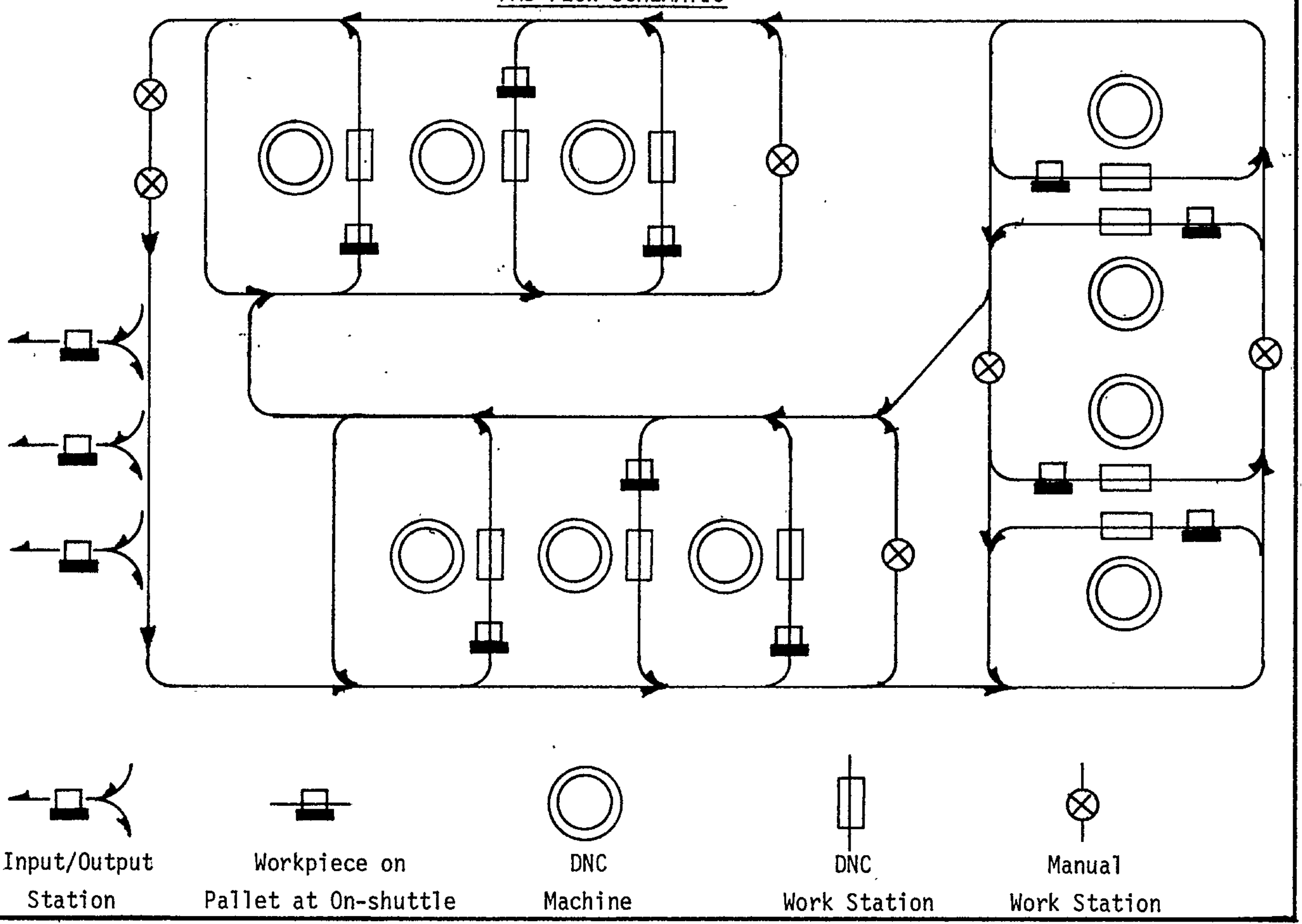
- the DNC utilization can be increased
- the elapsed time to produce parts can be reduced
- the labor content of production can be reduced at the same time as increasing satisfaction
- the necessary redundancy of the total system of production becomes less expensive
- the expediting of production becomes a routine part of the system, while being made less necessary due to the increased system responsiveness
- the men and computers can be combined to raise the process control decision effectiveness

In combination, these features result in dramatic indicated productivity increases. The primary measure of this is the joint decrease in both time and cost to produce equivalent parts.

Illustration 1, FMS Flow Schematic, on the next page synthesizes the most salient features of FMSes. Raw parts are introduced to, and finished parts are removed from, the FMS in fixtures which are mounted on pallets. These loaded pallets are carried upon carts which travel on the track network of the MHS sub-system. The pallets also carry fixtured parts onto shuttles preparatory to metal cutting operations by one of the DNCs. Other shuttles serve to store pallets containing

ILLUSTRATION 1.

FMS FLOW SCHEMATIC



parts completed by a DNC before returning them to the MHS sub-system.

The DNC machines are grouped physically on the basis of criteria designed to:

- associate like DNC machines for the purpose of providing part production redundancy
- ease machine maintenance and management of the various types of fixture
- minimize traffic jam, for both pallets and carts
- provide logically located cleaning, inspection, and fixture exchange work stations
- minimize the complexity of the cart sub-system network

III. PROBLEMS OF FMSes

The opportunities and net productivity increase cited above for FMS installations are not sought without encountering problems.

Cost, in terms of investment in high systems technology, is a severe problem. This investment has several distinct components. Most obvious is the capital cost of the physical equipment, comprised of; the DNC machines themselves, the MHS components, and the online computer installation ---all supported by the requisite emergency power supply facilities. Another major component is the development of the online decision-rule software for management of the FMS. A third cost component is the flexibility and recovery capability needed by an FMS. The dynamic workload mix which must be handled and the need to operate smoothly as the DNC machines move in and out of service dictate that a variety of ancillary equipments (fixtures, tools, pallets, and carts) be available in more than normal volumes. Last, the investment base of FMS systems can be extremely high due to the length of time involved before the benefits of an FMS installation result in revenue contributions.

A second major consideration is that of the opportunity cost. A firm for which an FMS is perhaps appropriate must face the fact that an FMS may also be appropriate for competitors. When a competitor converts to FMS-based production, the firm which does not do so can expect to be under a severe competitive disadvantage. This opportunity cost creates not only a real cost disadvantage but also a responsiveness and delivery time disadvantage. The latter may have a more significant negative impact on profits and/or growth than does the actual cost disadvantage.

Management uncertainty is a third major issue in deciding whether or not to invest in FMS production facilities. Certainly, the gamesmanship with respect to one or more competitors embracing the FMS technology is real. Beyond this, the determination of the range of parts mixes which the projected FMS installation must handle effectively is critical. Long-run marketing strategy must be an explicit consideration in the decision for or against commitment of corporate resources to an FMS. Finally, the threefold high technology involved in FMSes increases the management uncertainty. The joint use of many DNCs, the use of state-of-the-art computer controlled MHSes, and the development of very advanced total system online computer control software---all these combine to raise the uncertainty surrounding the FMS decision.

A fourth major problem associated with the opportunity to convert to FMS-based production is the complexity of the many considerations which must be resolved jointly. Product-market specifications, continuing industry competitive postures, company financial resources, engineering and production competences, and fundamental industrial relations issues are all integral to the FMS decision. Each of these factors is a primary element of total corporate strategy.

Even given a strategic framework which deals adequately with all these aspects, the design, development and management of an FMS is complex. Table 1, below, portrays an approach to the creation of an FMS. The strategic aspects are dealt with in stages. An answer to any one of the ten questions shown in Table 1 has a significant impact on at least one of the other representative issues.

The left edge of Table 1 shows the sequential approach to creation of a sound FMS concept. At each succeeding stage of analysis, different logical constraints become more specific and result in changed restraints. Thus, it is usually advantageous to return to an earlier stage of analysis so that a stable concept may be found. This allows the newly realized insights to be reflected in a more appropriate overall business design.

The remainder of this paper skethes an existing simulation tool for use in this iterative method of resolving the major interacting FMS design issues.

IV. SIMULATION APPROACH

The elements to be encompassed in an FMS design are presented in Illustration 2, FMS Design Elements, on the next page. The simulator which underlies most of the work reported here focuses upon the "conversion" module of Illustration 2. Some features of the "control" and "output" modules are also included within the existing Simscript model. These additional features are primarily of the diagnostic or status and results nature. They do not, as yet, include the interactive man-machine decision system elements.

The simulator itself was designed as a general "testbed" vehicle. That is, the simulator could be applied to a wide variety of FMS type processes, not merely to the simulation of FMSes. For example there is no logical reason why the existing simulator could not be applied to the clerical work processes of today's paperwork factories, although such an application would be highly inefficient.

TABLE 1

Iterative FMS Development Approach

Stages of FMS Development	Representative Strategic Questions by Stage
1. WORKLOAD	• What product- market is to be served? • What volume is the installation to produce?
2. MACHINES	• What tradeoff of capital investment for lower unit costs is economic? • How many DNCs of each separate capability or class are needed?
3. PHYSICAL LAYOUT	• Where is operational redundancy most effectively utilized? • How are maintenance and quality control requirements best served?
4. MATERIAL HANDLING SYSTEM	• What ranges of parts mixes can be produced profitably? • How rapidly must the system respond to shifts in demand?
5. OPERATING RULES	• What parts priority assignment logic fully uses FMS flexibility? • How are work-in-process imbalances avoided or overcome?

Within the context of FMS design simulation, our simulator can be described best in terms of:

- the initial conditions to be prescribed
- the operating parameters and decision rule specifications
- the diagnostic and results data wanted

The equipments configurations comprise one set of initial conditions to be stipulated. How many DNCs of each type are to be included? Which way are the machines to be grouped into banks? How many carts, pallets, and fixtures of each type are to be available? What MHS network design is to be evaluated? Which machine (or I/0) banks are able to receive carts directly from which other banks? Where are manual work stations to be inserted among the DNC transfer stations and the MHS interbranch stations? How many pallet positions are to be represented in each of the DNC on-shuttles and off-shuttles? What type and/or mix of shuttles are to be used; FIFO or random servicing shuttles? There are no inherent constraints which prescribe a logical solution to these equipment issues.

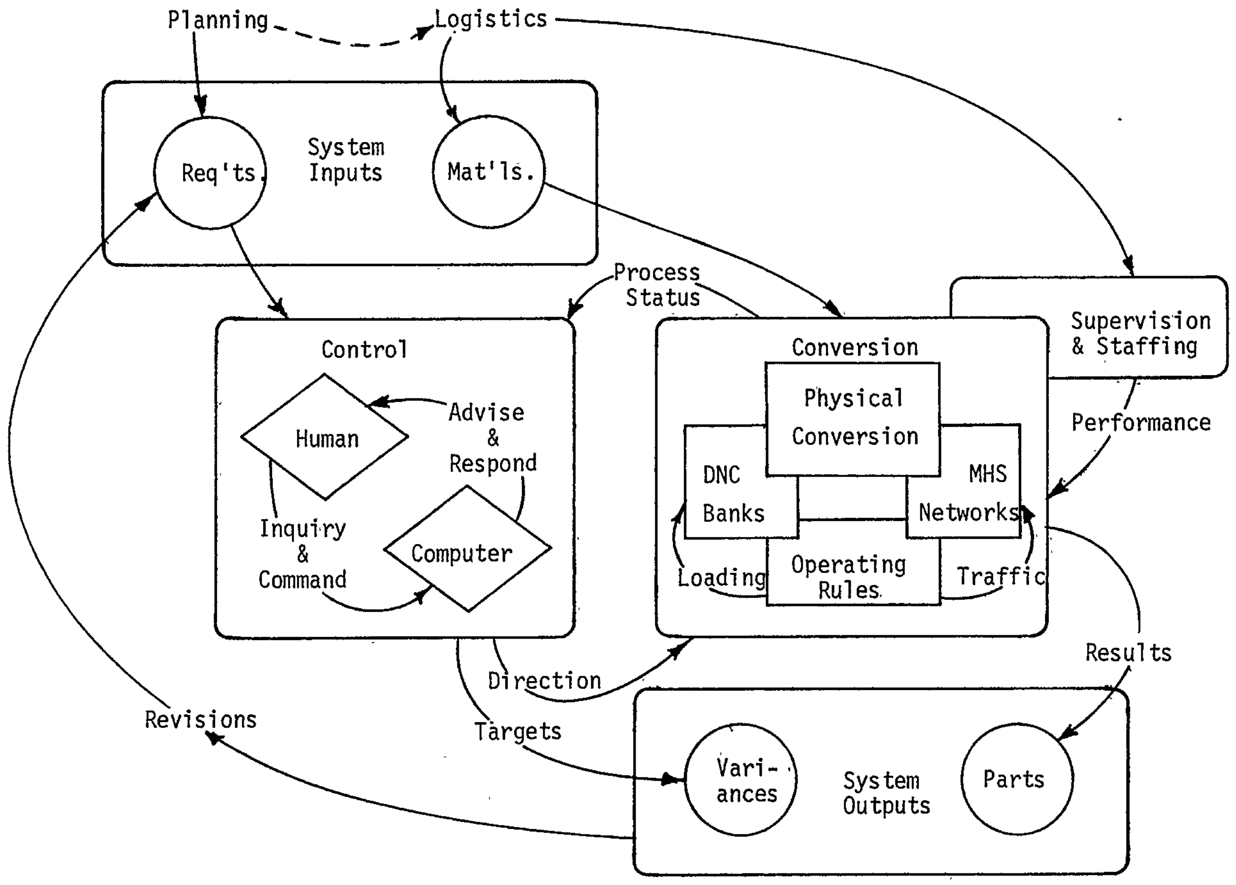
Another initial conditions specification to be stipulated is the beginning work-in-process. What parts and equipments are where within the FMS? How far has processing progressed for each of these parts?

Operating parameters to be set include the specific equipment downtime pattern, if any, for use in the simulation. Currently, this is not a probabilistic process. Instead it is a prespecified process so that identical conditions can be imposed upon the various FMS configurations. This assures comparable controlled contrasts in results.

Similarly, the work requirements are specified in terms of parts routings, work sequences within routings, and individual operations by a machine (and alternate machine) on each of the parts. The time required to perform each operation for a given part on each of the allowable machines is needed. The various transport and manual operation speeds are needed. And finally, the desired rate of production for parts and/or sets of parts must be specified. As with downtime, this can be a changing pattern of demand mix, but it is not exogenously probabilistic.

ILLUSTRATION 2.

FMS DESIGN ELEMENTS



The operating decision rules to be followed in utilization of the FMS also must be specified. These rules include priority assignment on a contingent basis. They also indirectly govern wheter queuing will tend to take place at the input or the output side of the DNC machines, or on the carts. Decision rules also specify the conditions under which an operation will be performed upon other than the preferred machine. Lastly, rules are needed to correct for deviations from targeted system output balance.

A wide variety of output is available from the simulator. System status "snapshots" can be obtained either by prescheduling or on a contingency basis. In either case a condition report of traffic density, queuing, instantaneous idleness, and part status relative to schedule can be obtained. The last ranges from specific detail about a particular part to the overall ability of the system to meet the desired production. A series of the snapshots enables the analyst to study dynamics which otherwise would be concealed. Study of these dynamics is particularly useful in confirming and understanding convergence towards desired system states.

Elapsed reports of two varieties are available. They may be cumulative totals and/or averages from the beginning of simulation. Alternatively, the elapsed reports also may be set to cover prespecified periods at intervals chosen by the user. The purpose of these reports is to give data on the utilization of each of the system resources and the production resulting from the use of these resources.

Debugging reports are available, but are not normally used by FMS investigators. These are for the use of the analysts in establishing model validity. All model applications provide a standard run report which summarizes the model's initial conditions. The run report summarizes the physical configuration, the workload and process parameters, and the set of decision rules applied. A run report's value lies in enabling the verification of the conditions of simulation and in preserving these conditions for subsequent use in analyzing results in the elapsed reports.

The Simscript program implementing the model consists of approximately 10,000 statements. Running on UCC's 1108, the rule of thumb developed for estimating run time was one minute of 1108 time for ten hours of simulated time. The run time is very sensitive to the workload and MHS configuration. A typical input data deck to the model has 600 cards. Half of these are Simscript initialization cards, remaining relatively constant from model to model. The other 300 cards serve to describe the user's particular model.

The FMS simulator has been run a large number of times for a variety of designs and operating rule sets. Further simulation variables have involved the production requirements and the equipment downtime pattern. Whatever the immediate purpose of any run, the value of the run comes from observing its net effect due to the complex interrelationships contained within the model in comparison with the results of a standard run.

Each run of the simulator produces one data point for each of the many dependent variables from the given set of independent variables. A number of runs must be made in order to identify a combination of the independent variables which generates superior results. This often requires a large number of simulation runs before conclusions can be reached. However, a typical FMS system may represent a ten million dollar investment. The operatings costs of an FMS may vary considerably as the FMS parameters change. Therefore, the expense of simulation can be cost justified from the vantage point of both the system vendor and the system purchaser. The more experience that is gained with the simulatyr, the more apparent it becomes that other methods of study probably would not serve -oth design engineering and management decision making as thoroughly.

V. REPRESENTATIVE RESULTS

The FMS simulator has been used for general research into advanced manufacturing systems. It has also been used for several years in connection with an FMS system which is now in production. The simulator helped in conducting the initial feasibility studies while the system installation sale was being negotiated. Subsequently, the simulator has been applied frequently, contributing to the evolving system design. It has also been used to evaluate some system operation rules which were based upon production experience and to develop other rules on the basis of FMS disclosed interactions. Finally, the simulator has been used as one basis for identifying realistic production expectations. Though the actual installation of the manufacturing system will not be complete for another six months, the actual production results to date are quite consistent with the simulator-based expectations.

Among the conclusions which have been reached from these and related simulation outcomes are:

- that the less expensive FIFO shuttles are preferable to the random sequence shuttles on a cost effectiveness basis
- that it is more effective to have parts waiting to be processed at on-shuttles than to have parts accumulate on the off-shuttles
- that DNC idle time is decreased if parts are not stored on carts because a higher proportion of the carts are available for the pickup of parts from off-shuttles
- that the projected demand should be no more than 75 to 80 percent of rated capacity of the collective DNC machines---or else the system recovery from the expected downtime will be erratic and unacceptably slow
- that investment in reserve carts, pallets, and fixtures of about 40 percent more than the expected normal requirements is needed to meet dynamic peak loads and restore normalcy
- that the system performance can be extremely sensitive to the availability (or lack) of extra fixtures

A general point to be emphasized as being more fundamental and valuable than any specific points, such as those made above, is that the FMS effectiveness is most sensitive to the particular set of operating rules which are applied by the system control computer in managing the flow of parts through the FMS. The control problems with which this set of rules must cope become more severe as the FMS is scaled more realistically.

For example, suppose that there are 20 different part types, each with their own distinct routing and production rates being processed simultaneously. The processing FMS contains 14 DNC machines and has 40 possible cart positions. Using 20 carts and an appropriate workload, the control computer decision rule set would send more than one command per second to the MHS sub-system of the FMS.

It is these FMS commands, derived from a set of decision rules for a specific FMS physical configuration and product mix spectrum, which govern the efficiency and effectiveness of the FMS. It is precisely this complex interaction which the FMS model simulates. And it is the FMS input/output and resource utilization measures of that simulation which the model provides as a basis for comparing alternative combinations of:

- DNC machines within the FMS
- MHS network links connecting the DNCs
- complements of ancillary equipments
- operating decision rule sets
- and, anticipated product mixes and loads

A firm seeks an FMS installation in order to gain the automation benefits of a transfer line while preserving the flexibility of stand alone NC machines. It should not be surprising that defining an acceptable FMS is an iterative process as illustrated in Table 1. Nor should it be surprising that very few generally applicable "rules-of-thumb" can be cited. The key fact is that FMSes have been designed, sold, and installed---using the simulation-based approach presented here.

VI. SUMMARY

We have illustrated that simulation is the most practical method for the initial designing and subsequent evolutionary tuning of the economically desirable FMS systems. Basic to this discussion was the ability of FMS simulation to reduce investment decision uncertainty for top management. The fact that the FMS simulator is also vital to the technical management charged with implementation of an approved FMS must be considered to be secondary.

While these two direct results of simulation are vital, there is an important additional effect. The FMS modeling not only allows but requires top management to focus upon their long-range issues of strategy. These issues, mentioned in the earlier discussion of problems, include: (1) product-market specification, (2) intercompany competitive postures, (3) company financial resources, (4) organization technical competences, and (5) manpower development and management.

Further work is in order. Reconsider Illustration 2. The simulation model which now exists does not encompass the complete "control" module. The value of combining humans and computers into joint decision making systems has been demonstrated in numerous settings. Fuller realization of the benefits of FMS installations will come about when the interactive "control" module is included in the simulation---and the findings are translated into the real time computer interface which supervises an actual FMS.

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