FMS PERFORMANCE VERSUS WIP UNDER DIFFERENT SCHEDULING RULES

by

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1.0 INTRODUCTION

Generally, individual machines in Flexible Manufacturing Systems (FMS) are quite versatile and capable of performing many different types of operations. These capabilities, in conjunction with automated material handling, can permit very general flow patterns. Consequently, operating such systems requires effective scheduling. In order to accomplish that a thorough understanding of these systems is required.

There are a number of approaches and proposed solution procedures reported in the FMS scheduling literature. However, in this study the focus will be on studying the impact of Work-In-Process (WIP) on an FMS under different scheduling rules. Research in this area is important because,

- scheduling rules are widely used in practice, ranging from direct use of scheduling scheme to indirect use as part of knowledge bases and static schedule generation schemes. Furthermore,
- results of these simulations are vital in understanding the dynamic nature of FMS scheduling problems (Sabunuoglu and Hommertzheim, 1992).

1.1 PROBLEM STATEMENT

Most studies have been concerned with the comparison of several, but simple scheduling rules related to the decision making for dispatching a part that should be performed next on a machine. However, several authors have indicated that other decision rules might affect systems performance (Denzler et al., 1987, Solot, 1990). For example, material handling decision rule, part release timing rule, and work station selection rule.

No studies have been done on how an FMS performs when the number of jobs allowed in the system is changed. Furthermore, it is not known how a combination of all decision rules in an integrated manner will affect throughput, due-date performance and system utilization.

1.2 PROJECT OBJECTIVE

This study evaluated the effect of work in process on FMS performance under different scheduling rules. Three performance measures namely,

- meeting due-dates,
- system utilization, and
- throughput

are utilized for that purpose. A scheduling rule set consists of the following dispatching decisions:

1. Input sequencing
2. AGV dispatching
3. Next station selection, and
4. Part dispatching

1.3 CASE STUDY OVERVIEW

Results of a survey by Smith et al., 1986 on the number of parts processed by FMS in the US are presented in Table I while Table II present results on the number of machines in the FMS. From this information a FMS model is assumed for this study that consists of the following components:

- One loading station and one unload station
- Four machining stations
- Three AGV's

Figure 1 represents the FMS model and indicates four scheduling decision points that were considered for this study. These four points are:

- Input sequencing
- AGV dispatching
- Next station selection, and
- Part dispatching

Upon arrival of an order, all the data associated with processing that part were generated such as due-date, arrival time of order, actual machining time of part. If there was a queue, the part with the highest priority was loaded into the system (input sequencing). Upon completion of service at the load station the part was transported by AGV to the machine selected from alternative machines available for processing its next operation (next station selection). There the part will join the queue in the buffer installed in front of the machine specified. The AGV that has to come and pick the part up had to be determined (AGV dispatching). Several scenarios existed:

1. If there was more than one idle AGV one had to be selected from that set. (work center initiated).
2. If there was more than one work center requesting a vehicle at a time (vehicle initiated).

When a machine was available, the part with the highest priority was processed next (part dispatching). After completion of all required processing, the part departs through the unload station.

However, WIP restrictions may stop a part from entering the system. Before a part is loaded into the system the number of parts already in the FMS is checked. If the number of parts is too high than the part will wait until the number is lowered so that the part is allowed to enter the system. If the number of parts in the system is lower than what is allowed than the part will be allowed to enter the system immediately.

Researchers have focused on numerous approaches to deal with such a situation and no one has studied the effect that the number jobs in an FMS have on performance of such a system. Following is a literature review that will present work done in the area of evaluation of scheduling rules in FMS by means of simulation.

Table I: Number of parts processed by FMS

(Source: Smith et al, 1986)

PART TYPE	PERCENTAGE OF TOTAL RESPONSES
1-10	22
11-20	14
21-30	7
31-50	14
51-100	7
>100	36

Table II: Number of machines in FMS

(Source: Smith et al., 1986)

NUMBER OF MACHINES	PERCENTAGE OF TOTAL RESPONSES
2-6	54
7-10	23
11-14	15
>14	8

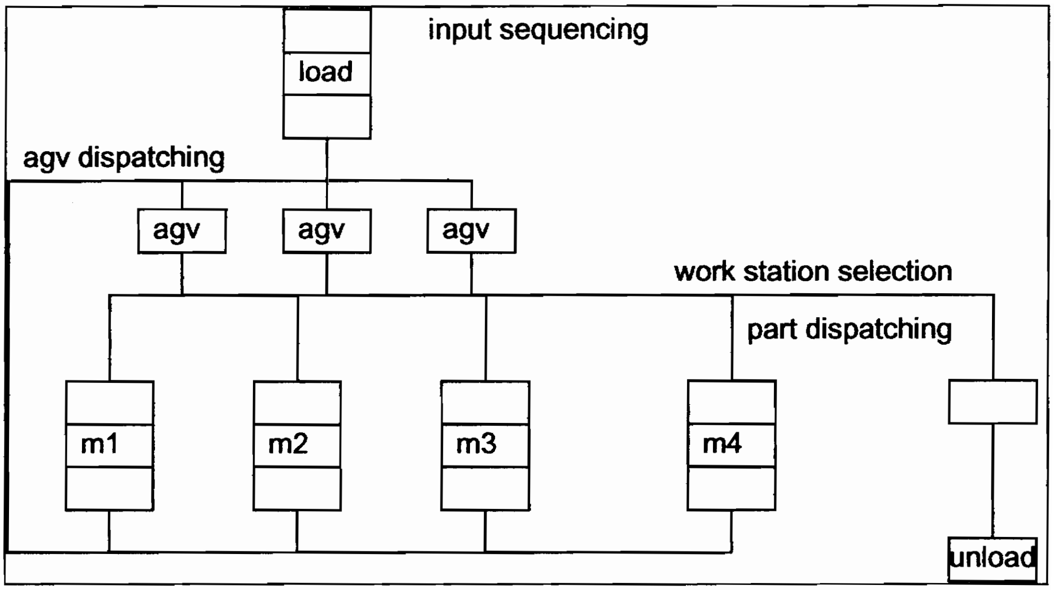

Figure 1: Schematic overview of FMS with scheduling decision points

1.4 ORGANIZATION OF THE REPORT

The remainder of this report is composed of four chapters. Chapter Two contains a review of the significant research done in the area of evaluating FMS scheduling by means of simulation. In Chapter Three, the experimental method and simulation model, utilized in this study, are explained. Chapter Four Contains the analysis and interpretation of results obtained through simulation, while conclusions of this study are presented in Chapter Five.

2.0 LITERATURE REVIEW

Three kinds of approaches are mainly used for FMS scheduling:

- Mathematical programming formulations, where FMS scheduling problems are formulated as a constrained optimization model in terms of an explicit objective function and explicit constraints and then solved by using an appropriate solution algorithm.

- AI techniques, where every scheduling system is considered unique to the given environment and therefore, a wide variety of technical knowledge and expertise should be taken into consideration to solve the scheduling problem, and

- Investigation of the performance of scheduling rules using simulation models.

Following, studies done in the area of evaluating performance of scheduling rules in FMS is reviewed. Special emphasis was placed on FMS layout, decision points for scheduling, scheduling rules, WIP and performance criteria utilized.

Stecke and Solberg, 1981, used simulation to investigate loading and control strategies on a particular FMS which consists of nine machines, an inspection station, and a centralized queuing area all interconnected by an automatic material handling mechanism. Sixteen different dispatching rules for five next station selection strategies were simulated. Some of those dispatching rules included:

SPT, shortest processing time first.
LPT, longest processing time first.
FOPR, fewest operations remaining of each part
MOPR, most operations remaining
SRPT, shortest remaining processing time of each part
LRPT, longest remaining processing time
SPT.TOT, smallest value of operation time multiplied by total processing time for the job
SPT/TOT, smallest value of operation time divided by total processing time for job
LPT.TOT, largest value of operation time multiplied by total processing time for job
LPT/TOT, largest value of operation time divided by total processing time for job

However, material handling priority rules and input sequencing rules were not considered in this study, which might affect performance of the system. Their study indicated that the SPT/TOT rule performed best for all loading strategies.

O'Gorman et al, 1986, compare four part dispatching rules based on throughput time for a flexible transfer line. However, parts follow a fixed route through the system. The part dispatching rules evaluated were:

SPT,
LPT,
FIFO, and

Johnson's Algorithm.

This system was simulated for 300 jobs and results indicated no difference in performance of those scheduling rules.

Denzler et. al., 1987, reported results of an experimental investigation of scheduling rules for a dedicated FMS with variable performance times and machine breakdowns. They specified three decisions at the operational level of an FMS namely:

- Loading: what part should be loaded next at the load station.
- Launching: when should that part just loaded be sent in the FMS.
- Routing: after launching how should it be routed through the system given the multiple route options.

An existing FMS was modeled using actual times. Performance of six heuristic scheduling rules were tested under differing uncertainty conditions. Namely: minor breakdowns, major breakdowns and operation time deviations, which ranged from 0-20 of standard time. Six different part loading rules were used to determine whether they could produce different performance results. However, for their part launching decision only next empty pallet (NEP) rule was utilized and for part routing they utilized only least work load (LWL) rule. The simulated system, consisted of 16 machining centers and 2 load/unload stations. Average machine utilization was used to measure overall performance of this system. Part loading rules utilized for this study were:

SPTL: load part that has the smallest proportion of its batch requirement started.
SPT: load part with the shortest total processing time.
S&S: load part with the smallest load station to total processing time ratio.

NEP: as each pallet is unloaded, load the next empty pallet with a like part, if WIP is available and there is demand for the product.

FEM: locate the first empty machine, then find a part needed and ready for loading that will require processing by that machine. If all machines are busy, load the first empty queue B, then queue A.

HPEM:locate the highest priority empty machine, then find a needed part that requires processing by that machine. If all machines are busy, apply the same logic to queue B, then to queue A. The machine priority scheme is obtained by ranking machines in order of descending machine work load.

They concluded that part loading, launching and routing heuristics can not satisfactory solve scheduling problems in an FMS. Furthermore they concluded that machine breakdowns and processing time uncertainty do not result in bigger reductions of machine utilization than that caused by their direct reduction in net capacity.

Choi and Malstrom, 1988, utilized a physical simulator to evaluate performance of 28 decision rule sets. For their evaluation they utilized six performance criteria. A decision rule set consisted of one part selection rule and one machine center selection rule. Their system consists of seven work stations, of which six were identical, and an AS/RS system. However, parts were undergoing only two operations on the FMS. The following part selection rules were utilized:

RANDOM, a storage area was selected randomly at time of dispatching.

FSFS, performance of this rule was based on traveling time of the AS/RS cart (first stop first served).

SPT, a storage area was selected whose first part had the shortest operation processing time.

DDATE, a storage area was selected whose first part had the earliest due-date.

SLACK, a storage area was selected whose first part had the least remaining slack time.

S/PT, a storage area was selected whose first part had the smallest ratio of slack time divided by the remaining processing time, and

VALUE, a storage area was selected whose first part had the highest (dollar) value.

The following machine center selection rules were utilized:

RANDOM, a machine center was randomly selected each time a part was put into the system.

FMFS, first machine, first served. The closest machine center had the highest priority.

NINQ, a machine center was selected that had the lowest number of parts in queue, and

WINQ, a machine center was selected that had the least work in queue in terms of process times.

There was no special dispatching rule utilized for the AS/RS system.

Co et al, 1988, tested effectiveness of sequencing rules on the throughput of an FMS when the queue length is small, which was defined as jobs per machine less than two. The following sequencing rules were analyzed:

FCFS, highest priority was given to the job that arrived at the queue first.

SPT, highest priority was given to the job with the shortest imminent operation time.

LWKR, highest priority was given to the job having the least total processing time for all operations not yet performed.

TWK, highest priority was given to the job with the least total processing time for all operations, and

NXQL, highest priority was given to the job whose direct successor operation station has the shortest queue. Jobs waiting for their last operation have the highest priority.

The objective of this study was to investigate effects of queue length on those sequencing rules. Various configurations were simulated to determine which rules minimize mean flow time or maximum throughput of jobs processed. The systems simulated consisted of 5, 7, 10, and 15 stations with 2, 4, and 6 job types. Operations required for each job type was 1.5-2 times number of stations with a maximum of 18 operations. Processing times were uniformly distributed between 5-19 minutes. For the 12 combinations of job types and number of stations, two sets of data pertaining to the number of operations, processing times or routing sequences were generated. Under each scenario various levels of system loading were investigated. Twelve runs were made for each dispatching rule. However, this system did not provide for alternative routing of parts and material handling was not modeled.

Montazeri and Van Wassenhove, 1990, evaluated effects of 14 different dynamic and static scheduling rules on a system that consisted of five machines, three load/unload stations, three carriers, and 11 WIP buffer positions. All machines had their own dedicated shuttle. Eleven different part types were produced by this system. In order to schedule this system different decision points were identified such as:

- Selection of next part to be processed by the machines
- Selection of next part to be moved in the system
- Selection of next part to be reclamped by the worker
- Selection of next part to be loaded on carrier from a facility

The performance criteria utilized were:

- Average and variance of waiting time
- Average and variance of machine utilization
- Average buffer utilization
- Average shuttle utilization
- Make span

The following scheduling rules were considered for this study;
SIO, SPT, SRPT, SMT (SIO.TP), SDT (SIO.TP), LIO, LPT, LRPT, LMT (LIO.TP), LDT (LIO/TP), MRO, FRO, FIFO, FASFO.

It was concluded that no single scheduling rule is favorable for all performance measures used and that dispatching rules have an important impact on system performance. The best dispatching rule to minimize average waiting time was SPT and the LPT rule maximized machine utilization. In this study, the part routing was fixed for each part type.

Ishii and Talavange, 1991, monitored system state of an FMS and depending on changes in the system state they proposed a single dispatching rule for the whole system, which consisted of three AGV's, four workstations and two load/unload stations. Simulation was used to predict an upcoming change in the system state and FIFO was used as scheduling rule. No multiple routing of parts was allowed, therefore treating this system more as a job shop where one does not take advantage of the flexibility FMS provides. The system state was monitored by a function called INDEX:

$$\text{INDEX}(t) = 1/n * \sum_{j=1}^{n} (PTj + WTj + TRj) / DTj$$

where,

n = number of parts in system at simulation time t.

PTj = Part j's total processing time

WTj = Part j's total waiting time (predicted by simulator)

TRj = Part j's total transportation time (predicted by simulator)

t = Simulation time at which INDEX is calculated

Each candidate dispatching rule was simulated and the rule that performed best to the performance criteria was selected as the dispatching rule for the next scheduling interval. Because of the short time interval, censored data effected the evaluation and four strategies were evaluated to deal with that problem.

The following dispatching rules were considered:

NINQ,

SI,

SLACK,

and FIFO.

While the performance criteria included:

Mean flow time,

Mean tardiness,

Mean flow time + mean tardiness,
weighted mean flow time,
weighted mean tardiness,
weighted mean flow time, and
weighted mean tardiness.

A comparison was made between a multi-pass scheduling algorithm where they evaluated the scheduling rules at a fixed time interval and a transient-based scheduling algorithm where they evaluated scheduling rules on a transient basis. That was compared to cases where just one fixed rule was used for the entire period. Those fixed dispatching rules were: NINQ, SI, SLACK, and FIFO. This system has a fixed part routing for each part type, therefore one of the major advantages FMS provides was not utilized.

O'Keefe and Kasirajan, 1992, investigated the interaction between nine dispatching rules and four next station selection rules in a dedicated FMS. This system consisted of 16 work stations with local buffers, nine load/unload stations and three AGV's and produces six part types. Results were generated during steady-state, rather than a more common approach of running the model until a terminating condition were reached. The major criterion for evaluating performance of the combinations was production rate. For input sequencing the only rule utilized was FIFO. Some of the dispatching rules utilized once a part was in a queue in front of a machine were:

FIFO, select a job that first entered the system.
SIO, select a job with the shortest imminent operation
LIO, select a job with the longest imminent operation
FRO, select a job with the fewest number of remaining operations

MRO, select a job with the most number of remaining operations
SIO/TOT, select a job with the smallest ratio obtained by dividing the processing time of the imminent operation by the total processing time for the part.
LIO/TOT, select a job with the largest ratio obtained by dividing the processing time of the imminent operation by the total processing time for the part.
SLACK, select a job with the least amount of slack

The next station selection rules utilized were:
NS, select the station that is nearest to where the job presently resides.
WINQ, select the station whose input buffer contains the smallest total amount of work.
NINQ, select the station with the fewest number of jobs in the buffer, and
LUS, select the station with the smallest total utilization rate.

The performance measure utilized to evaluate this system was production rate. This study indicated the importance of next station selection rules in scheduling. They concluded that the WINQ rule was the best next station selection rule when flow time was measured.

Table III presents, systematically, research in the area of evaluating scheduling rules by means of simulation while Table IV presents scheduling rules utilized at the decision points. The literature survey indicates that some researchers have identified the important scheduling decision points in an FMS and have done some studies to underline the importance of those points. However, AGV dispatching has not been addressed in those studies. Even though, selection of

AGV control measures can affect machine utilization, material flow, and buffer storage requirements (Egbelu and Tanchoco, 1984).

The problem situation addressed in this study is similar to the one considered in the CONWIP (Constant Work In Process) system as introduced by Spearman et. al. (1990, 1991), Hopp et. al., (1991). However, CONWIP is a job-shop system in which a fixed number of jobs are maintained in the system. As a job is completed another job is released from a predetermined backlog. This system is discussed in the literature for a serial system of work stations in which every job is processed by machines in the same sequence. As a result part dispatching, next station selection, AGV dispatching issues do not arise. The problem on hand considers an FMS and therefore requires consideration of AGV dispatching, part dispatching, next station selection and input sequencing. As a result , even though the number of jobs remains constant yet the problem scenario is more general. The focus is to determine how to process and route jobs in this FMS under different WIP levels. In the next Chapter the methodology of this approach will be explained.

Table III: Representation of work done in evaluation of scheduling rules by means of simulation.

AUTHOR	SYSTEM	DECISION POINTS	MATERIAL HANDLING	PERFORMANCE MEASURE	ROUTING	# OF PARTS	REMARKS
Stecke and Solberg, 1981	10 mach	next station selection and part dispatching	2 shuttles	output	flex	2	material handling is not considered nor is part sequencing
O'Gorman et al, 1986	3 mach	part dispatching	3 shuttles	throughput time	fixed	5	no machine breakdown
Denzler et al, 1987	16 machines	input sequencing, next station selection, part dispatching,	37 cart towline	machine utilization	flex	8	Determine impact of uncertainty on performance of heuristic loading rules
Choi et al, 1988	10 mach, AS/RS	input sequencing, next station selection, part dispatching	conveyors	actual system effectivity, total traveling time of parts, actual prod. output, total manuf. throughput time, WIP, total prod. lateness	flex	7	failures of AS/RS cart, machine centers and robot was taken into account
Co et al, 1988	5, 7, 10, 15 mach	part dispatching, input sequencing	not included in model	mean flow time	fixed	2, 4, 6	No failures and repairs.
Montazeri, and van Wassenhove, 1990	5 mach	select part to be processed by machine, select part to be moved in system, select part to be reclamped, select part to be loaded on carrier from a machine	3 carriers	avg. and var. of waiting time per part avg. and var. of machine utilization avg. buffer utilization avg. carrier utilization make span	fixed	11	Same rule is used for entire system
Iishi and Talavage, 1991	4 mach	part dispatching	3 AGV	mean flow time, mean tardiness (mean flow time + mean tardiness) weighted mean flow time, weighted mean tardiness, (weighted mean flow time + weighted mean tardiness)	fixed	6	Dispatching rule is changed based on conditions in FMS. One rule is used for the entire system. Different strategies to change rules are discussed
O'Keefe and Kasirajan, 1992	16 mach	next station selection, input sequencing, part dispatching	3 AGV	flow time (production rate)	flex	6	Use steady state and then start to collect statistics no machine break down or AGV failure

Table IV: Scheduling rules utilized at decision points in previous research

AUTHOR	INPUT SEQUENCING	AGV DISPATCHING	NEXT STATION SELECTION	PART DISPATCHING
Stecke and Solberg, 1981			5 strategies	Original, SPT, LPT, FOPR, MOPR, SRPT, LRPT, SPT.TOT, SPT/TOT, LPT/TOT, LPT.TOT, 4 rules based on part type priority
O'Gorman et al, 1986				SPT, LPT, FIFO, Johnson Algorithm
Denzler et al, 1987	NEP, FEM, HPEM, SPJL, SPT, S&S		LWL	FIFO
Choi et al, 1988	RANDOM, FSFS, SPT, DDATE, SLACK, S/PT, VALUE		RANDOM, FMFS, NINQ, WINQ	FIFO
Co et al, 1988	FCFS, SPT, LWKR, TWK, NXQL			FIFO
Montazeri,and van Wassenhove 1990				SIO, SPT, SRPT, SMT, SDT, LIO, LPT, LRPT, LMT, LDT, MRO, FRO, FIFO, FASFO
Iishi and Talavage, 1991				NINQ, SI, SLACK, FIFO
O'Keefe and Kasirajan, 1992	FIFO		NS, WINQ, NINQ, LUS	FIFO, SIO, LIO, FRO, MRO, SIO/TOT, LIO/TOT, SLACK, SIO*

3.0 METHODOLOGY

The methodology of this study is described below as a set of interrelated stages:

- Construction of an experimental FMS including parameter settings, variables to be studied, and frequency distributions to be used.
- Specification of statistical analyses to be used in studying performance of the FMS.
- Development of a simulation model for the FMS.
- Execution of statistical analyses to enable conclusions to be drawn.
- Formulation and presentation of conclusions drawn from this study.

3.1 SCHEDULING RULES CONSIDERED

For purposes of this study the following scheduling decision points were considered simultaneously:

- INPUT SEQUENCING: The order of releasing into the system the parts that had to be produced must be determined.
- WORK STATION SELECTION: When an operation could be performed on several machines the one to use had to be determined.
- PART DISPATCHING: The part that must be processed first on a work station had to be selected from the input queue at this station.
- AGV DISPATCHING: The AGV that had to come and pick up the part had to be determined.

For each of those decision points the following scheduling rules were considered:

INPUT SEQUENCING:

1. SPT, Select part that has shortest processing time.
2. LPT, Select part with longest processing time
3. FIFO, Select part that first entered the queue

WORK STATION SELECTION:

1. NINQ, Select work station with least number of jobs in queue.
2. WINQ, Select work station with least work in queue

PART DISPATCHING:

1. SPT, Select part with shortest processing time at station
2. LIFO, Select part that last entered queue
3. FIFO, Select part that entered queue first

AGV DISPATCHING:

AGV dispatching decisions fall in two categories:

1. Vehicle initiated
2. Work center initiated

Rule pairs are required to accomplish the vehicle dispatching requirements of an AGV based material handling system. For the purpose of this study the following pairs were selected:

1. Nearest Vehicle (NV)/ Random Work center (RW)
2. Nearest Vehicle (NV)/ Minimum Remaining Outgoing Queue Space (MROQS)

All possible combinations of scheduling rule sets were simulated and evaluated based on due-date performance, throughput and average machine utilization for an unconstrained WIP.

Consequently, parameters such as:

- Routing flexibility, which is the ability to route a part by multiple paths through the system.
- Arrival rate of parts entering the system,
- Product mix of parts arriving for processing and
- Processing time of parts on the different machines.

were altered for different WIP constraints to evaluate effects of WIP on the performance of the FMS.

3.2 CRITERIA USED FOR EVALUATION OF RESULTS

For purposes of this study the following performance criteria were used because they are considered the most important criteria by which FMS are being evaluated in industry (Smith et al., 1986).

Due-Date:

For the purpose of this study parts were assigned an exogenous due-date. Once a part arrived a due-date was set. On exit from the FMS it was determined if the due-date was met.

System Utilization:

The percentage of utilized capacity at the work centers was measured.

Throughput:

The number of parts completed after each run were counted.

3.3 ASSUMPTIONS OF SIMULATION MODEL

All simulation models are based on certain assumptions. For this simulation the following assumptions apply:

1. FMS consists of four machining stations for processing, one load station, one unload station, and three AGV's. See Figure 2.
2. The following assumptions were made for scheduling this FMS:

- No station can process more than one part at a time.
- Once any operation is started on a station, it is completed on the same station without any interruption.
- Each part is an entity.
- Parts have alternative routings.

3. Five parts are being produced by this system.
4. Routings and processing times of those parts are presented in Table V and VI.
5. Set up times are sequence-independent and included in the processing times.
6. The following performance measures are chosen:

- Meeting due-dates.
- System utilization.
- Throughput

7. All statistics will be collected once the system has reached steady state.

A SIMAN model and experimental file is presented in Appendix A.

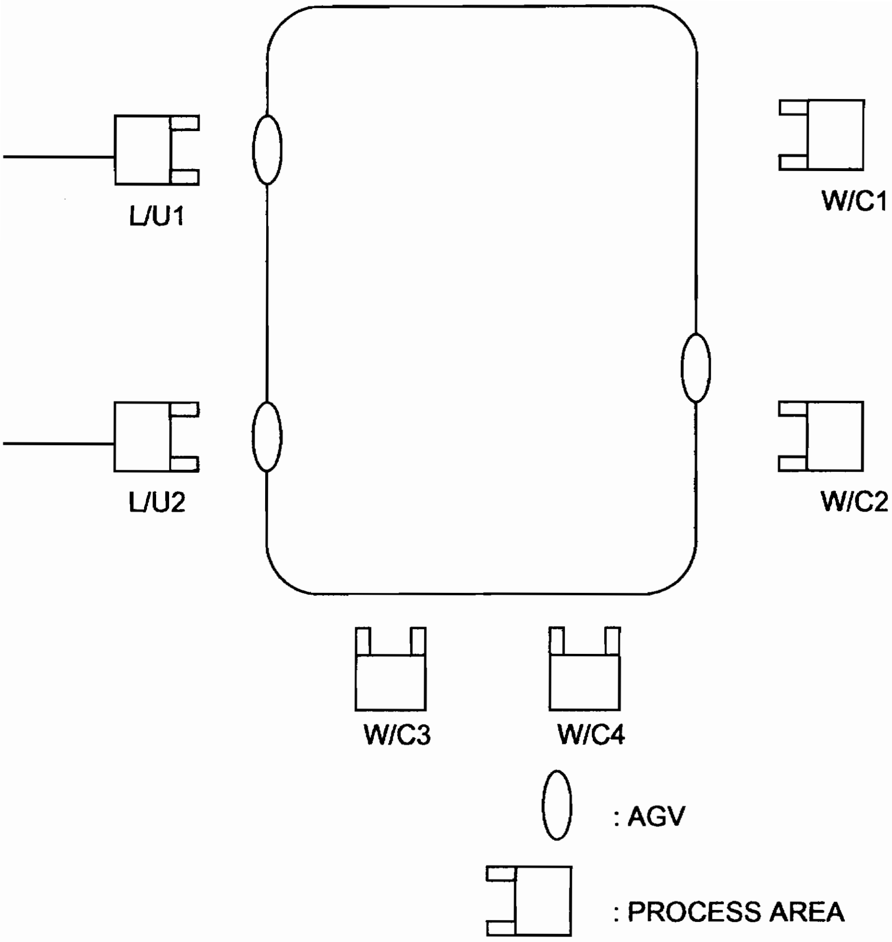

Figure 2: Physical Layout of the FMS Model.

Table V: Routings for Parts

PART	# OF OPER	WORK CENTER					
		1st oper	2nd oper	3th oper	4th oper	5th oper	6th oper
1	6	1	3	4,2	5	4,3	6
2	5	1	5	4,3	2,5	6	
3	6	1	2,5	3	4	3,2	6
4	6	1	4	5	4,3	2,5	6
5	5	1	3,4	2,5	3	6	

Table VI: Triangular Distribution of Processing Times (minutes) at Operations (min., mode, max.)

Part	1st oper	2nd oper	3th oper	4th oper	5th oper	6th oper
1	14,16,17	18,20,21	30,40,42	12,16,18	18,20,22	10,16,18
2	10,20,21	1,4,5	12,20,21	30,40,45	14,16,20	
3	4,8,9	10,15,16	2,6,7	4,8,9	8,12,14	3,9,10
4	4,8,10	2,5,6	3,5,6	8,14,15	8,12,13	3,9,11
5	3,8,10	5,11,13	10,18,20	2,5,6	5,9,10	

4.0 ANALYSIS AND INTERPRETATION OF RESULTS

Mean Tardiness, Throughput, and Machine Utilization were recorded during the simulation runs. In this Chapter the simulation output was examined in order to determine effects of WIP constraints on FMS performance when operating under different scheduling rules.

4.1 CALCULATION OF PERFORMANCE MEASURES

Performance measures were calculated after 30,000 minutes for each run. It should be noted that results gathered for the first 30,000 minutes were discarded. Therefore, results contain data on jobs completed from 30,000-60,000, 60,000-90,000 and 90,000-120,000 minutes. Numerical values of the performance measures were calculated as follows.

4.1.1 Determination of machine utilization

The formulation of average machine utilization (X) is:

$$X = \frac{1}{n}\sum_{j=1}^{n}[(1-\frac{total.idle.time.of.workcenter.j}{simulated.time})*100]$$

n = number of machines

4.1.2 Determination of due-date performance

This was measured by determining the mean tardiness of all jobs. If D_i is the due-date of job i .Then, tardiness T_i can be presented as:

$T_i = C_i - D_i$ for $T_i > 0$

$T_i = 0$, otherwise.

where, C_i = Completion time for job i.

It should be noted that a positive T_i indicates that a job is completed late. An average value of T_i was recorded for each simulation run.

4.1.3. Determination of throughput

This was measured by counting number of jobs completed after each run. This indicated the throughput since time per run remained constant.

4.2 SIMULATION RESULTS

Summarized simulation data generated are presented in Appendix B. Table VII present results of performance measures with unconstrained WIP. Table VIII present results of throughput and machine utilization for different WIP levels utilizing different AGV dispatching rules. The AGV dispatching rules examined were Nearest Vehicle/ Random Work Center (NV/RW) and Nearest Vehicle/ Minimum Remaining Outgoing Queue Space (NV/MROQS). Table IX present results of the performance of the FMS under different input sequences. The input sequencing rules examined are SPT, LPT, and FIFO. Table X present results of the performance under different part dispatching rules which in this case are SPT, FIFO and LIFO. Table XI present results of the performance under different next station selection rules NINQ and WINQ.

In order to determine the effect of a change in product mix on the performance of the FMS the same scenarios as described before were simulated under a different product mix. Table XII present results of throughput and average machine utilization for the different AGV dispatching rules. Table XIII presents summarized results of throughput and average machine utilization for different input sequencing rules. Table XIV present summarized results of throughput and machine utilization for different part dispatching rules. Table XV present results of throughput and machine utilization for different next station selection rules.

The effect of a change in process times was also evaluated. The processing times at the machines were increased and the same scenarios as described above were simulated. Table XVI present results of throughput and average machine utilization for the different AGV dispatching rules. Table XVII presents summarized results of throughput and average machine utilization for different input sequencing rules. Table XVIII present summarized results of throughput and machine utilization for different part dispatching rules. Table XIX present results of throughput and machine utilization for different next station selection rules.

Consequently, the mean arrival time was increased and the same scenarios were simulated. Table XX present results of throughput and average machine utilization for the different AGV dispatching rules. Table XXI presents summarized results of throughput and average machine utilization for different input sequencing rules. Table XXII present summarized results of throughput and machine utilization for different part dispatching rules. Table XXIII present results of throughput and machine utilization for different next station selection rules.

Routing flexibility was increased and the same scenarios were simulated. Table XXIV present results of throughput and average machine utilization for the different AGV dispatching rules. Table XXV presents summarized results of throughput and average machine utilization for different input sequencing rules. Table XXVI present summarized results of throughput and machine utilization for different part dispatching rules. Table XXVII present results of throughput and machine utilization for different next station selection rules.

4.3 STATISTICAL ANALYSIS OF RESULTS

An ANOVA was performed with respect to the performance measure to determine if there was a significant difference in means at a five percent level of significance. The ANOVA was performed if more than two cases had to be evaluated at the same time. Otherwise, a T-test for paired observations was performed to determine whether the difference in means. Therefore in order to evaluate the AGV dispatching rules and work station selection rule a T-Test was performed and to evaluate the input sequencing and part dispatching rules an ANOVA was performed. The software utilized for this purpose was excel. Appendix C presents the results of the statistical analysis.

4.4 Interpretation of Results

Following is a discussion of the FMS performance under different WIP levels and scheduling rules.

4.4.1 Effect of AGV dispatching Rules on FMS

When the WIP level is lowered and bottlenecks are created in the system the AGV dispatching rule becomes significant in determining the throughput and machine utilization as can be seen in Table XXXVII. In all other cases the AGV dispatching rule does not play a significant role in determining the throughput and machine utilization.

4.4.2 Effect of work center selection rules on FMS

Results indicate no significant difference in performance measures average tardiness, mean machine utilization and mean throughput regardless of the next station selection rule utilized. This has been the observation for all WIP levels, indicating that WIP does not influence the next station selection rule. As can be seen in Table XXXVI, XL, XLIV, and XLVIII.

Table XXVIII: ANOVA results used in determining whether there is a difference in Mean Machine Utilization, Mean Tardiness, and Mean Throughput with Unconstrained WIP

Performance Measure	F-VALUE
Mean Tardiness	1.9531*
Mean Machine utilization	0.9527
Mean throughput	0.8610

* Significant at the α=.05 level of significance

4.4.3 Effect of input sequence on FMS

Results indicate that input sequencing had a significant impact on average tardiness in 1 of 12 comparisons for a system with unconstrained WIP. The effect of Input Sequencing on this FMS was further evaluated by analyzing three scheduling rule sets, with different input sequencing rules for different WIP levels. Results indicate that when the WIP is small, input sequencing affects throughput and average machine utilization. Results presented in Figure 3, shows the effect of input sequencing on throughput, while Figure 4 shows the effect of input sequencing on average machine utilization. Results indicated that utilizing the LPT input sequencing rule resulted in a higher machine utilization and throughput when the WIP level is small. After the product mix was altered there was a significant difference in throughput and average machine utilization for all WIP levels studied. Figure 5 shows the effect of input sequencing rules on throughput when the product mix is altered. When processing times were increased there was a significant difference between the throughput when different input sequencing rules were used as depicted in Figure 6. However, when the arrival rate of jobs to the FMS was lowered there appeared to be a significant difference only when the WIP level was small. When routing flexibility was increased it appeared that there was a significant difference in throughput and average machine utilization between input sequencing rules when the WIP level was small with the LPT rule still dominating. This information is provided in Tables XXXIV, XXXVIII, XLII, and XLVI.

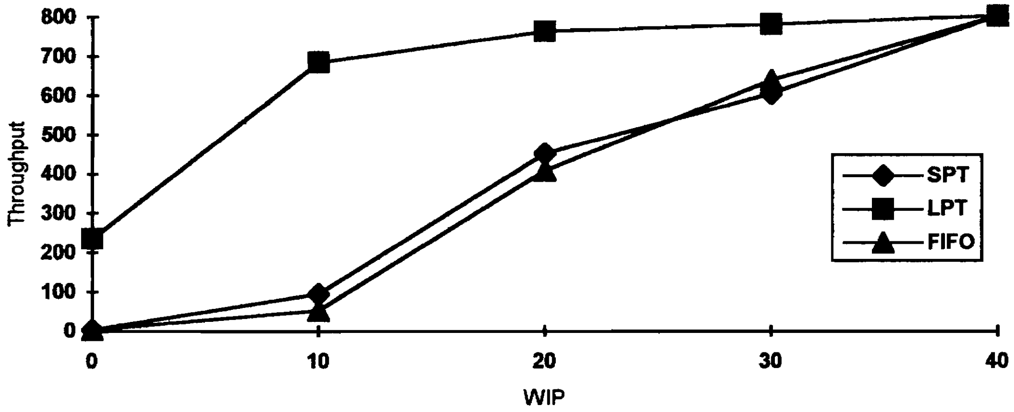

Figure 3: Effect of input sequencing on throughput

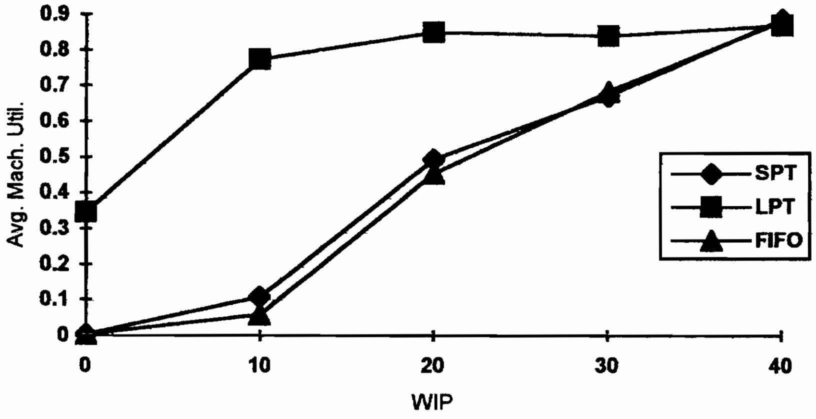

Figure 4: Effect of input sequencing on average machine utilization

4.4.4 Effect of part dispatching on FMS

Results indicate that part dispatching affected the mean tardiness of jobs in an FMS with unconstrained WIP. Figure 7 present results of those findings indicating the dominance of the SPT rule. The WIP level did not effect the performance of the different part dispatching rules evaluated. As can be seen in Table XXXV, XXXIX, XLIII, LI and XLVII.

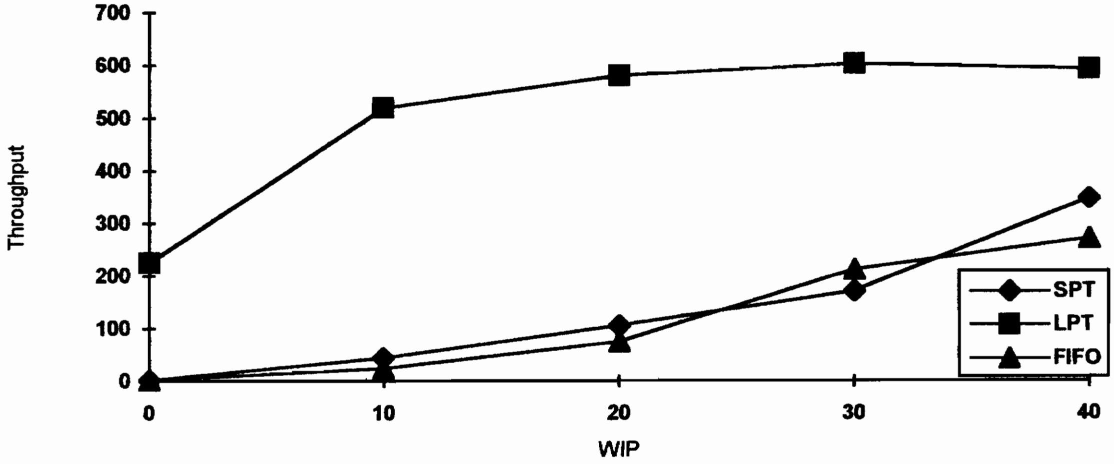

Figure 5: Effect of input sequencing on throughput when product mix was altered for different WIP levels

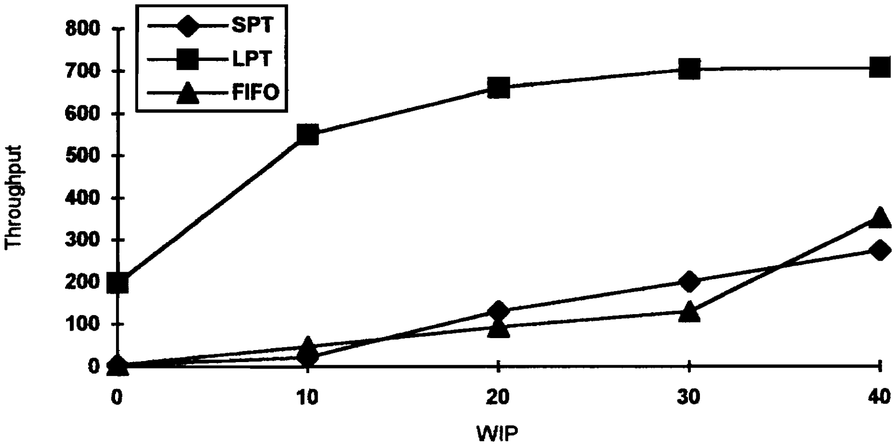

Figure 6: Effect of input sequencing on throughput when processing times were increased for different WIP levels

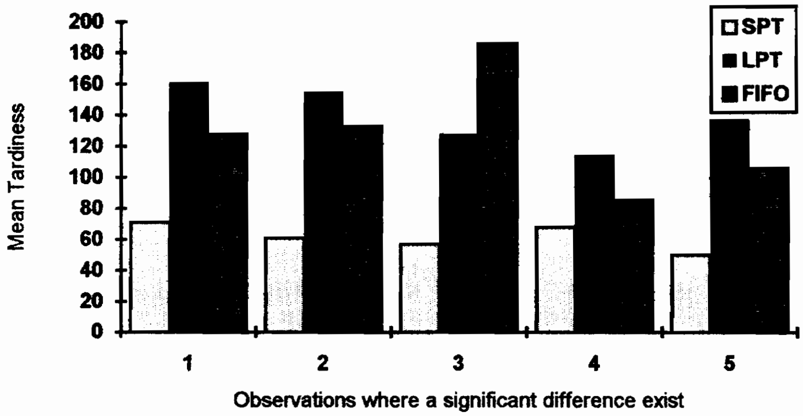

Figure 7: Effect of part dispatching on mean tardiness for unconstrained WIP of the FMS

5.0 CONCLUSIONS AND RECOMMENDATIONS

Results of this study have been analyzed in the previous Chapter. It will be meaningful to mention the objective of this study in order to draw conclusions. This study was conducted to investigate the performance of the FMS under different WIP levels and scheduling rules. The mean tardiness, throughput and machine utilization were used to evaluate this system. The scheduling rules utilized for this study were input sequencing rule, next station selection rule, AGV dispatching rule, and part dispatching rule. This study was conducted by simulating an FMS consisting of four machining centers, one load station, one unload station and three AGV's for various WIP levels. SIMAN was used to model this system. The following scheduling rules were evaluated:

Input sequencing: SPT, LPT, and FIFO
Work station selection: NINQ and WINQ
Part dispatching: SPT, LIFO, and FIFO
AGV dispatching: NV/RW and NV/MROQS

Due dates were assigned to jobs upon entering the queue in front of the load station. A triangular distribution was used to assign processing times at the stations. Job inter arrival times were assigned by an exponential distribution.

Previous research had indicated that results are dependent on conditions of the FMS. In this study however, the FMS was studied under several WIP levels. Furthermore, several conditions were altered to evaluate the system under all possible extreme conditions. For this purpose the system was analyzed after changes were made in the following conditions:

1. Routing flexibility
2. Arrival rate
3. Processing times
4. Product mix

These scenarios were evaluated for different WIP levels in order to evaluate the effect of those levels on FMS performance. Resulting in a total of 633 runs. Analysis of results indicated that WIP had a significant impact on system utilization and throughput. This study indicated that the best part dispatching rule was the SPT rule when the due-date was the measure of performance. This has been observed when decision points were studied separately. Input sequencing did impact the throughput and machine utilization with the LPT rule being the best rule when the WIP level was a constraint. However, when WIP became less of a constraint the input sequencing rules studied did not influence throughput and average machine utilization. Next station selection rules studied did not seem to influence the performance measures. This could be due to the fact that there is a correlation between number of jobs and total waiting time in the queues in front of the machines. Increased routing flexibility reduced the demand for WIP space. Therefore, allowing it to maximize its throughput and machine utilization with a lower WIP level than when the system is less flexible. Previous research has indicated that not one rule will be best for all performance measures which has been the case in this study as well. Researchers had indicated that AGV dispatching rules might affect system performance. In this study, AGV dispatching rules only affected throughput and machine utilization when the WIP is low and there were bottlenecks in the system.

Previous studies have not made an attempt to investigate the effect of WIP in an FMS. Furthermore, they have studied a fixed set of parameters and indicated that the results were valid only under those circumstances and that results may change if the system parameters would differ. However, in this study all possible decision points were integrated into the system. This system was furthermore studied under various extreme conditions with different WIP levels to see whether system parameters would alter results. Therefore making the findings more generic.

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Appendix A

Listing of Model and Experimental file of Simulation Model

MODEL FILE

```
BEGIN;
;*******************************************************
; This simulation will utilize the following rules:
; Work station selection: NINQ
; AGV dispatching: NV/RW
; This model is for unconstraint WIP
;*******************************************************
     CREATE:     EXPO(14):
             MARK(TIMEIN);     ! creation of parts
     ASSIGN:     NS=DISCRETE(.2,1,  ! parttype A
                  .4,2,  ! parttype B
                  .6,3,  ! parttype C
                  .8,4,  ! parttype D
                  1,5):  ! parttype E
             PARTTYPE=NS:NEXT(GO);
GO   BRANCH,     1:
             IF,PARTTYPE.EQ.1,ADUE:
             IF,PARTTYPE.EQ.2,BDUE:
             IF,PARTTYPE.EQ.3,CDUE:
             IF,PARTTYPE.EQ.4,DDUE:
             IF,PARTTYPE.EQ.5,EDUE;
ADUE  ASSIGN:    DUEDATE=TIMEIN+400:NEXT(GOON);
BDUE  ASSIGN:    DUEDATE=TIMEIN+260:NEXT(GOON);
CDUE  ASSIGN:    DUEDATE=TIMEIN+180:NEXT(GOON);
DDUE  ASSIGN:    DUEDATE=TIMEIN+170:NEXT(GOON);
EDUE  ASSIGN:    DUEDATE=TIMEIN+150:NEXT(GOON);
GOON  ASSIGN:    M=WORKCENTER1:
             TYPE=PARTTYPE+5:
             PROCESS=1;
;
; WORKCENTER1 SUBMODEL
;
     STATION,    WORKCENTER1;
WC1IB  ASSIGN:   timeq=TNOW:
             PROCTIME=TRIA(AMIN(PARTTYPE,PROCESS),
             MODE(PARTTYPE,PROCESS),BMAX(PARTTYPE,PROCESS));
     QUEUE,     WORKC1IB;
     SEIZE:     LOAD;
     DELAY:     PROCTIME;
     RELEASE:    LOAD;
     ASSIGN:     timeq=TNOW:
             IS=1:
             WC=1:
             PROCESS=PROCESS+1:
             PRIORITY=DISCRETE(.2,1,.4,2,.6,3,.8,4,1,5):
             NEXT(NSS);
WC1OB  QUEUE,     WORKC1OB;
```

```
      REQUEST,PRIORITY:     AGV(SDS),,INTX(1);
      TRANSPORT:    AGV,SEQ;
;
; WORKCENTER2 SUBMODEL
;
      STATION,      WORKCENTER2;
      BRANCH,       1:
               if,nq(workc1ob).gt.0.or.nq(
               workc2ob).gt.0.or.nq(
               workc3ob).gt.0.or.nq(
               workc4ob).gt.0.or.nq(
               workc5ob).gt.0,f1:
               else,sst2;
sst2   BRANCH,       2:
               always,sbk2:
               always,wc2ib;
sbk2   MOVE:         agv,staging:
               NEXT(freeagv);
f1     FREE:         AGV;
WC2IB  ASSIGN:       timeq=TNOW:
               PROCTIME=TRIA(AMIN(PARTTYPE,PROCESS),
               MODE(PARTTYPE,PROCESS),BMAX(PARTTYPE,PROCESS));
      QUEUE,        WORKC2IB;
      SEIZE:        MACHINE1;
      DELAY:        PROCTIME;
      RELEASE:      MACHINE1;
      ASSIGN:       timeq=TNOW:
               WC=2:
               PROCESS=PROCESS+1:
               PRIORITY=DISCRETE(.2,1,.4,2,.6,3,.8,4,1,5):
               NEXT(NSS);
WC2OB  QUEUE,        WORKC2OB;
      REQUEST,PRIORITY:     AGV(SDS),,INTX(3);
      TRANSPORT:    AGV,SEQ;
;
;
; WORKCENTER3 SUBMODEL
;
      STATION,      WORKCENTER3;
      BRANCH,       1:
               if,nq(workc1ob).gt.0.or.nq(
               workc2ob).gt.0.or.nq(
               workc3ob).gt.0.or.nq(
               workc4ob).gt.0.or.nq(
               workc5ob).gt.0,f2:
               else,sst3;
sst3   BRANCH,       2:
               always,sbk3:
               always,wc3ib;
sbk3   MOVE:         agv,staging:
               NEXT(freeagv);
```

```
f2     FREE:        AGV;
WC3IB    ASSIGN:      timeq=TNOW:
               PROCTIME=TRIA(AMIN(PARTTYPE,PROCESS),
               MODE(PARTTYPE,PROCESS),BMAX(PARTTYPE,PROCESS));
      QUEUE,       WORKC3IB;
      SEIZE:       MACHINE2;
      DELAY:       PROCTIME;
      RELEASE:     MACHINE2;
      ASSIGN:      TIMEQ=TNOW:
               WC=3:
               PROCESS=PROCESS+1:
               PRIORITY=DISCRETE(.2,1,.4,2,.6,3,.8,4,1,5):
               NEXT(NSS);
WC3OB    QUEUE,       WORKC3OB;
      REQUEST,PRIORITY:    AGV(SDS),,INTX(7);
      TRANSPORT:    AGV,SEQ;
;
;
; WORKCENTER4 SUBMODEL
;
      STATION,      WORKCENTER4;
      BRANCH,       1:
               if,nq(workc1ob).gt.0.or.nq(
               workc2ob).gt.0.or.nq(
               workc3ob).gt.0.or.nq(
               workc4ob).gt.0.or.nq(
               workc5ob).gt.0,f3:
               else,sst4;
sst4    BRANCH,      2:
               always,sbk4:
               always,wc4ib;
sbk4    MOVE:        agv,staging:
               NEXT(freeagv);
f3     FREE:        AGV;
WC4IB    ASSIGN:      timeq=TNOW:
               PROCTIME=TRIA(AMIN(PARTTYPE,PROCESS),
               MODE(PARTTYPE,PROCESS),BMAX(PARTTYPE,PROCESS));
      QUEUE,       WORKC4IB;
      SEIZE:       MACHINE3;
      DELAY:       PROCTIME;
      RELEASE:     MACHINE3;
      ASSIGN:      timeq=TNOW:
               WC=4:
               PROCESS=PROCESS+1:
               PRIORITY=DISCRETE(.2,1,.4,2,.6,3,.8,4,1,5):
               NEXT(NSS);
WC4OB    QUEUE,       WORKC4OB;
      REQUEST,PRIORITY:    AGV(SDS),,INTX(11);
      TRANSPORT:    AGV,SEQ;
;
;
```

```
; WORKCENTER5 SUBMODEL
;
      STATION,      WORKCENTER5;
      BRANCH,       1:
                if,nq(workc1ob).gt.0.or.nq(
                workc2ob).gt.0.or.nq(
                workc3ob).gt.0.or.nq(
                workc4ob).gt.0.or.nq(
                workc5ob).gt.0,f4:
                else,sst5;
sst5    BRANCH,       2:
                always,sbk5:
                always,wc5ib;
sbk5    MOVE:         agv,staging:
                NEXT(freeagv);
f4      FREE:         AGV;
WC5IB   ASSIGN:       timeq=TNOW:
                PROCTIME=TRIA(AMIN(PARTTYPE,PROCESS),
                MODE(PARTTYPE,PROCESS),BMAX(PARTTYPE,PROCESS));
      QUEUE,        WORKC5IB;
      SEIZE:        MACHINE4;
      DELAY:        PROCTIME;
      RELEASE:      MACHINE4;
      ASSIGN:       timeq=TNOW:
                WC=5:
                PROCESS=PROCESS+1:
                PRIORITY=DISCRETE(.2,1,.4,2,.6,3,.8,4,1,5):
                NEXT(NSS);
WC5OB   QUEUE,        WORKC5OB;
      REQUEST,PRIORITY:     AGV(SDS),,INTX(15);
      TRANSPORT:    AGV,SEQ;
;
;
; WORKCENTER6 SUBMODEL
;
      STATION,      WORKCENTER6;
      BRANCH,       1:
                if,nq(workc1ob).gt.0.or.nq(
                workc2ob).gt.0.or.nq(
                workc3ob).gt.0.or.nq(
                workc4ob).gt.0.or.nq(
                workc5ob).gt.0,f5:
                else,sst6;
sst6    BRANCH,       2:
                always,sbk6:
                always,wc6ib;
sbk6    MOVE:         agv,staging:
                NEXT(freeagv);
f5      FREE:         AGV;
WC6IB   ASSIGN:       timeq=TNOW:
                PROCTIME=TRIA(AMIN(PARTTYPE,PROCESS),
```

```
                MODE(PARTTYPE,PROCESS),BMAX(PARTTYPE,PROCESS));
      QUEUE,      WORKC6IB;
      SEIZE:     UNLOAD;
      DELAY:      PROCTIME;
      RELEASE:     UNLOAD;
      TALLY:      11,INT(TIMEIN);
      TALLY:      PARTTYPE,INT(TIMEIN):Next(new);
NEW    BRANCH,      1:
                IF,(TNOW-DUEDATE).LT.0,ASS1:
                ELSE,TAL;
ASS1   ASSIGN:      DUEDATE=TNOW;
TAL    TALLY:       TYPE,INT(DUEDATE);
      TALLY:      12,INT(DUEDATE):DISPOSE;
;
NSS    BRANCH,      1:
                IF,PARTTYPE.EQ.1,PA:
                IF,PARTTYPE.EQ.2,PB:
                IF,PARTTYPE.EQ.3,PC:
                IF,PARTTYPE.EQ.4,PD:
                IF,PARTTYPE.EQ.5,PE;
PA     BRANCH,      1:
                IF,PROCESS.EQ.2,PA1:
                IF,PROCESS.EQ.3.AND.NQ(
                WORKC2IB).LT.NQ(WORKC4IB),
                PA2:
                IF,PROCESS.EQ.3.AND.NQ(
                WORKC2IB).GE.NQ(WORKC4IB),
                PA21:
                IF,PROCESS.EQ.4,PA3:
                IF,PROCESS.EQ.5.AND.NQ(
                WORKC3IB).LT.NQ(WORKC4IB),
                PA4:
                IF,PROCESS.EQ.5.AND.NQ(
                WORKC3IB).GE.NQ(WORKC4IB),
                PA41:
                IF,PROCESS.EQ.6,PA5;
PB     BRANCH,      1:
                IF,PROCESS.EQ.2,PB1:
                IF,PROCESS.EQ.3.AND.NQ(
                WORKC3IB).LT.NQ(WORKC4IB),
                PB2:
                IF,PROCESS.EQ.3.AND.NQ(
                WORKC3IB).GE.NQ(WORKC4IB),
                PB21:
                IF,PROCESS.EQ.4.AND.NQ(
                WORKC2IB).LE.NQ(WORKC5IB),
                PB3:
                IF,PROCESS.EQ.4.AND.NQ(
                WORKC2IB).GT.NQ(WORKC5IB),
                PB31:
                IF,PROCESS.EQ.5,PB4;
```

```
PC     BRANCH,        1:
                IF,PROCESS.EQ.2.AND.NQ(
                WORKC2IB).LT.NQ(WORKC5IB),PC1:
                IF,PROCESS.EQ.2.AND.NQ(
                WORKC2IB).GE.NQ(WORKC5IB),PC11:
                IF,PROCESS.EQ.3,PC2:
                IF,PROCESS.EQ.4,PC3:
                IF,PROCESS.EQ.5.AND.NQ(
                WORKC3IB).LT.NQ(WORKC2IB),PC4:
                IF,PROCESS.EQ.5.AND.NQ(
                WORKC3IB).GE.NQ(WORKC2IB),PC41:
                IF,PROCESS.EQ.6,PC5;
PD     BRANCH,        1:
                IF,PROCESS.EQ.2,PD1:
                IF,PROCESS.EQ.3,PD2:
                IF,PROCESS.EQ.4.AND.NQ(
                WORKC4IB).LT.NQ(WORKC3IB),PD3:
                IF,PROCESS.EQ.4.AND.NQ(
                WORKC4IB).GE.NQ(WORKC3IB),PD31:
                IF,PROCESS.EQ.5.AND.NQ(
                WORKC2IB).LT.NQ(WORKC5IB),PD4:
                IF,PROCESS.EQ.5.AND.NQ(
                WORKC2IB).GE.NQ(WORKC5IB),PD41:
                IF,PROCESS.EQ.6,PD5;
PE     BRANCH,        1:
                IF,PROCESS.EQ.2.AND.NQ(
                WORKC3IB).LT.NQ(WORKC4IB),PE1:
                IF,PROCESS.EQ.2.AND.NQ(
                WORKC3IB).GE.NQ(WORKC4IB),PE11:
                IF,PROCESS.EQ.3.AND.NQ(
                WORKC5IB).LT.NQ(WORKC2IB),PE2:
                IF,PROCESS.EQ.3.AND.NQ(
                WORKC5IB).GE.NQ(WORKC2IB),PE21:
                IF,PROCESS.EQ.4,PE3:
                IF,PROCESS.EQ.5,PE4;
PA1     ASSIGN:      IS=2:
                NEXT(WC1OB);
PA2     ASSIGN:      IS=1:
                NEXT(WC3OB);
PA21     ASSIGN:      IS=3:
                NEXT(WC3OB);
PA3     ASSIGN:      IS=4;
     BRANCH,        1:
                IF,WC.EQ.2,WC2OB:
                IF,WC.EQ.4,WC4OB;
PA4     ASSIGN:      IS=3:
                NEXT(WC5OB);
PA41     ASSIGN:      IS=2:
                NEXT(WC5OB);
PA5     ASSIGN:      IS=5;
     BRANCH,        1:
```

```
                IF,WC.EQ.4,WC4OB:
                IF,WC.EQ.3,WC3OB;
PB1     ASSIGN:     IS=4:
                NEXT(WC1OB);
PB2     ASSIGN:     IS=3:
                NEXT(WC5OB);
PB21    ASSIGN:     IS=2:
                NEXT(WC5OB);
PB3     ASSIGN:     IS=1;
      BRANCH,     1:
                IF,WC.EQ.4,WC4OB:
                IF,WC.EQ.3,WC3OB;
PB31    ASSIGN:     IS=4;
      BRANCH,     1:
                IF,WC.EQ.4,WC4OB:
                IF,WC.EQ.3,WC3OB;
PB4     ASSIGN:     IS=5;
      BRANCH,     1:
                IF,WC.EQ.5,WC5OB:
                IF,WC.EQ.2,WC2OB;
PC1     ASSIGN:     IS=1:
                NEXT(WC1OB);
PC11    ASSIGN:     IS=4:
                NEXT(WC1OB);
PC2     ASSIGN:     IS=2;
      BRANCH,     1:
                IF,WC.EQ.5,WC5OB:
                IF,WC.EQ.2,WC2OB;
PC3     ASSIGN:     IS=3:
                NEXT(WC3OB);
PC4     ASSIGN:     IS=2:
                NEXT(WC4OB);
PC41    ASSIGN:     IS=1:
                NEXT(WC4OB);
PC5     ASSIGN:     IS=5;
      BRANCH,     1:
                IF,WC.EQ.3,WC3OB:
                IF,WC.EQ.2,WC2OB;
PD1     ASSIGN:     IS=3:
                NEXT(WC1OB);
PD2     ASSIGN:     IS=4:
                NEXT(WC4OB);
PD3     ASSIGN:     IS=3:
                NEXT(WC5OB);
PD31    ASSIGN:     IS=2:
                NEXT(WC5OB);
PD4     ASSIGN:     IS=1;
      BRANCH,     1:
                IF,WC.EQ.4,WC4OB:
                IF,WC.EQ.3,WC3OB;
PD41    ASSIGN:     IS=4;
```

```
      BRANCH,     1:
                IF,WC.EQ.4,WC4OB:
                IF,WC.EQ.3,WC3OB;
PD5    ASSIGN:    IS=5;
      BRANCH,     1:
                IF,WC.EQ.2,WC2OB:
                IF,WC.EQ.5,WC5OB;
PE1    ASSIGN:    IS=2:
                NEXT(WC1OB);
PE11   ASSIGN:    IS=3:
                NEXT(WC1OB);
PE2    ASSIGN:    IS=4;
      BRANCH,     1:
                IF,WC.EQ.3,WC3OB:
                IF,WC.EQ.4,WC4OB;
PE21   ASSIGN:    IS=1;
      BRANCH,     1:
                IF,WC.EQ.3,WC3OB:
                IF,WC.EQ.4,WC4OB;
PE3    ASSIGN:    IS=3;
      BRANCH,     1:
                IF,WC.EQ.2,WC2OB:
                IF,WC.EQ.5,WC5OB;
PE4    ASSIGN:    IS=5:
                NEXT(WC3OB);
freeagv FREE:     agv:
                DISPOSE;
END;
```

EXPERIMENTAL FILE

```
BEGIN;

;
; This simulation will utilize the following rules:
; Input sequencing: SPT
; Part dispatching: SPT
;

PROJECT,    FMS SCHED RULE SET SIM1,HAROLD;
ATTRIBUTES: PARTTYPE:
        PROCTIME:
        PROCESS:
        WC:
        PRIORITY:
        DUEDATE:
        TYPE:
        TIMEQ:
        TIMEIN;

VARIABLES:  MODE(5,6), 16, 20,  8,  8,  8,
               20,  4, 15,  5, 11,
               40, 20,  6,  5, 18,
               16, 40,  8, 14,  5,
               20, 16, 12, 12,  9,
               16,  0,  9,  9,  0:
        AMIN(5,6),  14, 10,  4,  4,  3,
               18,  1, 10,  2,  5,
               30, 12,  2,  3, 10,
               12, 30,  4,  8,  2,
               18, 14,  8,  8,  5,
               10,  0,  3,  3,  0:
        BMAX(5,6),  17, 21,  9, 10, 10,
               21,  5, 16,  6, 13,
               42, 21,  7,  6, 20,
               18, 45,  9, 15,  6,
               22, 20, 14, 13, 10,
               18,  0, 10, 11,  0;

QUEUES:    WORKC1IB, LVF(DUEDATE):
        WORKC1OB, LVF(PROCTIME):
        WORKC2IB, LVF(PROCTIME):
        WORKC2OB, LVF(PROCTIME):
        WORKC3IB, LVF(PROCTIME):
        WORKC3OB, LVF(PROCTIME):
        WORKC4IB, LVF(PROCTIME):
        WORKC4OB, LVF(PROCTIME):
        WORKC5IB, LVF(PROCTIME):
```

```
        WORKC5OB, LVF(PROCTIME):
        WORKC6IB, LVF(PROCTIME);

RESOURCES: LOAD:
        MACHINE1:
        MACHINE2:
        MACHINE3:
        MACHINE4:
        UNLOAD;

STATIONS: WORKCENTER1,1:
        WORKCENTER2,4:
        WORKCENTER3,8:
        WORKCENTER4,12:
        WORKCENTER5,16:
        WORKCENTER6,18:
        STAGING,20;

TALLIES: FLOWTIME A,:
        FLOWTIME B,:
        FLOWTIME C,:
        FLOWTIME D,:
        FLOWTIME E,:
        TARDINESS A:
        TARDINESS B:
        TARDINESS C:
        TARDINESS D:
        TARDINESS E:
        OVERALL FLOWTIME:
        OVERALL TARDINESS;


DSTATS: NQ(WORKC1IB),WORKCENTER1IB:
       NQ(WORKC1OB),WORKCENTER1OB:
       NQ(WORKC2IB),WORKCENTER2IB:
       NQ(WORKC2OB),WORKCENTER2OB:
       NQ(WORKC3IB),WORKCENTER3IB:
       NQ(WORKC3OB),WORKCENTER3OB:
       NQ(WORKC4IB),WORKCENTER4IB:
       NQ(WORKC4OB),WORKCENTER4OB:
       NQ(WORKC5IB),WORKCENTER5IB:
       NQ(WORKC5OB),WORKCENTER5OB:
       NQ(WORKC6IB),WORKCENTER6IB:
       NR(LOAD),load util:
       NR(MACHINE1),mach1 util:
       NR(MACHINE2),mach2 util:
       NR(MACHINE3),mach3 util:
       NR(MACHINE4),mach4 util:
       NR(UNLOAD),unload util:
       ((NR(MACHINE1)+NR(MACHINE2)+NR(MACHINE3
        )+NR(MACHINE4)))/4,avg. mach util:
```

```
        MAX(NT(1)-NL(24),0)*100/3,AGV util;
;
INTERSECTIONS: 1,INTWORKCENTER1,1:
          2,,1:
          3,,1:
          4,INTWORKCENTER2,1:
          5,,1:
          6,,1:
          7,,1:
          8,INTWORKCENTER3,1:
          9,,1:
          10,,1:
          11,,1:
          12,INTWORKCENTER4,1:
          13,,1:
          14,,1:
          15,,1:
          16,INTWORKCENTER5,1:
          17,,1:
          18,INTWORKCENTER6,1:
          19,,1:
          20,INTSTAGING,1:
          21,,1;

LINKS:  1, LINK1, 1, 2, 2, 10, U:
      2, LINK2, 2, 4, 2, 10, U:
      3, LINK3, 2, 3, 3, 10, U:
      4, LINK4, 4, 5, 2, 10, U:
      5, LINK5, 3, 5, 3, 10, U:
      6, LINK6, 5, 6, 2, 10, U:
      7, LINK7, 6, 8, 2, 10, U:
      8, LINK8, 6, 7, 3, 10, U:
      9, LINK9, 8, 9, 2, 10, U:
     10, LINK10, 7, 9, 3, 10, U:
     11, LINK11, 9, 10, 2, 10, U:
     12, LINK12, 10, 12, 2, 10, U:
     13, LINK13, 10, 11, 3, 10, U:
     14, LINK14, 12, 13, 2, 10, U:
     15, LINK15, 11, 13, 3, 10, U:
     16, LINK16, 13, 14, 2, 10, U:
     17, LINK17, 14, 16, 2, 10, U:
     18, LINK18, 14, 15, 3, 10, U:
     19, LINK19, 16, 17, 2, 10, U:
     20, LINK20, 15, 17, 3, 10, U:
     21, LINK21, 17, 18, 2, 10, U:
     22, LINK22, 18, 19, 2, 10, U:
     23, LINK23, 19, 21, 2, 10, U:
     24, LINK24, 19, 20, 3, 10, U:
     25, LINK25, 20, 21, 3, 10, U:
     26, LINK26, 21, 1, 2, 10, U;
```

```
NETWORKS: 1, AGVPATH,1-26;

TRANSPORTERS: 1, AGV, 3, NETWORK(AGVPATH)-S, 55, LINK(24)-A-ZONE(1);

SEQUENCES: 1, WORKCENTER1 & WORKCENTER2 & WORKCENTER3 & WORKCENTER4 &
             WORKCENTER5 & WORKCENTER6:
           2, WORKCENTER1 & WORKCENTER2 & WORKCENTER3 & WORKCENTER4 &
             WORKCENTER5 & WORKCENTER6:
           3, WORKCENTER1 & WORKCENTER2 & WORKCENTER3 & WORKCENTER4 &
             WORKCENTER5 & WORKCENTER6:
           4, WORKCENTER1 & WORKCENTER2 & WORKCENTER3 & WORKCENTER4 &
             WORKCENTER5 & WORKCENTER6:
           5, WORKCENTER1 & WORKCENTER2 & WORKCENTER3 & WORKCENTER4 &
             WORKCENTER5 & WORKCENTER6;


REPLICATE, 6,0,30000,NO,,30000;
;
END;
```

Appendix B

Summarized Results of Simulations

Table VII: Summary of Results on Mean Tardiness, Mean Machine Utilization and Mean Throughput with unconstrained WIP

Input sequence	Work center selection	Part dispatching	AGV dispatching	Mean tardiness	Mean Machine Utilization	Mean Throughput
SPT	NINQ	SPT	NV/RW	65.6685	.89607	2144
SPT	NINQ	SPT	NV/MROQS	61.2495	.878245	2106.25
SPT	NINQ	LIFO	NV/RW	88.5568	.880825	2092
SPT	NINQ	LIFO	NV/MROQS	114.6038	.88425	2117.5
SPT	NINQ	FIFO	NV/RW	110.228	.900718	2140
SPT	NINQ	FIFO	NV/MROQS	95.98425	.900065	2143.5
SPT	WINQ	SPT	NV/RW	67.7395	.904475	2141.75
SPT	WINQ	SPT	NV/MROQS	63.9605	.897368	2143
SPT	WINQ	LIFO	NV/RW	127.558	.878383	2099.25
SPT	WINQ	LIFO	NV/MROQS	133.9828	.88992	2126
SPT	WINQ	FIFO	NV/RW	73.31375	.87573	2097.5
SPT	WINQ	FIFO	NV/MROQS	138.7365	.908328	2166.25
LPT	NINQ	SPT	NV/RW	71.1555	.88255	2107.5
LPT	NINQ	SPT	NV/MROQS	127.5458	.910448	2155.225
LPT	NINQ	LIFO	NV/RW	160.62	.89551	2135.75
LPT	NINQ	LIFO	NV/MROQS	212.083	.904565	2160.75
LPT	NINQ	FIFO	NV/RW	128.3098	.879865	2087.75
LPT	NINQ	FIFO	NV/MROQS	122.467	.89708	2128
LPT	WINQ	SPT	NV/RW	60.84225	.892743	2128
LPT	WINQ	SPT	NV/MROQS	57.15875	.891753	2130
LPT	WINQ	LIFO	NV/RW	155.3	.888053	2097.75
LPT	WINQ	LIFO	NV/MROQS	127.5175	.890725	2133.75
LPT	WINQ	FIFO	NV/RW	132.7925	.910358	2155.5
LPT	WINQ	FIFO	NV/MROQS	186.36	.910158	2173.5
FIFO	NINQ	SPT	NV/RW	56.3405	.898695	2148.75
FIFO	NINQ	SPT	NV/MROQS	67.718	.9037	2155
FIFO	NINQ	LIFO	NV/RW	94.5205	.875333	2105.25
FIFO	NINQ	LIFO	NV/MROQS	113.9985	.891975	2120.5
FIFO	NINQ	FIFO	NV/RW	115.2758	.90137	2144.25
FIFO	NINQ	FIFO	NV/MROQS	84.966	.895078	2132.75
FIFO	WINQ	SPT	NV/RW	51.88675	.897573	2128
FIFO	WINQ	SPT	NV/MROQS	50.462	.892145	2138.5
FIFO	WINQ	LIFO	NV/RW	136.7183	.881658	2122.25
FIFO	WINQ	LIFO	NV/MROQS	136.9925	.889153	2142.25
FIFO	WINQ	FIFO	NV/RW	97.181	.887193	2125.75
FIFO	WINQ	FIFO	NV/MROQS	106.3033	.887523	2125

Table VIII: Summarized Data of Throughput and Machine Utilization for Different WIP levels for Different AGV Dispatching Rules

	Throughput		Machine Utilization	
WIP Level	NV/RW	NV/MROQS	NV/RW	NV/MROQS
9	4	5	.004	.005
19	95	88	.107	.082
29	451	469	.493	.508
39	604	641	.671	.714
49	800	800	.885	.880

Table IX: Summarized Data of Throughput and Machine Utilization at Different WIP Levels for Different Input Sequencing Rules

	Throughput			Machine Utilization		
WIP Level	SPT	LPT	FIFO	SPT	LPT	FIFO
9	4	236	4	.004	.346	.004
19	95	684	52	.107	.774	.058
29	451	763	407	.493	.849	.453
39	604	780	638	.671	.839	.683
49	800	800	800	.885	.868	.880

Table X: Summarized Data of Throughput and Machine Utilization at Different WIP Levels for Different Part Dispatching Rules

	Throughput			Machine Utilization		
WIP Level	SPT	LIFO	FIFO	SPT	LIFO	FIFO
9	4	4	4	.004	.004	.004
19	95	63	43	.107	.069	.048
29	451	312	208	.493	.325	.228
39	604	800	357	.671	.829	.410
49	800	800	641	.885	.829	.732

Table XI: Summarized Data of Throughput and Machine Utilization for WIP Levels for Different Work center Selection Rules

	Throughput		Machine Utilization	
WIP Level	NINQ	WINQ	NINQ	WINQ
9	4	4	.004	.004
19	95	96	.107	.106
29	451	221	.493	.256
39	604	489	.671	.571
49	800	800	.885	.918

Table XII: Summarized Data of Throughput and Machine Utilization for Different WIP levels for Different AGV Dispatching Rules Utilizing a Different Product Mix

	Throughput		Machine Utilization	
WIP Level	NV/RW	NV/MROQS	NV/RW	NV/MROQS
9	3	4	.004	.006
19	46	46	.059	.059
29	106	132	.139	.170
39	171	164	.223	.210
49	347	349	.450	.445

Table XIII: Summarized Data of Throughput and Machine Utilization at Different WIP Levels for Different Input Sequencing Rules Utilizing a Different product Mix

	Throughput			Machine Utilization		
WIP Level	SPT	LPT	FIFO	SPT	LPT	FIFO
9	3	226	3	.004	.394	.004
19	45	520	25	.059	.719	.033
29	106	579	75	.139	.773	.099
39	171	602	212	.223	.760	.261
49	347	591	271	.450	.760	.346

Table XIV: Summarized Data of Throughput and Machine Utilization at Different WIP Levels for Different Part Dispatching Rules Utilizing a Different product Mix

	Throughput			Machine Utilization		
WIP Level	SPT	LIFO	FIFO	SPT	LIFO	FIFO
9	3	3	3	.004	.004	.004
19	46	29	37	.059	.037	.048
29	106	107	121	.139	.134	.151
39	171	107	184	.223	.145	.239
49	347	215	224	.450	.277	.287

Table XV: Summarized Data of Throughput and Machine Utilization for WIP Levels for Different Work center Selection Rules Utilizing a Different Product Mix

	Throughput		Machine Utilization	
WIP Level	NINQ	WINQ	NINQ	WINQ
9	3	4	.004	.004
19	46	42	.06	.05
29	106	78	.139	.104
39	171	133	.223	.176
49	347	344	.450	.450

Table XVI: Summarized Data of Throughput and Machine Utilization for Different WIP levels for Different AGV Dispatching Rules Utilizing Higher Processing Times

	Throughput		Machine Utilization	
WIP Level	NV/RW	NV/MROQS	NV/RW	NV/MROQS
9	4	6	.006	.006
19	21	56	.03	.07
29	131	125	.18	.17
39	200	187	.28	.25
49	274	280	.37	.39

Table XVII: Summarized Data of Throughput and Machine Utilization at Different WIP Levels for Different Input Sequencing Rules Utilizing Higher Processing Times

	Throughput			Machine Utilization		
WIP Level	SPT	LPT	FIFO	SPT	LPT	FIFO
9	4	197	4	.006	.373	.006
19	21	550	46	.031	.816	.064
29	131	660	93	.181	.919	.123
39	200	703	129	.282	.943	.181
49	274	707	352	.374	.958	.483

Table XVIII: Summarized Data of Throughput and Machine Utilization at Different WIP Levels for Different Part Dispatching Rules Utilizing Higher Processing Times

	Throughput			Machine Utilization		
WIP Level	SPT	LIFO	FIFO	SPT	LIFO	FIFO
9	4	4	4	.006	.006	.006
19	21	28	30	.03	.04	.04
29	131	96	68	.18	.14	.09
39	200	217	111	.28	.29	.16
49	274	217	168	.37	.30	.25

Table XIX: Summarized Data of Throughput and Machine Utilization for WIP Levels for Different Work center Selection Rules Utilizing Higher Processing Times

	Throughput		Machine Utilization	
WIP Level	NINQ	WINQ	NINQ	WINQ
9	4	4	.006	.006
19	21	30	.03	.04
29	131	97	.181	.142
39	200	293	.282	.413
49	274	466	.374	.403

Table XX: Summarized Data of Throughput and Machine Utilization for Different WIP levels for Different AGV Dispatching Rules Utilizing a Slower Arrival Rate of Incoming Orders

	Throughput		Machine Utilization	
WIP Level	NV/RW	NV/MROQS	NV/RW	NV/MROQS
9	5	7	.005	.005
19	364	361	.412	.407
29	364	361	.412	.407
39	364	361	.412	.407
49	364	361	.412	.407

Table XXI: Summarized Data of Throughput and Machine Utilization at Different WIP Levels for Different Input Sequencing Rules Utilizing a Slower Arrival Rate of Incoming Orders

	Throughput			Machine Utilization		
WIP Level	SPT	LPT	FIFO	SPT	LPT	FIFO
9	5	211	5	.005	.267	.004
19	364	357	367	.412	.399	.417
29	364	357	367	.412	.399	.417
39	364	357	367	.412	.399	.417
49	364	357	367	.412	.399	.417

Table XXII: Summarized Data of Throughput and Machine Utilization at Different WIP Levels for Different Part Dispatching Rules Utilizing a Slower Arrival Rate of Incoming Orders

	Throughput			Machine Utilization		
WIP Level	SPT	LIFO	FIFO	SPT	LIFO	FIFO
9	5	5	5	.005	.005	.005
19	364	364	365	.412	.403	.401
29	364	364	365	.412	.403	.401
39	364	364	365	.412	.403	.401
49	364	364	365	.412	.403	.401

Table XXIII: Summarized Data of Throughput and Machine Utilization for WIP Levels for Different Work center Selection Rules Utilizing a Slower Arrival Rate of Incoming Orders

	Throughput		Machine Utilization	
WIP Level	NINQ	WINQ	NINQ	WINQ
9	5	5	.005	.005
19	364	379	.412	.431
29	364	379	.412	.431
39	364	379	.412	.431
49	364	379	.412	.431

Table XXIV: Summarized Data of Throughput and Machine Utilization for Different WIP levels for Different AGV Dispatching Rules with Increased Routing Flexibility

	Throughput		Machine Utilization	
WIP Level	NV/RW	NV/MROQS	NV/RW	NV/MROQS
9	4	4	.004	.004
19	31	83	.036	.094
29	386	368	.427	.420
39	800	800	.850	.901
49	800	800	.850	.901

Table XXV: Summarized Data of Throughput and Machine Utilization at Different WIP Levels for Different Input Sequencing Rules with Increased Routing Flexibility

	Throughput			Machine Utilization		
WIP Level	SPT	LPT	FIFO	SPT	LPT	FIFO
9	4	148	5	.004	.250	.005
19	31	645	65	.04	.768	.07
29	386	789	489	.427	.859	.539
39	800	800	800	.850	.879	.863
49	800	800	800	.850	.879	.863

Table XXVI: Summarized Data of Throughput and Machine Utilization at Different WIP Levels for Different Part Dispatching Rules with Increased Routing Flexibility

	Throughput			Machine Utilization		
WIP Level	SPT	LIFO	FIFO	SPT	LIFO	FIFO
9	4	3	4	.004	.003	.004
19	31	67	35	.036	.073	.037
29	386	753	244	.427	.856	.280
39	800	800	759	.850	.872	.857
49	800	800	800	.850	.905	.869

Table XXVII: Summarized Data of Throughput and Machine Utilization for WIP Levels for Different Work center Selection Rules with Increased Routing Flexibility

	Throughput		Machine Utilization	
WIP Level	NINQ	WINQ	NINQ	WINQ
9	4	4	.004	.004
19	31	40	.036	.045
29	386	430	.427	.477
39	800	800	.850	.860
49	800	800	.850	.874

Appendix C

Statistical Analysis of Simulation Runs

Table XXIX: ANOVA Results to Determine whether Part Dispatching (SPT/LIFO/FIFO) had an Effect on Mean Tardiness for a System with Unconstrained WIP

COMPARISON				
Input Sequence	Work center selection	Part Dispatching	AGV Dispatching	F-Value
SPT	NINQ	SPT/LIFO/FIFO	NV/RW	1.957
SPT	NINQ	SPT/LIFO/FIFO	NV/MROQS	2.18
SPT	WINQ	SPT/LIFO/FIFO	NV/RW	1.604
SPT	WINQ	SPT/LIFO/FIFO	NV/MROQS	1.967
LPT	NINQ	SPT/LIFO/FIFO	NV/RW	4.399*
LPT	NINQ	SPT/LIFO/FIFO	NV/MROQS	.549
LPT	WINQ	SPT/LIFO/FIFO	NV/RW	5.587*
LPT	WINQ	SPT/LIFO/FIFO	NV/MROQS	5.558*
FIFO	NINQ	SPT/LIFO/FIFO	NV/RW	3.121
FIFO	NINQ	SPT/LIFO/FIFO	NV/MROQS	5.552*
FIFO	WINQ	SPT/LIFO/FIFO	NV/RW	3.851
FIFO	WINQ	SPT/LIFO/FIFO	NV/MROQS	6.579*

* Significant at the α=.05 level of significance

Table XXX: ANOVA Results to Determine whether Input Sequencing (SPT/LPT/FIFO) had an Effect on Mean Tardiness for a System with Unconstrained WIP

COMPARISON				
Input Sequence	Work center selection	Part Dispatching	AGV Dispatching	F-Value
SPT/LPT/FIFO	NINQ	SPT	NV/RW	0.170
SPT/LPT/FIFO	NINQ	SPT	NV/MROQS	1.264
SPT/LPT/FIFO	WINQ	LIFO	NV/RW	3.873
SPT/LPT/FIFO	WINQ	LIFO	NV/MROQS	0.853
SPT/LPT/FIFO	NINQ	FIFO	NV/RW	0.331
SPT/LPT/FIFO	NINQ	FIFO	NV/MROQS	1.436
SPT/LPT/FIFO	WINQ	SPT	NV/RW	0.657
SPT/LPT/FIFO	WINQ	SPT	NV/MROQS	1.132
SPT/LPT/FIFO	NINQ	LIFO	NV/RW	0.154
SPT/LPT/FIFO	NINQ	LIFO	NV/MROQS	0.025
SPT/LPT/FIFO	WINQ	FIFO	NV/RW	4.671*
SPT/LPT/FIFO	WINQ	FIFO	NV/MROQS	1.680

* Significant at the α=.05 level of significance

Table XXXI: T-Test Results to Determine whether AGV Dispatching (NV/RW and NV/MROQS) had an Effect on Mean Tardiness for a System with Unconstrained WIP

COMPARISON				
Input Sequence	Work center selection	Part Dispatching	AGV Dispatching	T-TEST-VALUE
SPT	NINQ	SPT	NV/RW/NV/MROQS	0.32
SPT	WINQ	SPT	NV/RW/NV/MROQS	-1.84
SPT	NINQ	LIFO	NV/RW/NV/MROQS	0.51
SPT	WINQ	LIFO	NV/RW/NV/MROQS	1.69
SPT	NINQ	FIFO	NV/RW/NV/MROQS	-1.13
SPT	WINQ	FIFO	NV/RW/NV/MROQS	-1.66
LPT	NINQ	SPT	NV/RW/NV/MROQS	-1.09
LPT	WINQ	SPT	NV/RW/NV/MROQS	-0.46
LPT	NINQ	LIFO	NV/RW/NV/MROQS	0.10
LPT	WINQ	LIFO	NV/RW/NV/MROQS	0.36
LPT	NINQ	FIFO	NV/RW/NV/MROQS	0.76
LPT	WINQ	FIFO	NV/RW/NV/MROQS	-1.04
FIFO	NINQ	SPT	NV/RW/NV/MROQS	-0.46
FIFO	WINQ	SPT	NV/RW/NV/MROQS	-1.12
FIFO	NINQ	LIFO	NV/RW/NV/MROQS	1.58
FIFO	WINQ	LIFO	NV/RW/NV/MROQS	0.38
FIFO	NINQ	FIFO	NV/RW/NV/MROQS	-0.003
FIFO	WINQ	FIFO	NV/RW/NV/MROQS	-0.41

* Significant at the α=.05 level of significance

Table XXXII: T-Test Results to Determine whether Work center Selection (NINQ/WINQ) had an Effect on Mean Tardiness for a System with Unconstrained WIP

COMPARISON				
Input Sequence	Work center selection	Part Dispatching	AGV Dispatching	T-TEST VALUE
SPT	NINQ/WINQ	SPT	NV/RW	-0.21
SPT	NINQ/WINQ	SPT	NV/MROQS	.38
SPT	NINQ/WINQ	LIFO	NV/RW	-.84
SPT	NINQ/WINQ	LIFO	NV/MROQS	-.45
SPT	NINQ/WINQ	FIFO	NV/RW	1.87
SPT	NINQ/WINQ	FIFO	NV/MROQS	-1.20
LPT	NINQ/WINQ	SPT	NV/RW	0.28
LPT	NINQ/WINQ	SPT	NV/MROQS	1.39
LPT	NINQ/WINQ	LIFO	NV/RW	0.12
LPT	NINQ/WINQ	LIFO	NV/MROQS	.79
LPT	NINQ/WINQ	FIFO	NV/RW	-0.76
LPT	NINQ/WINQ	FIFO	NV/MROQS	-1.28
FIFO	NINQ/WINQ	SPT	NV/RW	.08
FIFO	NINQ/WINQ	SPT	NV/MROQS	.97
FIFO	NINQ/WINQ	LIFO	NV/RW	-1.17
FIFO	NINQ/WINQ	LIFO	NV/MROQS	-.70
FIFO	NINQ/WINQ	FIFO	NV/RW	.25
FIFO	NINQ/WINQ	FIFO	NV/MROQS	-1.85

* Significant at the α=.05 level of significance

Table XXXIII: T-Test Results from Comparison of Throughput and Machine Utilization for AGV Dispatching Rules NV/RW and NV/MROQS for Different WIP Levels

	T-Test Value	
WIP Level	Throughput	Machine Utilization
9	-.555	-.118
19	.162	.440
29	-.092	-.071
39	-.018	-.210
49	0.00	0.274

* Significant at the α=.05 level of significance

Table XXXIV: ANOVA Results from Comparison of Throughput and Machine Utilization for Input Sequencing Rules SPT, LPT, FIFO for Different WIP Levels

	F Value	
WIP Level	Throughput	Machine Utilization
9	321.8*	2749.9*
19	161.8*	156.1*
29	3.7	3.9
39	.6	.8
49	0.00	0.1

* Significant at the α=.05 level of significance

Table XXXV: ANOVA Results from Comparison of Throughput and Machine Utilization for Part Dispatching Rules SPT, LIFO, FIFO for Different WIP Levels

	F Value	
WIP Level	Throughput	Machine Utilization
9	0.0	0.0
19	.9	0.8
29	1.0	1.2
39	5.9*	5.1
49	3.9	3.6

* Significant at the α=.05 level of significance

Table XXXVI: T-Test Results from Comparison of Throughput and Machine Utilization for Work center Selection Rules NINQ and WINQ for Different WIP Levels

	T-Test Value	
WIP Level	Throughput	Machine Utilization
9	0.0	0.0
19	-.02	.01
29	2.42	2.22
39	-.6	.5
49	0.0	-2.67

* Significant at the α=.05 level of significance

Table XXXVII: T-Test Results from Comparison of Throughput and Machine Utilization for AGV Dispatching Rules NV/RW and NV/MROQS for Different WIP Levels Utilizing a Different Product Mix

	T-Test Value	
WIP Level	Throughput	Machine Utilization
9	-4*	-5.48*
19	-.03	-.03
29	-.7	-.62
39	.146	.23
49	-.02	0.046

* Significant at the α=.05 level of significance

Table XXXVIII: ANOVA Results from Comparison of Throughput and Machine Utilization for Input Sequencing Rules SPT, LPT, FIFO for Different WIP Levels Utilizing a Different Product Mix

	F Value	
WIP Level	Throughput	Machine Utilization
9	1482*	19608*
19	170*	674*
29	90*	115*
39	21*	29*
49	15*	17*

* Significant at the α=.05 level of significance

Table XXXIX: ANOVA Results from Comparison of Throughput and Machine Utilization for Part Dispatching Rules SPT, LIFO, FIFO for Different WIP Levels Utilizing a Different Product Mix

	F Value	
WIP Level	Throughput	Machine Utilization
9	0.0	0.0
19	.62	0.71
29	.07	.06
39	2.54	2.76
49	1.96	2.02

* Significant at the α=.05 level of significance

Table XL: T-Test Results from Comparison of Throughput and Machine Utilization for Work center Selection Rules NINQ and WINQ for Different WIP Levels Utilizing a Different Product Mix

	T-Test Value	
WIP Level	Throughput	Machine Utilization
9	0.0	-0.02
19	.21	.219
29	.78	.758
39	1.02	1.02
49	0.05	0.028

* Significant at the α=.05 level of significance

Table XLI: T-Test Results from Comparison of Throughput and Machine Utilization for AGV Dispatching Rules NV/RW and NV/MROQS for Different WIP Levels Utilizing Higher Processing Times

	T-Test Value	
WIP Level	Throughput	Machine Utilization
9	-1.21	.21
19	-3.21*	-3.44*
29	.18	.21
39	.24	.38
49	-.05	-.12

* Significant at the α=.05 level of significance

Table XLII: ANOVA Results from Comparison of Throughput and Machine Utilization for Input Sequencing Rules SPT, LPT, FIFO for Different WIP Levels Utilizing Higher Processing Times

	F Value	
WIP Level	Throughput	Machine Utilization
9	1869*	1821*
19	720*	1431*
29	233*	227*
39	119*	110*
49	8*	9*

* Significant at the α=.05 level of significance

Table XLIII: ANOVA Results from Comparison of Throughput and Machine Utilization for Part Dispatching Rules SPT, LIFO, FIFO for Different WIP Levels Utilizing Higher Processing Times

	F Value	
WIP Level	Throughput	Machine Utilization
9	0.0	0.04
19	.8	0.7
29	4.7	5.9*
39	1.7	1.4
49	.5	.4

* Significant at the α=.05 level of significance

Table XLIV: T-Test Results from Comparison of Throughput and Machine Utilization for Work center Selection Rules NINQ and WINQ for Different WIP Levels Utilizing Higher Processing Times

	T-Test Value	
WIP Level	Throughput	Machine Utilization
9	0.0	0.03
19	-2.0	-2.2
29	1.2	1.02
39	-1.0	-1.07
49	-1.2	-0.15

* Significant at the α=.05 level of significance

Table XLV: T-Test Results from Comparison of Throughput and Machine Utilization for AGV Dispatching Rules NV/RW and NV/MROQS for Different WIP Levels Utilizing a Lower Arrival Rate of Jobs

	T-Test Value	
WIP Level	Throughput	Machine Utilization
9	-0.9	-1.36
19	.18	.36
29	.18	.36
39	.18	.36
49	.18	.36

* Significant at the α=.05 level of significance

Table XLVI: ANOVA Results from Comparison of Throughput and Machine Utilization for Input Sequencing Rules SPT, LPT, FIFO for Different WIP Levels Utilizing a Lower Arrival Rate of Jobs

	F Value	
WIP Level	Throughput	Machine Utilization
9	1480*	589*
19	.17	.29
29	.17	.29
39	.17	.29
49	.17	.29

* Significant at the α=.05 level of significance

Table XLVII: ANOVA Results from Comparison of Throughput and Machine Utilization for Part Dispatching Rules SPT, LIFO, FIFO for Different WIP Levels Utilizing a Lower Arrival Rate of Jobs

	F Value	
WIP Level	Throughput	Machine Utilization
9	0.0	0.0
19	.01	.2
29	.01	.2
39	.01	.2
49	.01	.2

* Significant at the α=.05 level of significance

Table XLVIII: T-Test Results from Comparison of Throughput and Machine Utilization for Work center Selection Rules NINQ and WINQ for Different WIP Levels Utilizing a Lower Arrival Rate of Jobs

	T-Test Value	
WIP Level	Throughput	Machine Utilization
9	0.0	0.0
19	-1.9	-1.9
29	-1.9	-1.9
39	-1.9	-1.9
49	-1.9	-1.9

* Significant at the α=.05 level of significance

Table XLIX: T-Test Results from Comparison of Throughput and Machine Utilization for AGV Dispatching Rules NV/RW and NV/MROQS for Different WIP Levels with Increased Routing Flexibility

	T-Test Value	
WIP Level	Throughput	Machine Utilization
9	-0.71	-0.65
19	-1.81	-1.80
29	.07	.02
39	-1.0	-1.70
49	-1.0	-1.70

* Significant at the α=.05 level of significance

Table L: ANOVA Results from Comparison of Throughput and Machine Utilization for Input Sequencing Rules SPT, LPT, FIFO for Different WIP Levels with Increased Routing Flexibility

	F Value	
WIP Level	Throughput	Machine Utilization
9	1.2 E8*	1.5 E8*
19	2.1 E7*	2.5 E8*
29	3.03	3.3
39	.23	.55
49	.13	.23

* Significant at the α=.05 level of significance

Table LI: ANOVA Results from Comparison of Throughput and Machine Utilization for Part Dispatching Rules SPT, LIFO, FIFO for Different WIP Levels with Increased Routing Flexibility

	F Value	
WIP Level	Throughput	Machine Utilization
9	1.8	1.2
19	7.4*	9.6*
29	4.4	4.6
39	.4	.9
49	1.1	4.1

* Significant at the α=.05 level of significance

Table LII: T-Test Results from Comparison of Throughput and Machine Utilization for Work center Selection Rules NINQ and WINQ for Different WIP Levels with Increased Routing Flexibility

	T-Test Value	
WIP Level	Throughput	Machine Utilization
9	0.0	0.0
19	-0.8	-0.7
29	-0.2	-0.2
39	0.0	-0.3
49	-0.7	-1.7

* Significant at the α=.05 level of significance