III. PRODUCTION PLANNING

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MACHINE UTILIZATIONS ACHIEVED USING BALANCED FMS PRODUCTION RATIOS IN A SIMULATED SETTING

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Abstract

Stecke [21] has developed mathematical programming approaches for determining, from a set of part type requirements, the production ratios (part types to be produced next, and their proportions) which maximize overall machine utilizations by balancing machine workloads in a flexible manufacturing system (FMS). These mathematical programming (MP) approaches are aggregate in the sense that they do not take into account such things as contention for transportation resources, travel time for work-in-process, contention for machines, finite buffer space, and dispatching rules. In the current study, the sensitivity of machine utilizations to these aggregations is investigated through simulation modeling. For the situation examined, it is found that achieved machine utilizations are a strong function of some of the factors ignored in the MP methodology, ranging from 9.1% to 22.9% less than those theoretically attainable under the mathematical programming assumptions. The 9.1% degradation results from modeling with nonzero work-in-process travel times (i.e. 2 minutes per transfer) and using only central work-in-process buffers. Resource levels (e.g. the number of automated guided vehicles; the amount of work-in-process; the number of slack buffers) needed to limit the degradation to 9.1% correspond to FMS operating conditions which are feasible in practice.

Keywords

FMS, production ratios, mathematical programming, levels of detail in modeling, balanced machine workloads, machine utilizations, dispatching rules, simulation.

1. Introduction

An FMS manager carrying out short-term planning for FMS use is faced with the task of determining, from a set of part type requirements, the subset of part types to be produced next and the proportions in which to produce them. (Other short-term planning tasks faced by the FMS manager are discussed in [20].) The part types to produce next, and the proportions in which to produce these parts, are referred to as a set of *production ratios.*

Stecke [21] has developed mathematical programming (MP) formulations to determine production ratios which maximize overall machine utilization by balancing machine workloads in an FMS. (For the machining resources of which an FMS is composed, *overall machine utilization* is the average of the individual machine utilizations. Machine workloads are *balanced* as much as possible relative to a target workload when the sum of overloads and underloads on machines in the FMS is minimized.) However, these MP formulations only take into account the machining resources of the FMS, and the operation types and times needed to produce each of the required part types. The MP methodology is designed for making aggregate decisions at an early point in the planning phase (see Suri [27]).

The objective of the research reported here is to compare the theoretical overall machine utilization resulting from application of the MP methodology with the machine utilizations actually achieved in a model which more realistically accounts for such additional FMS characteristics as constrained resources for transporting work-in-process (WIP), transfer times, limited buffer space, contention for machines, and the rules used to dispatch WIP to machines. In particular, for a hypothesized FMS and a required set of part types, the main objectives are to: (1) determine the level (or alternative levels) of selected non-machining FMS resources needed to achieve theoretical overall machine utilizations when transfer times are realistic; (2) estimate the degradation in overall machine utilizations when there are inadequate non-machining resources; and (3) measure the sensitivity of overall machine utilizations to two alternative WIP dispatching rules. An additional objective is to: (4) measure the influence of two alternative WIP dispatching rules on the average and variance of part type manufacturing times. Common to each of these objectives is the goal of better understanding the underlying reasons for observed behavior by measuring and interpreting such things as the number of transfers of WIP into buffers, the residence time of WIP in buffers, and the fraction of the time that various numbers of buffers are occupied and various numbers of AGVs are in use.

Section 2 introduces and discusses the FMS scenario which is investigated here. Section 3 compares the simplifying assumptions made in the mathematical programming solution for such scenarios with some of the characteristics of a realistic FMS. Section 4 discusses the levels of aggregation used in this work, and section 5 explains how the section 2 FMS is interpreted as a flexible flow system for purposes of this study. Section 6 presents the details of the simulation model used for the study, and section 7 comments on model verification. Section 8 discusses the design of the simulation experiments. Section 9 presents and discusses results. Sections 10 and 11, respectively, summarize the work and comment on future research directions. Calculations are then shown in a series of three appendices.

2. The FMS scenario investigated

Assume the machining resources in an FMS consist of 1 mill, 2 drills, and 2 vertical turret lathes (VTLs). Suppose 10 types of parts are to be produced by this FMS, with the various part type machining and production requirements shown in table 1. In run 1 of the production process, the FMS is to be used to build a subset of the 10 part types. (Run 1 ends when the production requirement for one of the part types in this subset has been met; see below.) The run 1 production ratios are to be determined so that workloads on the three machine types are balanced.

Table 1

Specifications for a particular FMS problem

Part type	Machining times (minutes)			Total parts ordered
	Mill	Drill	VTL	
1	10	60	50	60
2	15	20	40	50
3	40	10	30	30
4	30	20	20	30
5	10	50	20	35
6	10	30	20	45
7	20	10	10	15
8	15	20	30	25
9	25	10	20	30
10	5	40	40	50

Stecke and Kim [23] have presented solutions both to the specific problem stated above, and to several variations on this problem. (Refer to Stecke and Kim [22,24,25] for treatment of the problem of how to operate the FMS *after* run 1 is finished.) A set of production ratios which balances machine workloads for this problem specifies that part types 2, 5, 6, 8, and 10 are to be built in proportions of 2, 1, 2, 1, and 1 [23]. That is, of every 7 parts built, 2 are to be of type 2; 1 is to be of type 5; 2 are to be of type 6; etc. The theoretical overall run 1 machine utilization corresponding to this set of production ratios (assuming zero WIP transfer time) is 95.2%, and the corresponding theoretical mill, drill, and VTL utilizations are 76.1%, 100%, and 100%, respectively. (The calculations are presented in appendix A.)

It is the set of FMS machining resources, the set of part type requirements, and the run 1 production ratios described above which are the basis for the study of overall machine utilization reported here.

3. FMS factors ignored in the MP solution

The mathematical programming solution for the section 2 problem only takes into account the machining resources of the FMS and the part type information in table 1. The solution ignores such *secondary* FMS resources as the number and types of buffers to provide for work-in-process (WIP). (The types of buffers provided might include central buffers and/or buffers local to machines.) The level of resources used to transfer WIP from point to point in the system is not taken into account, either, in the mathematical programming solution.

(Pallets and fixtures, loading and unloading stations, and washing and inspection stations are other secondary FMS resources not mentioned in the section 1 problem statement. As explained further below, however, these secondary resources can be taken into account in the MP solution of the machine balancing problem.)

Furthermore, the MP solution ignores such *geometric aspects* of the FMS as the absolute and relative locations of the various system resources, and the routes for transfer of WIP (such as pathways for automated guided vehicles and/or the placement of conveyors). (The role played by these geometric considerations in FMS design has recently been discussed by Heragu and Kusiak [8].)

Nor does the MP solution take into account such *secondary time requirements* as the time required to transfer WIP from point to point in the system, or the time required for palletizing, depalletizing, fixturing, defixturing, and refixturing parts. The time required to move empty pallets from unloading stations to loading stations is not considered, either. (As explained in section 5, however, such other secondary time requirements as the time needed to wash and/or inspect parts between operations, when such washing and/or inspection is necessary, can be taken into account in the MP formulation.)

FMS *operating policies* are ignored in the mathematical programming solution, too. One such operating policy involves the quantity of WIP permitted in the system. Another is the part input sequence. (That is, when work on a part is finished, what type of part is to be admitted next to take its place? For a given set of production ratios, there are usually many alternative part input sequences which could be specified. There are also many alternative part input sequences even when production ratios are not explicitly specified.)

A third type of operating policy not considered in the MP formulation involves the rules used to dispatch work to machines. For example, dispatching rules based on FIFO (first-in, first-out) might be used, or rules based on SPT (shortest processing time) might be used. (More of the specifics of the FIFO-based and SPT-based dispatching rules used in this study are given in detail in section 8.)

Potential system *operating discontinuities* resulting from tool failures, other types of machine breakdowns, and the periodic withdrawal of machines from service for such things as scheduled maintenance, are also not taken directly into account in the MP solution for the workload balancing problem. The possibility of machine substitution is not considered, either. (Machine substitution is the use of one type of machine to accomplish a step normally done by another type of machine. Machine substitution might take place when a preferred type of machine has broken down, or is undergoing periodic maintenance, or is being contended for in the short run by a large number of jobs.)

Finally, the mathematical programming solution does not take into account such *secondary job characteristics* as due dates or lateness penalties. (Note that no due dates or lateness penalties are included in table 1.) Also not considered is the order in which various types of jobs use various types of machines and whether there is any potential flexibility in this order.

In conclusion, the MP solution methodology for the workload balancing problem addresses only a subset of the issues involved in the realistic operation of a flexible manufacturing system. This leads to the question of how applicable the MP solution to a given problem will be in more realistic settings. What levels of secondary FMS resources are needed to achieve the overall machine utilizations promised in the MP solution? For a given level of secondary resources, what machine utilizations can be achieved? At what rate does overall machine utilization change with changing levels of secondary resources? And what influences do operating procedures have on the answers to these questions? The purpose of this study is to investigate the answers to such questions for a specific case, with the longer term goal of developing guidelines for answering questions of this type in general.

4. Model aggregation in this study

In modeling a system, it is important to determine which factors are to be aggregated or possibly even ignored for the purposes at hand. This section discusses why some of the features of flexible manufacturing systems outlined in section 3 can be ignored in the present study.

Machine breakdowns. If a machine breaks down, this causes the system (and therefore the problem) to change in the sense that the set of machining resources making up the FMS is (temporarily) reduced. The purpose of this study is to investigate machine utilizations achieved for a given set of system resources, prior to possible eventual change in the composition of these resources. Because we want to understand the issues separately, machine breakdowns (or, alternatively, the periodic withdrawal of machines from service for preventive maintenance) are not considered in this work. (For a recent study which deals with unreliable machines in an FMS, see Maimon and Gershwin [12].)

Due dates. The degree of importance of due dates varies from time to time and from FMS to FMS. Due dates can be of immediate importance in some cases (e.g. in a demand-driven FMS), and of lesser importance in other cases (e.g. when part type requirements have been specified to maintain inventory levels). For example, many systems are driven by weekly, or even monthly, production requirements. The planning horizon may then allow such systems to be operated with the objective of maximizing overall machine utilization in the shorter term. The periodic requirements may best be met by maximizing overall machine utilization in the shorter term, subject to possible longer term modifications designed to meet periodic due dates. It is assumed in this study that the objective is shorter term maximization of machine utilizations, and so due dates are not considered.

Refixturing of parts. In an FMS, some types of parts may have to leave the system temporarily from time to time to be refixtured. After refixturing, such parts are then reintroduced into the system and additional machining steps are performed on them. It is often possible to treat refixtured parts as new parts being introduced into the system, with the restriction that refixtured parts of a given type must be (re)introduced in ratios identical to those for the pre-refixtured parts of the same type. The refixturing complication can be taken into account in the MP methodology for determining production ratios which balance machine workloads. Because the purpose here is to study the sensitivity of achieved overall machine utilization to non-machining aspects of an FMS, refixturing is not an issue in this work.

Washing and inspection stations. After each operation (or after a series of operations), an in-process part may visit a washing station to remove chips from the part before it goes to its next machine or station. In addition, parts may be subject to in-process inspection and/or to inspection when finished. Washing and inspection stations, if present, can be treated as machines both for purposes of this study and in the MP formulations. We do not model these operations in this study.

5. Interpreting the FMS as a flexible flow system

For purposes of this study, the flexible manufacturing system described in section 1 is interpreted as a Flexible Flow System (FFS). This interpretation is pictured in fig. 1. All part types are assumed to use machines in a unidirectional mill-drill-lathe sequence. No machine type is used by a part type more than one time, and no machines can perform substitute functions. This flexible flow system has the characteristics of an FMS, except that alternative routings are not permitted.

In most previous studies of FFSs (e.g. [1,2,9,13,30]), the *production requirements* for the part types that will be produced are scaled down to their smallest integer multiples, and these are then used as the production ratios. (Producing in ratios proportional to production requirements defines the machine workloads, which are then almost always unbalanced.) This contrasts with the approach taken here of working with production ratios designed to balance machine workloads.

Previous FFS work has often included studying the effect on system performance of alternative choices of part input sequences. In contrast, the work

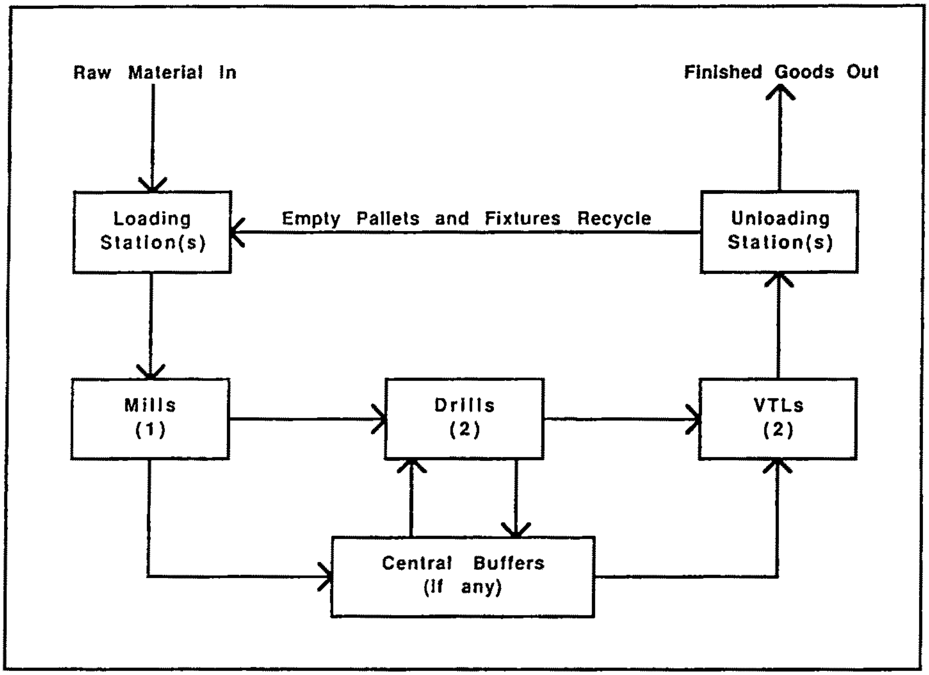


Fig. 1. Interpretation of the FMS as an FFS.

here focuses principally on the influence of secondary FMS resources on machine utilization, and does not include investigating how part input sequences for a given set of production ratios affect system performance.

The reported FFS studies typically ignore travel time and contention for transportation resources. These two important aspects of a realistic system are explicitly modeled in the current study.

As implied in fig. 1, we choose to work only with central buffers here, and do not provide buffers specific to individual machines (or machine groups). There are existing FMSs which only have central buffers (e.g. the Sundstrand/Caterpillar FMS in Peoria, Illinois [26]). Some other FFS studies ([24,25]) have also assumed that there are individual machine buffers in the system. In most of the reported FFS studies, however, small buffers of capacity 1 or 2 have been provided between machines. (In one study, however, the system modeled has 30 buffers for 4 machines [1].)

As also implied in fig. 1, no possibility of temporary storage is assumed for fixtured parts, either before the first operation or after the last operation. (Note that if neither loading or unloading is a bottleneck, such temporary storage may not be crucial.)

6. Overall particulars of the FFS simulation model

Some important aspects of the simulation model built and used for this study have been described and explained in sections 4 and 5. An overall summary of the characteristics and assumptions of the model is provided below, using categories introduced in section 3.

(1) *Secondary FMS resources*

Automated Guided Vehicles (AGVs) transport work-in-process, with the number of AGVs included as a model parameter. (The term AGV is used here for convenience and to provide vocabulary for later presentation of results and discussion; however, the model is not specific to AGVs as such, but applies for any vehicle- or carrier-based technology.)

Only central buffers are provided for work-in-process. The number of buffers is a model parameter.

Pallets and fixtures and loading and unloading stations are modeled explicitly, and are model parameters. Fixtures are specific to part types, but pallets are not.

(2) *Geometric considerations*

The geometry of the system is not modeled. This means that neither relative nor absolute locations of loading stations, machines, buffers, or unloading stations are explicitly represented in the model, and the positioning of AGV guidepaths is not taken into account.

(3) *Secondary time requirements*

Transfer time for work-in-process is a model parameter. As a first approximation, the transfer time between any two points in the system is assumed to be independent of the points involved.

Palletizing and depalletizing times, and fixturing and defixturing times, are also model parameters.

The time required for empty pallets and fixtures to move between he unloading and loading points is a model parameter. (The model parameter settings used in this study are given in section 8.4.)

(4) *Operating policies*

The model provides the user with a choice between either FIFO-based or SPT-based rules for sending WIP to machines.

The *FIFO-based dispatching rule* takes this form:

(a) When possible, send WIP to an idle machine from a preceding machine, rather than from a buffer. (In other words, give machine-to-machine transfer precedence over buffer-to-machine transfer. This approach unblocks the preceding machine as soon as possible, and reduces the number of transfers of WIP into buffers.)

(b) For machine-to-machine transfer, dispatch that unit of WIP which has been waiting the longest (FIFO) for the now-idle machine.

(c) For buffer-to-machine transfer, dispatch that unit of WIP which has been waiting the longest (FIFO) for the now-idle machine.

(d) In terms of machine-to-buffer transfer, dispatch that unit of WIP which has been waiting the longest (FIFO) to be moved from the machine at which it is now finished.

Note that the dispatching rule described above, although FIFO-*based,* is not truly FIFO because (a) gives preference to WIP coming from a preceding machine over WIP coming from a buffer.

The *SPT-based dispatching rule* takes this form:

(a) If two or more units of WIP are waiting for a machine which has just become idle, dispatch that unit which has the shortest processing time (SPT) on the machine. (No regard is paid to whether the WIP is coming from a preceding machine or from a buffer.)

(b) If there is an SPT-tie between WIP at a preceding machine and WIP in a buffer, give priority to the WIP at the preceding machine. (This unblocks the preceding machine as soon as possible and reduces the number of transfers of WIP into buffers.)

(c) If there is an SPT-tie between WIP in a common type of location (that is, at preceding machines or in buffers), use first-come, first-served to resolve the tie.

The quantity of work-in-process permitted in the system is a model parameter. The part input sequence is also a model parameter.

(5) *Operating discontinuities*

As explained in section 4, neither machine breakdowns nor the periodic removal of machines from service (such as for routine maintenance) is modeled. Neither breakdowns nor maintenance of equipment used for WIP transfer is modeled, either.

(6) *Secondary job characteristics*

Neither order due dates nor lateness penalties are specified in the section 1 description of the part type orders on hand, or are recognized in the simulation model as factors to be considered. The rationale for this is given in section 4.

7. Model construction and verification

The simulation model, which was built in GPSS/H, version 2 [7,16], was *verified* (that is, the correctness of the computer code was established) by techniques reported in [17]. These techniques included simulating with a series of increasingly more complicated cases for which model outputs were checked against correct results determined independently by hand, and interactively monitoring the movement of randomly chosen work-in-process as it passed through the system. Interested readers should refer to [17] for more particulars.

The model was built and verified by the first author in about seven working days. The model consists of about 150 GPSS blocks, and the model file contains about 425 statements. The computer time required to perform simulations with the model is given in section 8.

8. Design of the simulation experiments

The simulation experiments in this study were designed to measure overall machine utilization achieved by the FMS *at operating equilibrium* for the scenario described in section 2, and to determine (under the section 6 modeling assumptions) the sensitivity of key performance variables to: the number of AGVs, the number of buffers, the WIP level, and the rule used to dispatch parts to machines. The method used to establish conditions of operating equilibrium is explained in section 8.1. The resulting experimental design is presented in section 8.2. Section 8.3 then briefly indicates why a full factorial design was used in this work. Sample size and sample types are discussed in section 8.4, and section 8.5 describes the settings of model parameters for which experiments were performed.

8.1. ESTABLISHING OPERATING EQUILIBRIUM

Operating equilibrium corresponds to a dynamic situation in which measurements, produced by the model, cycle about their average values as the simulation proceeds. All simulated times used in this study (e.g. the machining times specified in table 1 and WIP transfer times) are *deterministic*, and so there are no variations in model behavior resulting from sampling from probability distributions. (No random number generators were used in the simulation.) The cycling in the values of measurements results from the fact that the part input sequence is cyclic. As pointed out in section 1, the part input sequence is composed of part types 2, 5, 6, 8, and 10 in proportions of 2, 1, 2, 1, and 1, respectively. An input cycle consists then of 7 parts in total (2 + 1 + 2 + 1 + 1). The input sequence used in this design, expressed in terms of part type numbers, is 2, 6, 5, 2, 8, 6, and 10. (The chronological order of part introduction is 2, 6, 5, 2, 8, 6, 10; and then 2, 6, 5, 2, 8, 6, and 10 again; etc.) This input sequence was *arbitrarily chosen* from the potential sequences derived as permutations of the production ratios, except that the repeating part types (types 2 and 6) were nonconsecutive. As stated above, this study is not directed at sequencing and/or scheduling, but considers other FMS influences on machine utilization; as a result, the part input sequence was not varied in the experimental design (however, see section 9.9).

In general, an FMS can spend part of its time operating at equilibrium and the rest of its time operating in transition, moving from one set of equilibrium operating conditions toward another. If part type production requirements are large enough, an FMS can reach operating equilibrium; otherwise, for a given set of production ratios, operating equilibrium may not be achieved before the production ratios have to be changed. This study focuses on overall machine utilization during conditions of operating equilibrium, for comparison purposes. It is assumed, then, that production requirements are large enough so that operating equilibrium will be reached and then sustained for some time (see [22,24,25] for studies of FMS behavior when operating during periods of transition).

The model as built was devoid of WIP initially. At simulated time zero, parts equal in number to the chosen WIP level, and with no operations yet performed on them, were admitted to the system. Prior to collecting model outputs for purposes of this study, it was then necessary to determine how long to simulate to arrive at conditions of operating equilibrium. This determination was accomplished experimentally for a number of alternative model settings in the following way:

(1) After admitting the initialization parts, start the simulation and proceed until an entire 7-part input sequence has been admitted to the model.

(2) Suspend the simulation, obtaining output but leaving work-in-process as is.

(3) Resume the simulation, proceeding until another 7-part input sequence has been admitted to the model.

(4) Suspend the simulation, obtaining output but leaving work-in-process as is.

(5) Repeat (3) and (4) a large number of times (e.g. 50 times).

(6) Study the pattern of simulated time elapsed between consecutive sets of output. When this pattern begins to cycle (that is, to repeat itself), operating equilibrium has been established.

A numeric example will help to clarify this procedure. Consider table 2, which shows a hypothetical time series of simulated time elapsed between consecutive sets

Table 2

An example of repeating patterns of elapsed simulated time between consecutive output sets

Output set	Simulated time (minutes) elapsed since preceding output set was produced	
1	110	(transient period)
2	114	
3	119	
4	116	
5	120	(equilibrium; model cycle 1)
6	117	
7	121	
8	114	
9	122	
10	120	(equilibrium; model cycle 2)
11	117	
12	121	
13	114	
14	122	
15	and so on	

of output produced per the above scheme. During the period of model operation corresponding to output sets 1 through 4, transient conditions are in effect. For the next 5 sets of output, the elapsed simulated time between output sets is 120, 117, 121, 114, and 122. This pattern then repeats itself for the following 5 sets of output, and for the 5 sets of output after that (not shown in table 2), ad infinitum. We conclude that in this case, operating equilibrium has set in after only 459 simulated minutes of model operation (459 = 110 + 114 + 119 + 116).

The number of output sets produced before operating equilibrium was established was found to depend on the setting of the model parameters (e.g. the number of AGVs, the level of work-in-process, and the number of slack buffers, if any). Among the cases we experimented with, the most extreme case required that 15 output sets be produced before equilibrium was established. (This case involved 3 AGVs, 2 slack buffers, and a WIP level of 7 (see section 9.2).) This corresponded to 1731 minutes of simulated time, or less than four 8-hour shifts.

The number of output sets per repeating pattern (that is, per model cycle) at operating equilibrium was also found to depend on the setting of the model parameters. In the most extreme case found, there were 27 output sets per repeating pattern. (This case also involved 3 AGVs, 2 slack buffers, and a WIP level of 7.) This corresponded to 2 896 minutes of simulated time, or slightly more than six 8-hour shifts.

Having gained these insights into the duration of transient model operation and the duration of a model cycle under conditions of operating equilibrium, the experimental plan described in the next subsection was devised.

8.2. EXPERIMENTAL DESIGN

For a given setting of model parameters, it would only be necessary to measure the model outputs of interest during one model cycle under conditions of operating equilibrium. However, this approach would require prior experimentation to determine both the duration of transient operation and the duration of a model cycle for each model setting. This approach was impractical because it was labor intensive, and because 240 model settings were involved. Therefore, the following experimental design was used as an alternative:

1. Simulate for twenty-five 8-hour shifts.
2. Suspend the simulation, suppressing output and reinitializing the various statistical accumulators, but leaving work-in-process as is.
3. Resume the simulation for an additional two hundred and fifty 8-hour shifts.
4. Stop the simulation, obtaining output in the process.

Step (1) was designed to move well beyond transient model operation and into conditions of operating equilibrium. Step (3) was designed to move through a large number of model cycles (25 or more) at operating equilibrium. Although step (3) likely did not move through an integral number of model cycles, model outputs collected during the large number of simulated cycles would swamp the slightly imbalanced outputs collected during the partial model cycles likely involved at the beginning and the end of step (3). The motivation for this design was to standardize and automate the work.

8.3. FULL FACTORIAL DESIGN

Depending on the WIP level and the number of AGVs in the model, each simulation run, consisting of the four steps described in section 8.2, consumed about 2 CPU seconds on an IBM 3090-400 computer. (It is estimated that the corresponding time required on a PC-AT would be about 1 500 CPU seconds, or 25 minutes.) For the billing algorithm in use at The University of Michigan (where the experiments were performed), this translated into an average cost per run of about U.S.$3.00 during high-rate (daytime) periods, or about 60¢ during low-rate (overnight) periods.

Because the simulation costs were modest, especially during low-rate periods, a full factorial design was used in examining the various FMS conditions studied.

8.4. SAMPLE SIZES AND SAMPLED VARIABLES

For each experimental setting, observations gathered for reporting purposes were recorded by the model under conditions of operating equilibrium for a single simulation consisting of two hundred and fifty 8-hour shifts (see step (4) in section 8.2). For example, overall machine utilization for shift 1, shift 2, shift 3, . . . , shift 250 was recorded, and then the mean, standard deviation, and frequency class counts (as well as relative and cumulative frequencies) for the resulting sample of size 250 were computed and reported out by the model. (This methodology is known as the method of batch means [14].) Analogous recording and processing of machine utilization by machine type was accomplished by the model.

System residence time provides another example of a type of variable observed during each simulation. An observation was made on this variable each time a finished part left the system. The observed value was placed in each of two samples: a sample of system residence times common to all types of parts which the FMS produces (overall system residence times); and a sample of system residence times specific to the type of part. For a simulation of two hundred and fifty 8-hour shifts, the overall residence time sample is much greater than 250 (about 6 250, because about 25 parts are produced per 8-hour shift for the FMS scenario studied here). As in the case of all samples formed by the model, the mean, standard deviation, and frequency class counts (as well as relative and cumulative frequencies) for the resulting residence time samples were computed and reported out by the model.

The number of occupied buffers provides an example of yet another type of variable observed during each simulation. An observation was made on this variable at each reading of the simulated clock. Each such observation was made immediately after the clock had been advanced from its previous reading to its new reading. The observed value (weighted by the number of simulated time units through which the clock had been advanced) was placed in a sample of such observations. At the end of the simulation, the mean, standard deviation, and frequency class counts for the resulting sample of occupied buffers were computed and reported out by the model.

Machine utilizations, system residence times, and the number of occupied buffers are representative of the types of variables whose values were observed in this study. Other values observed include the number of buffer entries per shift, the time-weighted number of AGVs in use, production rates, fraction of the time that machines were feed-starved, and fraction of the time that machines were output-blocked. More particulars are provided in section 9, along with numbers for selected cases.

8.5. EXPERIMENTAL SETTINGS

All experimental results reported here are based on the assumptions that there is no limit to the number of pallets and fixtures; and that palletizing, fixturing, defixturing, and depalletizing are done external to the system (or, equivalently, are done in zero time). In other words, these resources and/or timings were not allowed to be bottlenecks in this study.

The time required for an AGV to transport WIP between any two points (e.g. from the loading station to the mill; from one machine to another; from a machine to a buffer; from a buffer to a machine; from a vertical turret lathe to an unloading station) was assumed to be a constant 2 minutes per transfer. This assumed transport time of 2 minutes is the sum of four components: (1) time for the AGV to travel to the sending point (loading station; machine; or buffer); (2) time for the palletized unit of WIP to move onto the AGV; (3) time for the loaded AGV to travel to its destination; and (4) time for the palletized unit of WIP to move off the AGV to its receiving machine, buffer, or unloading station. More details about the handling of travel time in the model are reported in appendix B.

An important experimental variable is the *quantity of work-in-process.* In this FMS scenario, the *minimum* quantity of work-in-process *of interest* is 5 (because there are 5 machines in the system). The logical *maximum* for this quantity is the *minimum* of (i) the number of pallets; (ii) the number of fixtures; (iii) the *sum* of the number of machines and the number of buffers. With *no limit* assumed for pallets and fixtures, the maximum quantity of WIP in this research equals the sum of the number of machines and the number of buffers. (Each WIP unit must be either at a machine or in a buffer, except during the time interval when it is being transferred from one location to another.)

With WIP at its maximum level, there are no *slack buffers* in the system. (A slack buffer is a buffer not strictly needed to accommodate the quantity of work-in-process.) With the quantity of WIP set at one or more units below this maximum level, the system has one or more slack buffers. Slack buffers can play a key role by reducing the occurrence of *output-blocking* at machines. (Output-blocking occurs when WIP cannot be removed from a machine and remains there, temporarily preventing use of the machine by the next unit of WIP.) Experiments were performed for the cases of 0, 1, 2, and 3 slack buffers.

In some experiments, the FIFO-based dispatching rule described in section 6 was used. In other experiments, the SPT-based dispatching rule was used. These rules were used under identical scenarios, for comparison purposes.

9. Experimental results

Representative experimental results are presented and discussed in this section. To provide a basis for the discussion, the steps making up a machine cycle are summarized in section 9.1. The two primary performance measures on which this study focuses, overall machine utilization and system residence time, are then reported and discussed in sections 9.2 and 9.4, respectively. Selected subsidiary performance measures (e.g. the numbers and sources of buffer entries and the fraction of the time that machines are either feed-starved or output-blocked), which provide insights for better understanding the behavior of the primary performance measures, are then presented in additional subsections.

9.1. THE STEPS MAKING UP A MACHINE CYCLE

In general, a machine cycles repeatedly through the three-phase process of being feed-starved, productively engaged, and output-blocked. (Consistent with assumptions made in this study, the preceding statement ignores the possibility of machine breakdowns.) The particulars of these three phases are spelled out below, using the vocabulary of AGVs and assuming that a system provides only central buffers.

(1) *Feed-starved*

A machine is feed-starved when it is ready to work but has no work to do. During the feed-starved portion of a cycle, a machine:

(a) waits (if necessary) for a next part to need it,
(b) then waits (if necessary) for an AGV to become available;
(c) and finally waits for the AGV to bring the part to the machine.

(2) *Productively engaged*

The machine is productively engaged ("utilized") while it is machining the part.

(3) *Output-blocked*

During the output-blocked portion of a cycle, a machine:

(a) waits (if necessary) for a destination (a next machine, or a buffer, or an unloading station) to become available for the part on the machine;
(b) then waits (if necessary) for an AGV to become available;
(c) and finally waits for the AGV to come to the machine and remove the part.

As described above, the feed-starved, productively engaged, and output-blocked parts of a machine cycle are mutually exclusive and collectively exhaustive. Note in particular that the feed-starved part of a cycle does not begin until the output-blocked part of the preceding cycle has ended.

The overall machine utilizations corresponding to the fraction of the time machines spend in phase (2) are reported in section 9.2. The fraction of the time machines spend either in phase (1) or phase (3) are given for selected cases in section 9.6.

9.2. OVERALL MACHINE UTILIZATIONS AND THEIR VARIABILITY

Tables 3 and 4 display information about the overall machine utilizations (expressed as percentages) achieved when the FIFO- and the SPT-based dispatching rules were used, respectively. Each *nonparenthesized* table entry is the *average* utilization resulting from one simulation consisting of two hundred and fifty 8-hour shifts under conditions of operating equilibrium (see section 8). (Utilization typically varies from shift to shift because the operating conditions in effect during a shift are undergoing cyclical change.) The *parenthesized* table entries show the corresponding sample standard deviations. The rows in each of tables 3 and 4 correspond to WIP levels ranging from 5 to 10 in steps of 1. The columns correspond to numbers of AGVs ranging from 1 to 5 in steps of 1. For each WIP/AGV combination, overall machine utilizations are shown for the alternative cases of 0, 1, 2, and 3 slack buffers (see the legend at the bottom of the tables).

The theoretical maximum overall machine utilization achievable for all simulations performed in this work is 86.6%. (The calculation is given in appendix B.) If travel time were zero, the theoretical maximum overall machine utilization would be 95.2% for the scenario under study. (Appendix A gives this calculation.) The combination of realistic travel times and the use of only central system buffers consequently degrades the maximum feasible overall machine utilization by 9.1% (or by 8.6 percentage points in absolute terms).

For the FIFO-based dispatching rule, table 3 indicates that the 86.6% theoretical maximum overall utilization was not achieved at WIP levels of 5 or 6, but was consistently achieved with 2 and 3 slack buffers when the WIP level was 7 or more and there were at least 4 AGVs. The least complicated operating conditions under which the theoretical maximum overall utilization is achieved in table 3 correspond to a WIP level of 8, 2 AGVs, and 2 slack buffers. These conditions correspond to reasonable levels of resources in an FMS, which means that it is reasonable to expect to achieve maximum machine utilizations in practice.

The highlighted cells in table 3 are those for which the maximum overall machine utilization of 86.6% was realized. Note that there are many cells for which the maximum utilization was *almost* realized. For example, utilizations of 85.8% were realized with 4 or 5 AGVs at a WIP level of 6, and with 2 or 3 slack buffers.

It would be tempting to use a t (or z) statistic to make inferences (e.g. confidence intervals; hypothesis testing) both within and between cells in tables 3 and 4. However, this cannot be justified unless the shift-by-shift overall machine

Table 3

Means and (standard deviations) of overall machine utilizations with the FIFO-based dispatching rule

	Number of AGV's									
WIP Level	1		2		3		4		5	
5	73.5 (0.44)	75.6 (0.51)	74.6 (0.38)	78.1 (0.41)	75.8 (0.40)	78.1 (0.46)	75.8 (0.40)	78.1 (0.46)	75.8 (0.40)	78.1 (0.46)
	73.0 (0.30)	73.0 (0.30)	79.1 (0.29)	79.1 (0.29)	79.4 (0.27)	79.4 (0.27)	79.4 (0.27)	79.4 (0.27)	79.4 (0.27)	79.4 (0.27)
6	73.7 (0.57)	77.8 (0.57)	75.2 (0.41)	83.7 (0.07)	75.8 (0.30)	85.1 (0.20)	75.8 (0.29)	85.1 (0.21)	75.8 (0.29)	85.1 (0.21)
	78.7 (1.11)	78.7 (1.12)	84.5 (0.40)	84.5 (0.42)	84.7 (0.19)	84.7 (0.19)	85.8 (0.21)	85.8 (0.21)	85.8 (0.21)	85.8 (0.21)
7	74.0 (0.65)	78.1 (0.53)	76.3 (0.47)	81.3 (0.28)	76.5 (0.44)	85.2 (0.34)	76.6 (0.43)	85.3 (0.30)	76.6 (0.43)	85.3 (0.30)
	80.0 (0.30)	79.5 (0.40)	85.1 (0.32)	85.2 (0.38)	86.6 (0.21)	86.6 (0.23)	86.6 (0.20)	86.6 (0.20)	86.6 (0.20)	86.6 (0.20)
8	73.9 (1.29)	78.7 (0.35)	75.2 (0.51)	82.1 (0.17)	78.2 (0.74)	85.9 (0.49)	78.1 (1.02)	86.6 (0.20)	78.1 (1.02)	86.6 (0.20)
	78.9 (0.59)	78.9 (0.57)	86.6 (0.20)	86.6 (0.20)	86.3 (0.28)	86.3 (0.28)	86.6 (0.17)	86.6 (0.17)	86.6 (0.18)	86.6 (0.18)
9	73.9 (0.56)	77.6 (0.81)	75.2 (0.40)	83.5 (1.32)	76.6 (0.54)	86.2 (0.21)	75.8 (0.34)	86.0 (0.22)	75.8 (0.31)	86.0 (0.23)
	78.7 (0.42)	78.8 (1.06)	85.5 (0.43)	85.5 (0.43)	86.6 (0.21)	86.6 (0.20)	86.6 (0.19)	86.6 (0.19)	86.6 (0.20)	86.6 (0.20)
10	73.4 (0.52)	78.1 (0.37)	77.5 (0.52)	82.8 (1.22)	77.9 (0.49)	86.6 (0.21)	77.2 (1.08)	85.8 (0.21)	77.2 (1.08)	86.6 (0.22)
	79.2 (0.76)	80.6 (0.32)	85.1 (0.50)	86.1 (0.45)	86.1 (0.50)	86.1 (0.39)	86.6 (0.19)	86.6 (0.19)	86.6 (0.21)	86.6 (0.21)

Legend:

0	1
2	3

Slack Buffers

Table 4

Means and (standard deviations) of overall machine utilizations with the SPT-based dispatching rule

Number of AGV's

WIP Level	1		2		3		4		5	
5	73.5 (0.36)	75.8 (0.35)	75.5 (0.46)	77.5 (0.37)	76.3 (0.49)	78.1 (0.46)	76.3 (0.49)	78.1 (0.46)	76.3 (0.49)	78.1 (0.46)
	75.8 (0.36)	75.8 (0.36)	79.1 (0.29)	79.1 (0.29)	79.4 (0.27)	79.4 (0.27)	79.4 (0.27)	79.4 (0.27)	79.4 (0.27)	79.4 (0.27)
6	74.6 (0.35)	78.7 (0.38)	81.3 (0.34)	84.4 (0.42)	78.1 (0.54)	84.7 (0.19)	78.3 (0.48)	85.8 (0.21)	78.3 (0.48)	85.8 (0.21)
	78.1 (0.37)	78.1 (0.37)	84.5 (0.40)	84.5 (0.31)	84.7 (0.19)	84.7 (0.20)	85.8 (0.21)	85.8 (0.21)	85.8 (0.21)	85.8 (0.21)
7	74.6 (0.35)	78.7 (0.49)	82.0 (0.25)	85.1 (0.38)	82.3 (0.21)	86.6 (0.23)	78.3 (0.48)	86.6 (0.20)	78.3 (0.48)	86.6 (0.20)
	78.1 (0.51)	78.1 (0.51)	85.1 (0.32)	85.1 (0.28)	86.6 (0.21)	86.4 (0.21)	86.6 (0.20)	86.6 (0.21)	86.6 (0.20)	86.6 (0.21)
8	74.6 (0.36)	78.7 (0.38)	82.0 (0.25)	86.6 (0.20)	82.3 (0.21)	86.3 (0.28)	78.3 (0.50)	86.6 (0.17)	78.3 (0.50)	86.6 (0.18)
	78.1 (0.41)	78.1 (0.41)	86.6 (0.20)	85.1 (0.28)	86.3 (0.28)	86.4 (0.22)	86.6 (0.17)	86.6 (0.20)	86.6 (0.18)	86.6 (0.21)
9	74.6 (0.36)	78.7 (0.38)	82.0 (0.25)	85.5 (0.43)	82.3 (0.22)	86.6 (0.20)	78.3 (0.51)	86.6 (0.19)	78.3 (0.51)	86.6 (0.20)
	78.1 (0.48)	78.1 (0.48)	85.5 (0.43)	85.1 (0.31)	86.6 (0.21)	86.6 (0.21)	86.6 (0.19)	86.6 (0.21)	86.6 (0.20)	86.6 (0.21)
10	74.6 (0.35)	78.3 (0.37)	81.3 (0.34)	86.1 (0.45)	78.1 (0.25)	86.1 (0.39)	78.3 (0.52)	86.6 (0.19)	78.3 (0.52)	86.6 (0.21)
	78.1 (0.31)	78.1 (0.31)	85.1 (0.50)	85.4 (0.25)	86.1 (0.50)	86.6 (0.20)	86.6 (0.19)	86.6 (0.19)	86.6 (0.21)	86.6 (0.19)

Legend:

0	1
2	3

Slack Buffers

utilizations are (approximately) normally distributed. We tested the hypothesis of normality by using UNIFIT [11] to perform Chi-square, Kolmogorov–Smirnov, and the Anderson–Darling tests on the shift-by-shift utilizations for arbitrarily selected cases, but the large values of the resulting test statistics forced strong rejection of the null hypothesis of normality.

The simplest operating conditions in table 3 correspond to a WIP level of 5, 1 AGV, and 0 slack buffers (see the uppermost left cell in the table). The overall machine utilization realized under these conditions is 73.5%, which is 84.9% of the theoretical maximum. Hence, the number of AGVs must be increased from 1 to 2, the WIP level from 5 to 8, and the number of slack buffers from 0 to 2, to increase machine utilization by 11.4 percentage points.

We conjecture that WIP levels of 5 or 6 are inadequate for achieving the maximum theoretical overall machine utilization because machines are too often feed-starved under these operating conditions (see section 9.7).

As table 3 demonstrates, the addition of slack buffers can improve overall machine utilizations. ("More may be better".) With 2 AGVs and at a WIP level of 8, for example, going from 0 to 1 slack buffers improves utilization from 75.2% to 82.1%; and going from 1 to 2 slack buffers improves utilization to the theoretical maximum of 86.6%. We conjecture that this beneficial effect of more slack buffers results from reducing the level of output-blocking at machines (by providing a temporary destination for parts which cannot be transferred immediately from their current machine to their next machine) (see section 9.7).

Beyond a certain level, however, additional slack buffers are not useful. ("More is not necessarily better".) At a WIP level of 6, for example, and for all five alternative AGV cases, going from 2 to 3 slack buffers fails to improve overall machine utilization at all, even though utilization is short of the theoretical maximum for each of these cases. We conjecture that this results because beyond a certain number of slack buffers, feed-starving dominates output-blocking when machine utilizations are below their theoretical maximum.

In table 3, increasing the WIP level in some cases results in increased overall machine utilization, other things being equal. (Again, "more may be better".) For example, with 2 AGVs and 2 slack buffers, going from a WIP level of 6 to 7 to 8 results in utilizations increasing, respectively, from 84.5% to 85.1% to 86.6%. We conjecture that this is because feed-starving dominates output-blocking under these conditions, and increasing the WIP level decreases the degree of feed-starving.

On the other hand, increasing the WIP level in some of the table 3 cases results in *decreased* overall machine utilization, other things being equal. ("More may be worse".) For example, with 2 AGVs and 2 slack buffers, going from a WIP level of 8 to 9 to 10 results in utilizations dropping, respectively, from 86.6% to 85.5% to 85.1%. The increased WIP levels reduce the ratio of WIP to slack buffers, and so increases the degree of output-blocking, which we conjecture dominates feed-starving in these cases.

In table 3, increasing the number of AGVs results in increased overall machine utilization in most cases, other things being equal. For example, at a WIP level of 7 and with 3 slack buffers, going from 1 to 2 to 3 AGVs results in utilizations increasing, respectively, from 79.5% to 85.2% to 86.6%. We conjecture that output-blocking dominates in these cases, and that its detrimental effect decreases when there are more AGVs to move WIP from machines into buffers.

There are almost no cases in table 3 in which increasing the number of AGVs *decreases* overall machine utilization, other things being equal. This does happen in going from 2 to 3 AGVs at a WIP level of 8, and with 3 slack buffers. The decrease in utilization is small in this case, from 86.6% to 86.3%. (If AGV paths and contention among AGVs for segments along these paths had been modeled, machine utilization might more often have been found to decrease with an increasing number of AGVs beyond some level.)

As in table 3, highlighting is used in table 4 to indicate operating conditions under which the theoretical maximum utilization of 86.6% is achieved.

Comparison of tables 3 and 4 indicates that when overall machine utilization is below the maximum, the SPT-based dispatching rule almost always outperforms the FIFO-based rule with respect to the utilization measure. For example, at a WIP level of 7 and with 2 AGVs and 1 slack buffer, overall machine utilization is 85.1% for SPT, but only 81.3% for FIFO. Similarly, at a WIP level of 6 and with 4 AGVs and 0 slack buffers, the utilization is 78.3% for SPT but only 75.8% for FIFO. Also, there are two cases in table 5 where the maximum machine utilization is achieved with only 1 slack buffer (3 AGVs, WIP level 7; and 2 AGVs, WIP level 8) by SPT, but not with FIFO. This demonstrates the potentially important influence of dispatching rules on FMS performance.

We observe that the SPT-based dispatching rule *reduces the average part-by-part variation* in the machining times required by the parts using a given type of machine. For example, the time required by the *j*th part to use a drill differs less *on average* from the time required by the preceding part (to use a drill) under the SPT rule than under the FIFO rule. We conjecture that this reduced variation decreases the amount of output-blocking and feed-starving at the bottleneck machines (drills and VTLs; see appendix A) in this FMS, and so increases overall machine utilization.

Table 4 (SPT) shows 32 cases in which the theoretical maximum overall machine utilization was achieved, whereas table 3 (FIFO) shows 26 such cases. Here again, the SPT-based dispatching rule is more successful than the FIFO-based rule. A direct comparison of the operating conditions under which FIFO and/or SPT resulted in 86.6% utilization is given in table 5. As shown there, each WIP/AGV combination resulting in 86.6% utilization with FIFO also resulted in 86.6% utilization with SPT. For eight WIP/AGV combinations, however, SPT achieved 86.6% utilization with only 1 slack buffer (e.g. WIP level 8, and 2 AGVs; WIP level 7 and 3 AGVs), whereas FIFO required at least 2 slack buffers.

Table 5

Operating conditions achieving the theoretical maximum overall machine utilizations with the FIFO and SPT-based dispatching rules.

	Number of AGV's									
WIP Level	1		2		3		4		5	
5										
6										
7						SPT		SPT		SPT
					FIFO SPT	FIFO	FIFO SPT	FIFO SPT	FIFO SPT	FIFO SPT
8				SPT				FIFO SPT		FIFO SPT
			FIFO SPT	FIFO			FIFO SPT	FIFO SPT	FIFO SPT	FIFO SPT
9						SPT		SPT		SPT
					FIFO SPT	FIFO SPT	FIFO SPT	FIFO SPT	FIFO SPT	FIFO SPT
10						FIFO		SPT		FIFO SPT
						SPT	FIFO SPT	FIFO SPT	FIFO SPT	FIFO SPT

Legend:

0	1
2	3

Slack Buffers

The same "more may be better", "more is not necessarily better", "more may be worse" observations made about table 3 can be made about table 4. We suggest that table 4 be examined carefully in this regard.

The trends in tables 3 and 4 are difficult to quantify in general, or even to rank in general. For example, when overall machine utilization is short of the theoretical maximum, does increasing the WIP level by 1 or the number of AGVs by 1 have the more beneficial effect? The answer depends on the operating conditions assumed. In table 3, for example, assuming a WIP level of 5, 2 AGVs, and 2 slack buffers, adding 1 to the WIP level increases utilization from 79.1% to 84.5% (an improvement of 5.4

percentage points), whereas adding an AGV increases utilization from 79.1% to 79.4% (an improvement of only 0.3 percentage points). In this case, adding 1 to the WIP is far more beneficial. On the other hand, when the WIP level is 7 and there is 1 AGV and 2 slack buffers, adding 1 to the WIP level *decreases* utilization from 80.0% to 78.9%, whereas adding an AGV *increases* utilization from 80.0% to 85.1%. In this case, adding 1 to the WIP level has a counterproductive effect, whereas adding an AGV has a very productive effect.

Situations analogous to those described in the preceding paragraph can be found elsewhere in tables 3 and 4. We conclude that when the overall machine utilization is below the theoretical maximum and there is a shortfall in the WIP level, and in slack buffers, and in the level of transportation resources, or in any two of these three factors, it cannot be stated in general (at this time) which single factor should be improved to obtain the greatest benefit in terms of increased overall machine utilization. (That is, the ranking of the gradients associated with these factors is a function of the conditions of FMS operation.)

9.3. OVERALL PRODUCTION RATES AND THEIR VARIABILITY

For a given FMS scenario and a set of production ratios, *average* overall production rate, and *average* production rates by part type, are proportional to the overall average machine utilizations. This means that average production rates can be derived from the information in tables 3 and 4. *Variability* in production rates is not easily derived, but of course can be estimated by simulation.

The theoretical maximum production rate corresponding to the FMS scenario used in this work is 29.09 parts per 8-hour shift. (Appendix B shows that 115.5 minutes are required under the ideal operating conditions described there to produce the 7 parts making up one input cycle. At this rate, 29.09 parts can be produced per 8-hour shift.) Consistent with the small standard deviations in tables 3 and 4, the standard deviations of part production rates are small, and are similar for all alternative operating conditions studied and for use of either the FIFO- or SPT-based dispatching rule. For example, with 2 AGVs, 2 slack buffers, a WIP level of 8, and the FIFO-based rule, the maximum part production rate of 29.09 parts per hour results, with a standard deviation of 0.76. Under the same operating conditions, but with the SPT-based rule, the maximum part production rate also results, with a standard deviation of 0.70. In general, the standard deviation of part production rates ranges from about 2.5% to 3% of the mean. Individual results are not shown here.

9.4. OVERALL SYSTEM RESIDENCE TIMES AND THEIR VARIABILITY

Tables 6 and 7 show overall WIP system residence times (in minutes) with the FIFO- and SPT-based dispatching rules, respectively. (Overall system residence time is the simple average of the residence times experienced by all parts which moved

Table 6

Means and (standard deviations) of overall system residence times with the FIFO-based dispatching rule

	Number of AGV's									
WIP Level	1		2		3		4		5	
5	97.1 (10.6)	94.5 (10.6)	95.7 (10.0)	91.4 (10.7)	94.3 (10.0)	91.4 (10.7)	94.3 (10.0)	91.4 (10.7)	94.3 (10.0)	91.4 (10.7)
	97.9 (9.7)	97.9 (9.7)	90.4 (8.0)	90.4 (8.0)	90.0 (8.0)	90.0 (8.0)	90.0 (8.0)	90.0 (8.0)	90.0 (8.0)	90.0 (8.0)
6	121.7 (19.7)	110.2 (23.1)	114.0 (25.1)	102.4 (10.4)	113.1 (25.3)	100.7 (10.1)	113.1 (25.0)	100.7 (10.1)	113.1 (25.0)	100.7 (10.1)
	108.1 (19.4)	109.0 (19.4)	101.4 (11.7)	101.5 (13.2)	101.1 (14.6)	101.1 (14.6)	99.9 (14.7)	99.9 (14.7)	99.9 (14.7)	99.8 (14.7)
7	135.2 (35.6)	128.0 (9.1)	131.0 (41.0)	123.0 (8.4)	130.8 (40.9)	117.3 (9.6)	130.5 (40.8)	117.3 (9.2)	130.5 (40.8)	117.3 (9.2)
	125.0 (16.9)	125.8 (20.1)	117.5 (19.2)	117.4 (16.4)	115.5 (14.0)	115.5 (19.5)	115.5 (5.0)	115.5 (5.0)	115.5 (4.9)	115.5 (4.9)
8	154.6 (77.6)	145.1 (30.0)	152.0 (60.0)	139.1 (10.9)	146.1 (49.1)	133.1 (20.0)	146.3 (51.0)	132.0 (17.9)	146.3 (51.0)	132.0 (15.6)
	144.8 (34.4)	144.8 (34.4)	132.0 (15.3)	132.0 (15.3)	132.5 (15.5)	132.5 (15.5)	132.0 (15.3)	132.0 (15.3)	132.0 (15.5)	132.0 (15.5)
9	174.0 (99.4)	165.8 (45.4)	171.0 (80.0)	153.9 (32.1)	167.8 (95.8)	149.1 (22.0)	169.7 (79.2)	149.5 (18.9)	169.7 (79.2)	149.5 (18.9)
	163.3 (45.0)	163.2 (44.3)	150.4 (22.8)	150.4 (22.8)	148.5 (12.9)	148.5 (14.3)	148.5 (9.0)	148.5 (9.0)	148.5 (13.9)	148.5 (13.9)
10	194.7 (118.4)	182.8 (9.3)	184.3 (78.8)	172.5 (40.1)	183.5 (78.6)	165.0 (13.2)	185.2 (90.9)	166.4 (11.7)	185.2 (90.1)	165.0 (13.2)
	180.5 (54.9)	177.2 (55.5)	167.8 (33.4)	166.0 (17.6)	165.8 (20.8)	166.0 (24.0)	165.0 (12.7)	165.0 (12.7)	165.0 (8.4)	165.0 (8.4)

Legend:

0	1
2	3

Slack Buffers

through the model for a given level of FMS resources.) Each nonparenthesized table entry is the average overall system residence time resulting from one simulation consisting of two hundred and fifty 8-hour shifts under conditions of operating equilibrium. The parenthesized table entries show the sample standard deviations for the corresponding shift-by-shift average residence times. The format of tables 6 and 7 matches that of tables 3 and 4. The table rows correspond to WIP levels ranging from 5 to 10 in steps of 1. The columns correspond to numbers of AGVs ranging from 1 to 5 in steps of 1. For each WIP/AGV combination, overall system residence times are shown for the alternative cases of 0, 1, 2, and 3 slack buffers.

Table 7

Means and (standard deviations) of overall system residence times with the SPT-based dispatching rule

Number of AGV's

WIP Level	1		2		3		4		5	
5	97.1 (7.9)	94.3 (10.1)	94.6 (13.1)	92.1 (10.8)	93.6 (13.5)	91.4 (10.7)	93.6 (13.5)	91.4 (10.7)	93.6 (13.5)	91.4 (10.7)
	94.3 (7.0)	94.2 (7.0)	90.0 (8.0)	90.4 (8.0)	90.0 (8.0)	90.0 (8.0)	90.0 (8.0)	90.0 (8.0)	90.0 (8.0)	90.0 (8.0)
6	114.9 (18.6)	108.9 (17.8)	105.4 (14.3)	101.1 (13.8)	109.7 (20.5)	100.7 (13.8)	109.4 (20.4)	101.6 (10.6)	109.4 (20.4)	101.6 (10.6)
	109.7 (16.4)	109.7 (16.4)	101.4 (13.9)	101.4 (13.9)	101.1 (15.6)	101.1 (15.6)	100.0 (14.7)	99.9 (14.7)	99.9 (14.7)	99.9 (14.7)
7	134.0 (54.5)	126.0 (22.6)	122.0 (45.1)	119.2 (26.5)	121.5 (63.2)	119.0 (24.5)	127.7 (70.5)	118.7 (17.2)	127.7 (70.5)	118.7 (17.2)
	128.0 (28.5)	128.0 (28.5)	117.9 (19.5)	117.6 (20.0)	115.7 (16.3)	115.7 (16.3)	115.5 (5.2)	115.5 (5.2)	115.5 (5.2)	115.5 (5.2)
8	153.2 (100.0)	145.1 (54.6)	139.4 (86.5)	133.1 (45.4)	138.9 (125.1)	134.3 (59.3)	145.9 (122.8)	134.0 (57.1)	145.9 (122.8)	136.0 (55.8)
	146.3 (47.7)	146.3 (47.7)	133.9 (29.7)	134.4 (31.3)	132.3 (27.9)	132.3 (28.5)	132.0 (20.7)	132.0 (20.7)	132.0 (21.0)	132.0 (21.0)
9	172.3 (146.4)	163.3 (77.4)	156.9 (128.8)	149.8 (84.0)	156.2 (187.4)	153.0 (95.4)	164.2 (180.0)	152.7 (87.1)	164.2 (179.7)	152.7 (87.1)
	164.6 (67.2)	164.6 (67.2)	151.1 (62.4)	151.1 (62.4)	149.1 (57.3)	148.5 (38.4)	148.5 (54.6)	148.5 (49.6)	148.5 (54.6)	148.5 (49.6)
10	191.5 (193.0)	182.5 (93.3)	175.7 (172.2)	166.4 (89.5)	182.9 (235.2)	167.8 (139.5)	182.3 (234.4)	167.5 (137.4)	182.3 (234.4)	167.5 (137.4)
	182.9 (87.7)	182.9 (87.7)	167.9 (81.4)	167.3 (76.3)	165.6 (72.9)	165.0 (76.5)	165.2 (73.4)	165.0 (68.6)	165.0 (66.0)	165.0 (65.9)

Legend: Slack Buffers

0	1
2	3

Assuming WIP never has to wait either for a machine or for an AGV, the overall system residence time in the FMS scenario studied here would be 79.4 minutes. (The calculation is given in appendix C.)

With the FIFO-based dispatching rule (table 5), system residence times range from 91.4 to 194.7 minutes, or from about 15% to about 145% above the theoretical minimum. With the SPT-based rule (table 6), system residence times range from 91.4 to 191.5 minutes, and in this measure are similar to FIFO.

Conditions for which theoretical maximum overall machine utilization is achieved have been highlighted in tables 6 and 7. In table 6, system residence times for these cases range from 115.5 to 165 minutes, or from about 45% to about 108% above the theoretical minimum. In table 7, residence times for these cases vary over a virtually identical range, from 115.5 to 165.2 minutes.

Although the ranges of *average* system residence times are about the same for the FIFO versus SPT dispatching rule, tables 6 and 7 indicate that the *variations* in individual system residence times are greater for SPT than for FIFO in many cases. (High variability in system residence times has negative implications for forecasting product completion times, and for meeting due dates.) For the most part, the FIFO residence time standard deviations range from about 10% to 20% of the mean, whereas the SPT standard deviations range from about 15% to 30% of the mean. As one example, consider the case of 3 AGVs, 2 slack buffers, and a WIP level of 8. With FIFO (table 6), the overall system residence time is 132.5 minutes and the standard deviation is 15.5, or 11.7% of the mean. With SPT (table 7), the overall system residence time for this case is 132.3 minutes and the standard deviation is 27.9, or 21% of the mean.

Like tables 3 and 4, tables 6 and 7 have been highlighted to emphasize cases for which the theoretical maximum overall machine utilization is achieved. For these cases, system residence time variability with FIFO is relatively small, ranging from 4.2% of the mean (5 AGVs, 2 or 3 slack buffers, and a WIP level of 7) to 11.7% of the mean (all highlighted cases for 2 or 3 slack buffers at a WIP level of 8). Variability with SPT is higher, ranging from 4.5% of the mean (4 or 5 AGVs, 2 or 3 slack buffers, and a WIP level of 7) to 82% of the mean (4 or 5 AGVs, 1 slack buffer, and a WIP level of 10).

For the two simplest alternative operating conditions under which the theoretical maximum overall machine utilization is achieved by both FIFO and SPT (case 1: 3 AGVs, 2 slack buffers, and a WIP level of 7; case 2: 2 AGVs, 2 slack buffers, and a WIP level of 8), FIFO and SPT perform about the same in terms of the residence time measures for case 1, but FIFO is notably superior to SPT in terms of the smaller variability of residence time for case 2. Case 2 is probably the preferred case, assuming that the cost of adding 1 to the WIP level is more than offset by the savings resulting from eliminating 1 AGV.

It is easy to understand why the variability of residence times under SPT tends to be greater than under FIFO. WIP with relatively large next-operation times must wait under the SPT rule until there is no other WIP in the system competing for the same type of next machine and having a smaller next-operation time. This results in cases for which the system residence time for some types of parts is relatively large (e.g. part type 10; part type 5; see table 1), and this increases the system residence-time variability. In contrast, WIP headed for a given type of machine comes either from its preceding machine or from a buffer in FIFO order with the FIFO-based dispatching rule. This reduces or eliminates cases in which some WIP experiences relatively large system residence times. The effect is to reduce residence-time variability. Results such as these are known and have been discussed in the literature (e.g. [4,6]).

9.5. THE AVERAGE NUMBER OF BUFFER ENTRIES PER SHIFT

Useful insights into overall machine utilizations achieved by the FMS in this study can be gained by considering in quantitative terms the role played by the central buffers under various operating conditions.

By way of background, note that WIP moves into buffers only by coming from the mill, or by coming from one or another of the two drills (see fig. 1). Also, note that the mill is a slack machine in the system, whereas the drills and the VTLs are bottleneck machines (see appendix A).

Movement of WIP from a machine into a buffer is one way to eliminate output-blocking at the machine. It is important to reduce output-blocking at *bottleneck* machines, letting them start earlier on their next unit of work. It is less important to reduce output-blocking at *slack* machines. (For a given set of production ratios, it is impossible to avoid experiencing some idleness at slack machines anyway. In contrast, there will be no idleness at bottleneck machines in a system which operates perfectly.) With this in mind, note that buffer entries from the mill are less important than buffer entries from the drills in the FMS studied here.

Table 8

Means and (standard deviations) of the number of buffer entries per shift with the FIFO- and SPT-based dispatching rules

		FIFO				SPT			
		Number of AGV's				Number of AGV's			
		2		3		2		3	
WIP Level	7	11.9 (0.71)	37.1 (0.64)	11.9 (0.72)	50.1 (1.48)	23.6 (0.49)	49.7 (1.90)	23.7 (0.46)	48.4 (0.57)
		53.1 (1.33)	54.4 (1.40)	58.2 (0.86)	58.2 (0.84)	56.6 (1.04)	55.8 (0.96)	58.1 (0.77)	58.1 (0.77)
	8	11.7 (0.75)	41.4 (0.61)	15.3 (1.44)	53.6 (1.98)	23.6 (0.49)	57.7 (0.81)	23.7 (0.46)	50.9 (1.85)
		58.2 (0.79)	58.2 (0.79)	57.1 (1.16)	57.1 (1.16)	56.6 (1.06)	55.8 (0.96)	58.0 (0.85)	58.1 (0.75)
	9	10.8 (0.64)	44.4 (3.12)	11.0 (0.83)	49.7 (0.71)	23.6 (0.49)	57.7 (0.80)	23.7 (0.46)	48.4 (0.57)
		55.9 (1.43)	55.9 (1.43)	58.2 (0.63)	58.2 (0.71)	55.8 (0.91)	55.8 (0.91)	58.0 (0.92)	58.0 (0.74)

Legend:

0	1
2	3

Slack Buffers

Table 8 shows the average number of buffer entries per 8-hour shift from the mill and drills with the FIFO- and SPT-based dispatching rules. The cases of 2 and 3

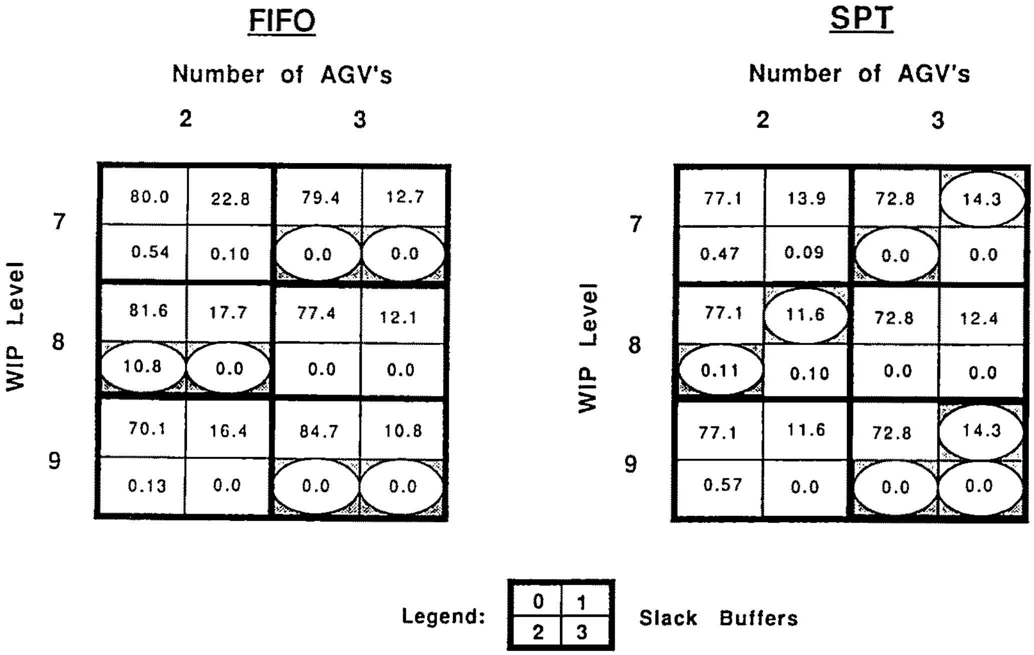
AGVs are shown for WIP levels of 7, 8, and 9 and for 0, 1, 2, and 3 slack buffers. This subset of all operating conditions investigated covers the cases in which there is a transition of overall machine utilization from sub-maximum to the theoretical maximum as the levels of system resources are increased. Cases in table 8 in which the theoretical maximum machine utilizations are achieved are highlighted.

As the number of WIP transfers from drills to buffers increases in table 8, output-blocking at the drills decreases and overall machine utilization increases (as can be seen by cross comparison of table 8 with tables 3 and 4). It is especially interesting in table 8 to see how providing 1 slack buffer (instead of having no slack buffers) causes the WIP transfer rate from drills to buffers to increase from 0 to about 30 on average (e.g. from 11.7 to 41.4 for 2 AGVs and a WIP level of 7 in the FIFO case). For the FIFO-based dispatching rule, the rate of buffer entries from the drills reaches its maximum when the overall machine utilization reaches its maximum theoretical level. This is also true for the SPT-based dispatching rule, except when the theoretical maximum machine utilization is reached in the case of 3 AGVs and 1 slack buffer.

Table 8 (and tables 3 and 4) show that going from 2 to 3 slack buffers has essentially no effect. For all practical purposes, the third slack buffer is superfluous. This fact is further demonstrated in table 9, where the percent of the time that all

Table 9

Percent of the time that all buffers are occupied with the FIFO- and SPT-based dispatching rules



FIFO

WIP Level	Number of AGV's 2		Number of AGV's 3	
7	80.0	22.8	79.4	12.7
	0.54	0.10	0.0	0.0
8	81.6	17.7	77.4	12.1
	10.8	0.0	0.0	0.0
9	70.1	16.4	84.7	10.8
	0.13	0.0	0.0	0.0

SPT

WIP Level	Number of AGV's 2		Number of AGV's 3	
7	77.1	13.9	72.8	14.3
	0.47	0.09	0.0	0.0
8	77.1	11.6	72.8	12.4
	0.11	0.10	0.0	0.0
9	77.1	11.6	72.8	14.3
	0.57	0.0	0.0	0.0

Legend:

0	1
2	3

Slack Buffers

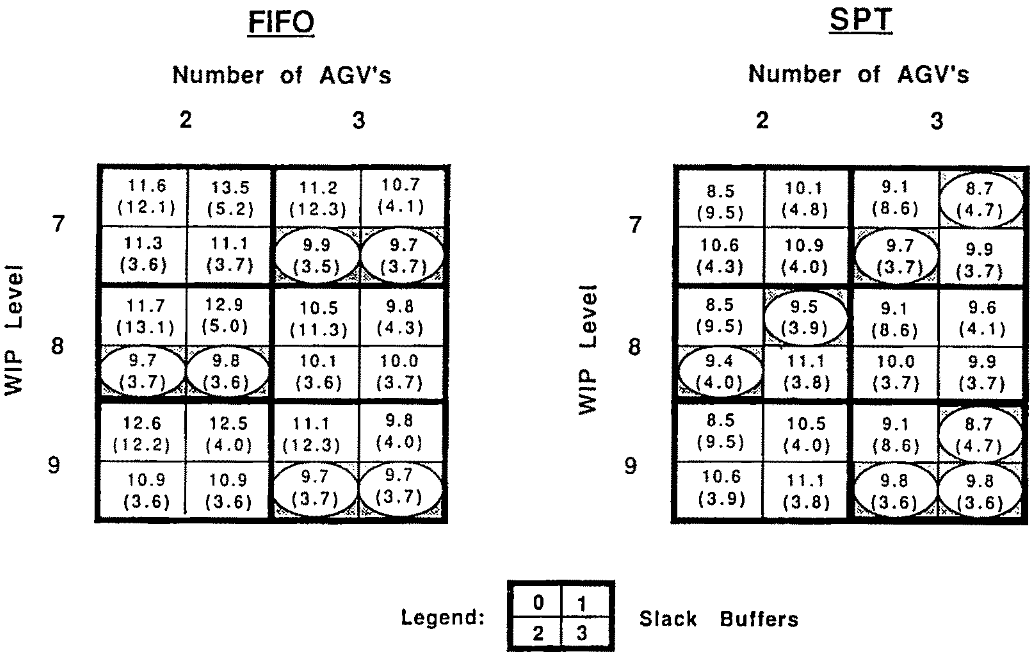
buffers are occupied is shown for the various table 8 cases. There are only two cases in table 9 (2 AGVs; a WIP level of 7; and either FIFO or SPT as the basis for the dispatching rule) for which there is some (extremely small) occupancy of the third slack buffer.

9.6. MACHINE FEED-STARVING AND OUTPUT-BLOCKING

Table 10 shows the percentage of the time that machines are feed-starved (or output-blocked) on average on an overall basis with the FIFO- and SPT-based dispatching rules. By an overall basis is meant that these percentages are the sample averages (based on samples consisting of two hundred and fifty 8-hour shifts) taken with respect to all machines in the FMS. Sample standard deviations were also computed, but they are very small, and are not reported.

Table 10

Fraction of the time machines are feed-starved or (output-blocked) with the FIFO- or SPT-based dispatching rule



FIFO

WIP Level	Number of AGV's 2		3	
7	11.6 (12.1)	13.5 (5.2)	11.2 (12.3)	10.7 (4.1)
	11.3 (3.6)	11.1 (3.7)	9.9 (3.5)	9.7 (3.7)
8	11.7 (13.1)	12.9 (5.0)	10.5 (11.3)	9.8 (4.3)
	9.7 (3.7)	9.8 (3.6)	10.1 (3.6)	10.0 (3.7)
9	12.6 (12.2)	12.5 (4.0)	11.1 (12.3)	9.8 (4.0)
	10.9 (3.6)	10.9 (3.6)	9.7 (3.7)	9.7 (3.7)

SPT

WIP Level	Number of AGV's 2		3	
7	8.5 (9.5)	10.1 (4.8)	9.1 (8.6)	8.7 (4.7)
	10.6 (4.3)	10.9 (4.0)	9.7 (3.7)	9.9 (3.7)
8	8.5 (9.5)	9.5 (3.9)	9.1 (8.6)	9.6 (4.1)
	9.4 (4.0)	11.1 (3.8)	10.0 (3.7)	9.9 (3.7)
9	8.5 (9.5)	10.5 (4.0)	9.1 (8.6)	8.7 (4.7)
	10.6 (3.9)	11.1 (3.8)	9.8 (3.6)	9.8 (3.6)

Legend:

0	1	Slack Buffers
2	3	

Operating conditions represented in table 10 correspond to those in tables 8 and 9. Conditions which succeed in achieving the maximum theoretical overall machine utilizations are highlighted in table 10. It is interesting that for these cases, machines are feed-starved about 2 to 2.5 times as long as they are output-blocked under conditions when the maximum overall machine utilizations are realized. With a maximum overall machine utilization of 86.6%, it is of course true that on an overall basis, machines must either be feed-starved or output-blocked 13.4% of the time.

9.7. OTHER RESULTS

The model produced many types of output, only some of which have been reported here. For example, the percent of the time that machines were feed-starved or output-blocked was reported by type of machine, as well as on the overall basis given in table 10. Also, the percentage of the time that 0, or 1, or 2, etc. buffers were occupied was reported, as well as the percentage of the time that all buffers were occupied (see table 9). Included among other output produced by the model are: the means and standard deviations of residence time per buffer entry; the means and standard deviations of the number of AGV captures per 8-hour shift; and the percentage of the time that 0, or 1, or 2, etc. AGVs were captured. The outputs displayed here are those judged to bear most directly on the objectives of the study.

9.8. USE OF AN ALTERNATIVE INPUT SEQUENCE

As stated earlier, it was not an objective here to study the effect of alternative input sequences on FMS performance. Nevertheless, simulations were performed for the case of one input sequence differing from the sequence used for the study proper. The alternative input sequence took the form 2, 2, 5, 6, 6, 8, 10 (admit a part of type 2; then admit another of type 2; then one of type 5; etc.) This contrasted with the input sequence of 2, 6, 5, 2, 8, 6, 10 which was otherwise used in the work. In the alternative sequence, instead of dispersing the two repeating part types (types 2 and 6) within the input sequence, part types were simply introduced in increasing order of part type number.

Overall machine utilizations for the alternative input sequence are shown in table 11 for the FIFO- and SPT-based dispatching rules under 24 differing FMS conditions corresponding to 2 and 3 AGVs, WIP levels of 7, 8, and 9, and 0, 1, 2, and 3 slack buffers. Cases for which the maximum machine utilizations are achieved are highlighted in the table.

The table 11 utilizations can be compared directly with the corresponding utilizations in tables 3 (FIFO) and 4 (SPT). In general, the alternative input sequence did not perform quite as well as the one otherwise used in the study, achieving the maximum utilization a total of only five times. (The maximum utilization was achieved thirteen times under the corresponding FMS conditions in tables 3 and 4.) Looked at in another way, however, the average FIFO-based utilizations for the 24 FMS conditions in table 11 is 82.5% versus 83.2% for these same 24 FMS conditions in table 3. This difference is small. Also, the average SPT-based utilizations for the 24 FMS conditions in table 11 is 83.2% versus 85.0% for these same 24 FMS conditions in

Table 11

Means and (standard deviations) of overall machine utilizations for an alternative part input sequence with the FIFO- and SPT-based dispatching rules

FIFO

WIP Level	Number of AGV's: 2		3	
7	73.4 (1.41)	84.3 (0.29)	75.8 (0.81)	84.3 (0.29)
	85.1 (0.45)	83.5 (0.11)	86.0 (0.38)	83.6 (0.09)
8	72.5 (0.70)	84.8 (0.35)	82.0 (0.23)	86.1 (0.19)
	85.0 (0.34)	82.6 (0.36)	86.3 (0.21)	83.5 (0.11)
9	76.2 (0.59)	83.9 (0.87)	76.6 (0.61)	85.8 (0.21)
	85.1 (0.42)	82.8 (0.56)	86.6 (0.13)	83.8 (0.06)

SPT

WIP Level	Number of AGV's: 2		3	
7	75.8 (0.27)	84.7 (0.17)	77.2 (0.40)	82.6 (0.12)
	84.9 (0.40)	84.9 (0.40)	86.6 (0.22)	86.2 (0.21)
8	75.8 (0.32)	84.7 (0.17)	77.2 (0.38)	86.6 (0.18)
	85.1 (0.19)	˙85.1 (0.19)	86.6 (0.19)	86.3 (0.26)
9	75.8 (0.32)	84.7 (0.16)	77.2 (0.39)	82.6 (0.13)
	85.8 (0.19)	85.8 (0.19)	86.6 (0.19)	86.3 (0.26)

Legend:

0	1
2	3

Slack Buffers

table 4. This difference, although larger, is also fairly small. For both input sequences, SPT outperformed FIFO with respect to this average machine utilization measure.

The influence of the part input sequence on system performance should be studied further. There is insufficient evidence presented here to even conjecture on the relative importance of the choice of a part input sequence.

10. Summary and conclusions

This research compares the theoretical overall machine utilizations resulting from the applications of mathematical programming to the machine utilizations achieved using a detailed simulation model. Unlike the MP methodology, the simulation model accounts for FMS characteristics such as constrained resources for transporting work-in-process, transfer times, limited buffer space, contention for machines, and the rules used to dispatch WIP to machines. For the specific case investigated here, it has been found that:

(1) Using a set of production ratios resulting from the application of mathematical programming methodology, the maximum theoretical overall machine

utilization (with 2-minute WIP transfer times) of 86.6% can be achieved under relatively realistic FMS operating conditions (that is, in a model which relaxes many of the MP assumptions).

(2) As well as being realistic, the FMS operating conditions also seem to be feasible, requiring in the two simplest cases only 2 AGVs, a WIP level of 8 (when there are 5 machines), and 4 central buffers; or 3 AGVs, a WIP level of 7, and 3 central buffers.

(3) The degradation in overall machine utilization attributable to having minimum levels on non-machining FMS resources (1 AGV, a WIP level of 5, and no buffers) is on the order of 15%. (The overall machine utilization drops from a theoretical maximum of 86.6% to an achieved level of 73.5%.)

(4) When there is a shortfall in overall machine utilization, the change in utilization resulting from increasing the level of a resource is not easily predicted (at this time), even qualitatively. More *may* be better, but more is *not necessarily* better, and more may even be somewhat worse. It cannot in general be stated (at this time) which single design parameter should be changed to obtain the greatest benefit in terms of increased utilization.

(5) On average, overall machine utilization achieved with an SPT-based dispatching rule is somewhat better than that achieved with an FIFO-based dispatching rule. However, the system residence time *variance* is greater for SPT than for FIFO under many FMS operating conditions. (This result is consistent with other findings reported in the literature.)

11. Future research

Many aspects of this work, and of work of this type, require further study. For a given set of production ratios, for example, the influence of alternative part input sequences on overall and individual machine utilizations needs to be studied. If an important influence is found, guidelines need to be developed for determining good part input sequences. (Because a set of production ratios developed from the MP methodology balances the machine workloads, it is conjectured that a part input sequence which is any permutation of these would also tend to balance machine workloads over time and achieve relatively good overall machine utilizations.)

There is often more than one set of production ratios which balances machine workloads. Further research is needed to determine whether some of these ratios are better than others in the sense of being able to achieve maximum overall machine utilization under simpler operating conditions (e.g. level of transportation resources; WIP levels; number of slack buffers). If important differences are found, then guidelines need to be developed for selecting the best set of production ratios from a list of candidates.

When only central buffers are provided, the possibility of reserving some buffers for use by WIP coming from bottleneck machines needs to be investigated. The objective here would be to reduce output-blocking at bottleneck machines, letting them start earlier on their next unit of work.

The influence of other dispatching rules on overall machine utilization and variability of WIP residence time needs to be studied.

For a given FMS, various alternative scenarios (that is, characteristics of parts in the input sequence) need to be studied to determine the extent to which system performance depends on the scenario itself, apart from such operating conditions as the WIP level, the number of slack buffers, and the level of transportation resources.

When overall machine utilization is short of the theoretical maximum for given operating conditions, methods must be developed for predicting whether increasing the WIP level, or increasing the number of slack buffers, or increasing the level of transportation resources, will have the most beneficial effect. Perturbation analysis may be of use in this regard [28]. Another possibility might be to develop regression models for various ranges of operating conditions.

The importance of aggregation versus disaggregation in the modeling of FMSs needs to be further assessed. For a given issue or issues, it must be determined which factors outlined in section 3 are important to model, and at which levels of detail, and which can be ignored. Relatively general guidelines must be developed for estimating the impact on FMS performance of such controllable factors as the WIP level, the number of slack buffers, the level of transportation resources, and dispatching rules.

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Appendix A

CALCULATION OF THE THEORETICAL MAXIMUM OVERALL MACHINE UTILIZATION FOR THE FMS SCENARIO IN SECTION 2

(Basis: zero travel time)

Table A.1 shows the individual and total machining requirements, by machine type, of the parts making up one input cycle for the set of production ratios used in this study and discussed in section 2. As indicated in the table, each drill and each VTL must be used for 105 machining minutes per input cycle, whereas the mill must be used for 80 minutes.

Table A.1

Machining requirements per part input cycle

Part type	Machining time per part (minutes) Mill	Drill	VTL	No. of parts per input cycle	Machining time per input cycle (minutes) Mill	Drill	VTL
2	15	20	40	2	30	40	80
5	10	50	20	1	10	50	20
6	10	30	20	2	20	60	40
8	15	20	30	1	15	20	30
10	5	40	40	1	5	40	40
		Total for all machines of each type:			80	210	210
		Total per machine of each type:			80	105	105

For the table A.1 scenario, the drills and VTLs are *bottleneck* machines. (Bottleneck machines are ones which must be used to the greatest extent in producing the sets of parts making up an input cycle. For the scenario at hand, the bottleneck machine type is tied between drills and VTLs.) In contrast, the mill is a *slack* machine. (Slack machines are ones which have more capacity than is needed to produce the set of parts making up an input cycle.)

Now assume the following idealized operating conditions are in effect:

(1) A bottleneck machine never has to wait for a part to need it.

(2) A slack machine never has to wait *counterproductively* for a part to need it. (Within certain limits, a slack machine can wait in a non-counterproductive fashion for a part to need it, because slack machine utilization will be less than 100% anyway.)

(3) WIP being taken to or from a bottleneck machine never has to wait to get the AGV needed to perform the transfer. (This is equivalent to assuming an unlimited number of AGVs in the system.)

(4) WIP being taken to or from a slack machine never has to wait counterproductively to get the AGV needed to perform the transfer.

(5) WIP travel time is zero. (That is, AGVs move instantaneously from point to point.)

Under these ideal conditions, and consistent with the information in table A.1, the 7 parts making up one input cycle can be manufactured in 105 minutes. The number of machining minutes achieved in 105 minutes is 500 (500 = 80 + 2 x 105 + 2 x 105). During these 105 minutes, the bottleneck machines (the 2 drills and 2 VTLs) will be 100% utilized, but there will be a 25 minute shortfall in use of the mill, which is the slack machine. (The mill's utilization will be 80/105=0.761, or 76.1%.) Of the potential 525 machining minutes (525 = 5 x 105) in a 105 minute time interval, then, only 500 machining minutes will be achieved. This results in an overall machine utilization of 0.952 (0.952 = 500/525), or 95.2%.

Appendix B

CALCULATION OF THE THEORETICAL MAXIMUM OVERALL MACHINE UTILIZATION FOR THE FMS SCENARIO IN SECTION 2

(Basis: 2 minute travel time)

In calculating the theoretically achievable maximum overall machine utilization when travel time is non-zero, assumptions (1) through (4) of appendix A are in effect, but the zero travel time assumption (assumption (5) of appendix A) is eliminated.

This study assumes that in transferring a part from one point (the sending point) to another (the destination), it takes 1 minute for an empty AGV to move to the sending point and pick up the part, and then takes 1 more minute for the loaded AGV to move from the part's sending point to its destination and unload the part there. The total time required for a unit of WIP to move between any two points in the system is then 2 minutes.

When a bottleneck machine finishes working on a part, the machine becomes idle and remains idle for 1 minute under assumption (3) of appendix A, while the finished part is cleared from the machine. This is "from-time". The machine then remains idle for 2 more minutes under assumptions (1) and (3) of appendix A, while an AGV fetches the machine's next part and brings that part to the machine. This is "to-time".

In the model used in this study, no provision is made to overlap "to-time" and "from-time", and there are no local machine buffers. This means that even under the otherwise ideal assumptions (1) through (4), there are 3 minutes of enforced machine idleness per machine operation.

Table B.1 repeats table A.1 by showing the individual and total machining requirements, by machine type, of the parts making up one input cycle for the sets of production ratios used in this study and discussed in section 2. Table B.1 also indicates the 1 minute "from-time" and the 2 minute "to-time" which is part of each machine use.

Table B.1

Machining requirements and travel times per part input cycle

Part type	Machining time plus to-and-from travel time per part (minutes)			No. of parts per input cycle	Machining time plus to-and-from travel time per input cycle (minutes)		
	Mill	Drill	VTL		Mill	Drill	VTL
2	15 + 3	20 + 3	40 + 3	2	30 + 6	40 + 6	80 + 6
5	10 + 3	50 + 3	20 + 3	1	10 + 3	50 + 3	20 + 3
6	10 + 3	30 + 3	20 + 3	2	20 + 6	60 + 6	40 + 6
8	15 + 3	20 + 3	30 + 3	1	15 + 3	20 + 3	30 + 3
10	5 + 3	40 + 3	40 + 3	1	5 + 3	40 + 3	40 + 3
		Total for all machines of each type:			80 + 21	210 + 21	210 + 21
		Total per machine of each type:			101	115.5	115.5

Under the above assumptions, table B.1 indicates that the 7 parts making up one input cycle can be manufactured in 115.5 minutes. The number of machining minutes achieved during these 115.5 minutes is 500 ($500 = 80 + 2 \times 105 + 2 \times 105$). Of the potential 577.5 machining minutes ($577.5 = 5 \times 115.5$) available in a 115.5 minute time interval, then, only 500 machining minutes would be achieved. This results in an overall machine utilization under these assumptions of 0.8658 ($0.8658 = 500/577.5$), or 86.6% (as used in tables 1 and 2). Corresponding utilizations for each of the machine types would be 0.693 (or 69.3%) for the mill ($0.693 = 80/115.5$); and 0.909 (or 90.9%) for the drills and VTLs ($0.909 = 105/115.5$).

Appendix C

CALCULATION OF THE THEORETICAL MINIMUM OVERALL SYSTEM RESIDENCE TIME FOR THE FMS SCENARIO IN SECTION 2

(*Basis: 2 minute travel time*)

The overall system residence time is the average time in the system per part, with the average taken over the 7 parts making up an input cycle. The theoretical minimum overall system residence time is the overall system residence time realized when assumptions (1) through (4) of appendix A are in effect, and when the 2 minute travel time assumption of appendix B is in effect.

Table C.1

Individual step times and minimum system residence time (minutes) by part type

Step type	Part type				
	2	5	6	8	10
Transport	2	2	2	2	2
Mill	15	10	10	15	5
Transport	2	2	2	2	2
Drill	20	50	30	20	20
Transport	2	2	2	2	2
VTL	40	20	20	30	40
Transport	2	2	2	2	2
Total	83	88	68	73	93

Table C.1 shows the individual step times and resulting minimum total time in the system (labeled "Total" in table C.1) for each type of part which moves through the system, by part type. The average of these minimum in-system times, with the average taken over the 7 parts making up an input cycle, is 79.4 minutes.

References

[1] R. Akella, Y. Choong and S.B. Gershwin, Real-time production scheduling of an automated cardline, Ann. Oper. Res. 3(1985)403.

[2] P. Afentakis, Maximum throughput in flexible manufacturing systems, *Proc. 2nd ORSA/TIMS Conf. on Flexible Manufacturing Systems* (Elsevier, Amsterdam, 1986) p. 509.

[3] M. Berrada and K.E. Stecke, A branch and bound approach for machine load balancing in flexible manufacturing systems, Manag. Sci. 32, 10(1986)1316.

[4] R.W. Conway, W.L. Maxwell and L.W. Miller, *Theory of Scheduling* (Addison-Wesley, Reading, MA, 1967).

[5] J. Erschler, D. Lévêque and F. Roubellat, Periodic loading of flexible manufacturing systems, *Proc. IFIP Congress APMS* (Bordeaux, France, 1982).

[6] S. French, *Sequencing and Scheduling* (Ellis Harwood Ltd., Chichester, England, 1972).

[7] J.O. Henriksen and R.C. Crain, *GPSS/H User's Manual*, 3rd ed. (Wolverine Software Corporation, Annandale, VA, 1988).

[8] S.S. Heragu and A. Kusiak, Machine layout problem in flexible manufacturing systems, Oper. Res. 36, 2(1988)258.

[9] K.L. Hitz, Scheduling of flexible flow shops – II, Report LIDS-FR-1049, Laboratory of Information and Decision Systems, MIT, Cambridge, MA (1980).

[10] A. Kusiak, The part families problem in flexible manufacturing systems, Ann. Oper. Res. 3(1985)279.

[11] A.M. Law and S.G. Vincent, *UNIFIT User's Manual* (Simulation Software and Analysis, Tucson, AZ, 1986).

[12] O.Z. Maimon and S.B. Gershwin, Dynamic scheduling and routing for flexible manufacturing systems that have unreliable machines, Oper. Res. 36, 2(1988)279.

[13] M.L. Pinedo, B. Wolf and S.T. McCormick, Sequencing in a flexible assembly line with blocking to minimize cycle time, *Proc. 2nd ORSA/TIMS Conf. on Flexible Manufacturing Systems* (Elsevier, Amsterdam, 1986) p. 499.

[14] B. Schmeiser, Batch size effects in the analysis of simulation output, Oper. Res. 30, 3(1982) 556.

[15] T.J. Schriber, *Simulation Using GPSS* (Wiley, New York, 1974).

[16] T.J. Schriber, A GPSS/H model for a hypothetical flexible manufacturing system, Ann. Oper. Res. 3(1985)171.

[17] T.J. Schriber and K.E. Stecke, Machine utilizations achieved using balanced FMS production ratios in a simulated setting, Working Paper 486, Graduate School of Business, The University of Michigan, Ann Arbor, MI (1986).

[18] T.J. Schriber and K.E. Stecke, Using mathematical programming and simulation to study FMS machine utilizations, *Proc. 1987 Winter Simulation Conf.* (Society for Computer Simulation, San Diego, CA, 1987) p. 725.

[19] J.G. Shanthikumar and K.E. Stecke, Reducing work-in-process inventory in certain classes of flexible manufacturing systems, Eur. J. Oper. Res. 26(1986)266.

[20] K.E. Stecke, Design, planning, scheduling, and control problems of flexible manufacturing systems, Ann. Oper. Res. 3(1985)3.

[21] K.E. Stecke, Procedures to determine both appropriate production ratios and minimum inventory requirements to maintain these ratios in flexible manufacturing systems, Working Paper 448, Graduate School of Business, The University of Michigan, Ann Arbor, MI (1988).

[22] K.E. Stecke and I. Kim, A flexible approach to implementing the short-term FMS planning function, *Proc. 2nd ORSA/TIMS Conf. on Flexible Manufacturing Systems* (Elsevier, Amsterdam, 1986).

[23] K.E. Stecke and I. Kim, Decision aids for FMS part type selection using aggregate production ratios to study pooled machines of unequal sizes, Working Paper 478, Graduate School of Business, The University of Michigan, Ann Arbor, MI (1986).

[24] K.E. Stecke and I. Kim, A study of unbalancing and balancing for systems of pooled machines of unequal sizes, *Proc. IEEE Robotics and Automation Conf.* (Raleigh, NC, 1987).

[25] K.E. Stecke and I. Kim, A study of FMS part type selection approaches for short-term production planning, Int. J. FMS 1, 1(1988).

[26] K.E. Stecke and J.J. Solberg, Loading and control policies for a flexible manufacturing system, Int. J. Prod. Res. 19, 5(1981)481.

[27] R. Suri, An overview of evaluative models for flexible manufacturing systems, Ann. Oper. Res. 3(1985)13.

[28] R. Suri and J.W. Dille, A technique for on-line sensitivity analysis of flexible manufacturing systems, Ann. Oper. Res. 3(1985)381.

[29] C.K. Whitney and T.S. Gaul, Sequential decision procedures for batching and balancing in FMSs, Ann. Oper. Res. 3(1985)301.

[30] R.J. Wittrock, Scheduling algorithms for flexible flow lines, IBM Journal of Research and Development 29, 4(1985)401.