SIMULATION OF SCHEDULING RULES IN A FLEXIBLE MANUFACTURING SYSTEM

by

GURMIT KAUR AULAKH

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
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Department of Mechanical Engineering
Industrial Engineering Program
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ABSTRACT

In this thesis, an information-based scheduling rule is developed. A GPSS simulation model is developed to compare the performance of the rule with that of the some existing scheduling rules using alternate machines in a flexible manufacturing environment; the performance measure being mean flow time of the jobs processed in the system. The rule is illustrated with a numerical example and also applied to a couple of problems from the literature. Simulation results obtained show that the combination of information-based scheduling rule and the rule which is the difference of two other rules (i.e. of the most imminent due time and least processing done) is a clear winner in minimizing the mean flow time of the jobs under certain well defined conditions.

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Chapter I

INTRODUCTION

A Flexible Manufacturing System (FMS) is a production system consisting of numerically controlled machines linked by a computer controlled automated material handling system. The necessary tools are stored at the machines or transferred to them from a central store. The machines are programmed to select the tool from those stored at the machine as required. The basic objective of the flexible manufacturing system is to achieve the efficiency and utilization levels of mass production, while retaining the flexibility of manually operated job shops. The individual machines are quite versatile and capable of performing many different types of operations (Stecke and Solberg 1981). The term "flexible" is coined to these systems because of three reasons:

(i) the ability to perform a variety of operations on a workpiece;

(ii) the ability to produce a variety of parts by a simple change of software;

(iii) the ability to respond flexibility to unforeseen events, such as machine breakdown and temporary overloads, by using alternate routings.

Browne et al. (1984) and Kusiak (1985) have described in detail different types of flexibility. Various levels of flexibility enables an FMS to produce different sets of part types economically, quickly, in several different ways and and at different production levels. Due to the flexibility, the main advantages offered by a flexible manufacturing system reported in the literature are:

1. High machine utilization,
2. Reduced set up time,
3. Reduced work-in-process and production cycle time,
4. Ability to operate more hours,
5. Reduced manpower requirement,
6. High product quality,
7. Improved responsiveness to changing production requirement,
8. Possible continuation of production even in the case of machine breakdown, since the system can handle down-graded control modes,
9. Long economic life due to system flexibility,
10. Shorter delivery times.

For a detailed discussion of the advantages, the reader is referred to Edward (1983).

Despite the above given advantages, the flexibility in an FMS has provided new and unique problems in the area of design, planning, scheduling, and control of a Flexible

Manufacturing System (FMS) (Stecke 1984). This thesis concentrates on the scheduling problem in an FMS.

1.1 THE SCHEDULING PROBLEM IN FMS

Once the system has been set up during the planning stage, the FMS scheduling problem deals with the real time control of the running of an FMS. The scheduling problem in Flexible Manufacturing Systems (FMSs) arises from the complexity and uncertainty associated with flexible manufacturing environments. The scheduling problem can be described as follows: given n jobs (parts) and m machines/workcenters, determining the optimal solution to allocate the n jobs over time to the m machines/workcenters. Various common objectives have been: to minimize mean flow time, minimize makespan, minimize lateness, or to minimize the number of tardy jobs.

1.2 OBJECTIVE

The objective of this thesis is to minimize the mean flow time (or maximize throughput) of the parts processed in a Flexible Manufacturing System using alternate machines. Mean flow time is the average time a part spends in the system before reaching completion. The proposal for improving the mean flow time of parts in the system is to consider information of operations in making scheduling decisions. In this thesis, a heuristic scheduling rule is developed that minimizes the mean flow time of the parts using alternate machines in the system. The rule is based on an information-theoretic approach.

1.3 ORGANIZATION OF THE THESIS

The thesis is organised as follows:

Chapter 2 reviews the approaches developed in the literature to solve the scheduling problem of FMS. A brief introduction of the simulation tool GPSS is also given in the same chapter. The information-based scheduling rule, the model, its structure and features are explored in chapter 3. The chapter four analyzing the results for three problems shown both in tabular form and SAS Bar Graphs, evaluates the selected scheduling rules. Finally, conclusions are drawn in chapter 5.

Chapter II

LITERATURE REVIEW

The problem of scheduling and controlling the flow of work in modern manufacturing systems has received important attention in industrial engineering. This chapter provides a review of the approaches developed in the literature to solve the scheduling and sequencing problem of Flexible Manufacturing Systems (FMSs). These approaches may be classified into three categories: Analytical Approach, Artificial Intelligence Approach, and Simulation Approach.

The plan of this chapter is as follows. Section one presents the analytical approach using four different kinds of formulation, namely, the network analysis, hierarchical approach, integer pogramming approach, and alternate routing combination approach. In section two, the artificial intelligence approach is explored where two basic formulations, the rule-based and the pattern-directed approaches are presented. In the third section, the simulation approach using scheduling rules which is the concentration of this thesis is discussed. In the section that follow, the simulation approach using scheduling rules introduces the GPSS simulation programming tool. Finally, section five introduces and reviews the application of the information-theoretic approach in manufacturing.

2.1 ANALYTICAL APPROACH

Management science has attempted to use analytical approaches as a way of providing optimal solutions to the job-shop scheduling problem. Unfortunately, such approaches, while theoretically valid, are useless on a more practical level. The scheduling of flexible, dynamic environments is a member of a class of problems whose optimal solutions are too complex to be tractable (Newman 1988). However, they are powerful and can be used for initial approximate results and for providing optimal solutions for special cases of real size problems. Different analytical approaches have been proposed by different authors. They are:

- Network Analysis
- Hierarchical Approach
- Integer Programming Approach
- Alternate Routing Combination Approach

2.1.1 Network Analysis

Network formulations were the first considered in the scheduling modeling. In particular the popularity won by PERT and CPM techniques during the 1960s has made them the primary ones for some time. Network methods can be applied for scheduling in advance but are not useful for dynamic scheduling due to the constantly changing precedence network.

In the network formulation, a Flexible Manufacturing System (FMS) can be viewed as a network in which the multiple-tool-carrying machines are represented by nodes, and arcs between nodes represent routes for performing operations on the parts. Since there are queues of parts building up in front of nodes, the network is more precisely termed as the network of queues (Sarin and Dar-El 1984).

A mathematical programming model based on the network flow analysis is given by Kimemia and Gershwin (1979). They seek to determine the flow of different parts on arcs so as to maximize the production rate of parts which flow through the machines in a predetermined part mix. The approach considers aggregate flow of parts between nodes and not the individual movements of parts through the machines. The pattern used to schedule parts to machines is first come first served. The variables and parameters which they include are:

S_n = Strategies to produce part type n

t_{nmk} = Operation time for the kth operation for part type n on machine m

α_n = Fraction of total production for part type n

X_{nmk} = Flow rate of part type n to machine m for operation k

Y_{nj} = Flow rate of part type n on arc j

$$I(X,Y) = \sum_m q(X) + \sum_{t_j} \sum_n t_j Y_{n_j}$$

= Average number of parts in the system

where:

$q_m(X)$ = Average queue length at machine m

t_j = time to move along arc j

Mathematical formulation

Objective function

$$\text{Maximize } \sum_n X_{n11} \tag{1}$$

Constraints

Production ratio constraint

$$\frac{\sum_m X_{nm1}}{\sum_{nm} X_{nm1}} = \alpha_n \qquad n = 1,2,\text{-------},N \tag{2}$$

Input = output at each node

$$\sum_{n} Y_{n_j} = \sum_{j'} Y_{n_{j'}} \qquad j = 1,2,\text{-------},J \qquad (3)$$

Machine capacity constraint

$$\sum_{nk} t_{nmk} X_{nmk} \le 1 \qquad m = 1,2,\text{-------},M \qquad (4)$$

Work-in-process constraint

$$I(X,Y) \le C \qquad (5)$$

Arc capacity constraint

$$\sum_{n} Y_{n_j} \le d_j \qquad j = 1,2,\text{-------},J \qquad (6)$$

Nonnegativity constraints

$$X_{nmk}, \quad Y_{nj} \ge 0 \quad \text{for every } n,m,k, \text{ and } j \qquad (7)$$

The problem is a nonlinear problem which can be solved using an augmented Lagrangian method in combination with Dantzing-Wolfe decomposition and gives optimal plans for routing parts to maximize production output (Sarin and Dar-El 1984).

Nof et al. (1980) proposed a network approach to scheduling automatic manufacturing systems. They present an Evaluation-Net (E-Net) approach, a network knowledge represention. Of particular interest in E-Nets are the "resolution nodes," which define network positions at which decisions are required. Their paper provides a general conceptual discussion of the FMS planning and scheduling problem and suggests the use of modified Petri-Nets (E-Nets) for decision making.

Finke and Kusiak (1985) formulated the scheduling problem for flexible manufacturing modules and cells with sequence-dependent changeover costs as a two commodity network flow problem and solved by a branch and bound algorithm. Moreover, Kusiak (1983) has also reported some formulations of the FMS loading problem with algorithms to solve them.

2.1.2 Hierarchical Approach

Most manufacturing systems are large and complex. It is natural, therefore, to divide the control into a hierarchy consisting of a number of different levels. A multilevel approach for real-time control of FMS is proposed by Hildebrandt and Suri (1980) for application to large-scale systems. The problem is to determine how to schedule a given set of parts at failure-prone machines to minimize total completion time.

The problem is divided into three stages of decision making. At stage one , the problem is to determine the aggregate flow of parts through machines during the machine-failure conditions. The machines and pallets are considered as critical resources. The following notation is used for the formulation of stage one problem.

I	Set of system failure states
N	Set of different parts
R_{ni}	Set of routes parts can take through the system during the system state i, $n \in N$, $i \in I$
N_n	Total number of parts n to be produced
P_i	Fraction of total time the system spends on state i
T	Completion time for all parts
f_{nri}	Average number of pallets for route r of part n during state i
t_{nrm}	Average time of part n , using route r, on machine m
F	Maximum number of pallets in the system.
F_n	Maximum number of pallets available for part n.

The objective function and constraints based on above variables are following

$$\text{Minimize} \quad T \tag{8}$$

s.t.

Processing time requirement

$$\frac{N_n}{\sum_{i \in I} P_i \sum_{r \in R_{ni}} [f_{nri} / \sum_m t_{nrm}(f,t)]} \le T \qquad (9)$$

Pallet availability for each part type

$$\sum_r f_{nri} \le F_n \quad \text{for every } n \text{ and } i \qquad (10)$$

Pallet availability in the system

$$\sum_n \sum_r f_{nri} \le F \quad \text{for every } i \qquad (11)$$

Nonnegativity constraints

$$f_{nri}, \; T \ge 0 \quad \text{for every } n, r, \text{ and } i \qquad (12)$$

The procedure for determining nonlinear function $t_{nrm}(f,t)$ using mean value analysis is given by Hildebrandt (1980).

The stage two problem using a dynamic programming procedure determines when the allocated work during each failure period is to be performed. The stage three problem resolving short-time conflicts for resources to minimize the average delay of tasks is very detailed and difficult to formulate. It is, therfore, handled in real-time as the system evolves by using interactive dispatching rules.

The study by Kimemia and Gershwin (1983) determines the scheduled times for part dispatch based on current process flow rates. The method for flow rate calculation and dispatching policies is based on optimal control policies which are feasible for only small problems. (The example solved in their paper is only a 2-product, 2-machine problem). By using an estimate of the optimal policy function, they increase the feasible size of the problem which can be handled.

2.1.3 Integer Programming

Integer programming also called mathematical programming is a technique for optimizing a function subject to constraints upon the independent variables. In scheduling we wish to optimize a performance measure subject to technological constraints on the allowable processing order. Some problems are formulated into integer programming and solved by branch and bound with the bounds based upon general integer programming theory.

Hitz (1979) developed a mathematical programming formulation for scheduling in flexible manufacturing system (FMS). His periodic release strategy was explored in Erschler et al. (1984). Stecke (1983) presented a 0-1 nonlinear mixed integer programming (MIP) formulation to address the grouping and loading problems in FMS . To solve these problems she developed several linearization methods.

An integer programming formulation for the real time scheduling of parts in FMS is proposed by Chang and Sullivan (1984).

Notation

The following notation for indices, parameters, and decision variables is introduced in their study for the mathematical formulation.

Subscripts

Operation indices	k, k_1, and k_2
Part indices	n, n_1, and n_2
Machine indices	m, m_1, and m_2

Parameters

t_{nmk} = Processing time of operation k of part n on machine m

$K(n)$ = Last operation of part n

$d_{m_1 m_2}$ = Transit time from machine m_1 to machine m_2

Q = A large positve number

S_{nmk} = Start time of operation k of part n on machine m

T_{nmk} = Finish time of operation k of part n on machine m

Decision variables

R_{nmk} = 1 If operation k of part n requires machine m

0 , Otherwise

$X_{nm_1m_2k}$ = 1 If operation k of part n is assigned to m_1 , and operation k+1 is assigned to m_2

0 , Otherwise

$Y_{n_1k_1mn_2k_2}$ = 1 If operation k_1 of part n_1 precedes k_2 of n_2 on machine m

0, Otherwise

Mathematical formulation

The problem is to determine X's, S's, and Y's to:

$$\text{Minimize } \sum_m \sum_n T_{nmk_n} \qquad (13)$$

s.t.

$$\sum_{m_1} X_{nm_1m_2k} - \sum_{m_1} X_{nm_2m_1k+1} = 0$$

for all m, n, and k except for k= K(n) (14)

$$\sum_m R_{nmk} S_{nmk} \geq \sum_{m_1} R_{nm_1k} \left(S_{nm_1k} + t_{nm_1k} + \sum_{m_2} d_{m_1m_2} X_{nm_1m_2k} \right)$$

for all n and k (15)

$$S_{n_2 m k_2} + Q\,(\,1 - Y_{n_1 k_1 m n_2 k_2}\,) \geq T_{nmk}$$

$$\text{for all } m,\ n_1,\ n_2,\ k_1, \text{ and } k_2 \qquad (16)$$

Equation (13) corresponds to the objective of minimizing the total cycle time of all parts. Constraint (14) ensures that operation k+1 must be assigned to machine m_2 and the constraint represented by (15) shows that the sum of starting times of each operation of each part on all machines is at least equal to the sum of start times, duration times of that operation on machine m_1, and transport time from machine m_1 to m_2. Finally, constraint (16) specifies that no more than one operation is performed by a machine at a given time. To solve the problem they proposed a two-phase algorithm.

2.1.4 Alternate Routing Combination (ARC) Approach

In scheduling of FMS, most of the researchers have considered only the flexibility that pertains to performing an operation on alternate machines . Actually, there are three other levels of flexibility, namely, part mix flexibility,operation set flexibility, and operation sequencing flexibility (Sarin and Dar-El 1984). A generalized concept of flexibility in the context of FMS is described in Sarin and Dar-El (1984).

Considering these four levels of flexibility, Sarin and Dar-El (1984) developed an approach for FMS scheduling in which each of the alternate ways of performing operations on part lead to an alternate routing combination (ARC). They proposed a heuristic algorithm to solve it.

The first step of the approach is to determine optimal ARCs to perform operations on a set of parts among the parts dedicated for FMS scheduling. The second step is to formulate the real time scheduling in FMS using these optimal ARCs in order to maximize machine utilization. The notation used in their formulation is following:

Variables

$X_{jakmm''t}$ = 1 , If the kth operation of the ath ARC of job j starts at time t on machine m" after coming from machine m.

= 0 , Otherwise.

Z_{ja} = 1 , If the ARC a of job j is selected for processing.

= 0 , Otherwise.

Parameters

T = Target finish time of jobs.

n_j = Number of operations required for job j.

A_j = Number of ARCs corresponding to job j.

$g_{mm''}$ = Transport time from machine m to m".

P_{jak} = Processing time of operation k of job j for ARC a.

Q = A large positive number.

N = A set of parts available at the start of the planning period.

The general formulation of the problem is stated as follows.

$$\text{Minimize } NT - \sum_{j} \sum_{a \in A_j} \sum_{t} t \, X_{jan_j mm''t} \, Z_{ja} \qquad (17)$$

subject to:

$$\sum_{a \in A_j} Z_{ja} = 1 \quad , \; j = 1,2,\text{------},N \qquad (18)$$

$$\begin{aligned} \sum_{a \in A_j} \sum_{t} t.X_{jak+1mm''t} \, Z_{ja} \geq{} & \sum_{a \in A_j} \sum_{t} t.X_{jakmm''t} \, Z_{ja} + \sum_{a \in A_j} Z_{ja} \, P_{jak} \\ & + \sum_{a \in A_j} \sum_{t} g_{mm''} \, X_{jak+1mm''t} \, Z_{ja} \end{aligned}$$

$$j = 1,2,\text{------},N \; , \qquad k = 1,2,\text{------},n \qquad (19)$$

$$\sum_{j} \sum_{a \in A_j} \sum_{k} X_{jakmm''t} \, Z_{ja} \leq 1$$

$$m'' = 1,2,\text{------},m \; , \; t = 0,\text{------},T \qquad (20)$$

$$\sum_{a\in A_j} t\, X_{jakmm''t}\, Z_{ja} + \left(1-\sum_{a\in A_j} X_{jakmm''t}\, Z_{ja}\right)Q \geq$$

$$\sum_{j'\neq j}\ \sum_{a\in A_j}\ \sum_{k}\ \sum_{l<t} (1 + P_{j'ak'mm''})X_{jak'mm''l}\, Z_{ja}$$

$$m'' = 1,2,\text{-------},m \ , \ k = 1,2,\text{-------},n_j$$

$$t = 0,1,\text{-------},T \ , \ j = 1,2,\text{-------},N \qquad (21)$$

The objective function represented by (17) minimizes the total machine idle time (or maximizes machine utilization). Constraint (18) ensures that only one ARC for a job j would be selected. The beginning of a next operation after the completion of the previous operation of a job including travel time between machines is represented by constraint (19). Constraints (20) and (21) represent the assignment of at most one operation to a machine at a given time and machine availability respectively.

In addition to the analytical approaches discussed so far, Kusiak (1986) presented a heuristic scheduling algorithm for a flexible manufacturing system where the system is considered as a two part system: 1) flexible machining system and 2) assembly system. Considering the FMS scheduling problem as a multicriteria problem (Kusiak, 1985) involving scheduling of parts, pallets and fixtures, tools, and material handling system, he decomposed the problem into two subproblems. The level one problem scheduling jobs is solved by a heuristic algorithm and level two problem solved by the Johnson's algorithm, schedules the assembled products while minimizing the product assembly and product machining makespan.

2.2 ARTIFICIAL INTELLIGENCE APPROACH

Artficial Intelligence (AI) is a branch of computer science which tries to get computers to make decisions like human beings. Expert Systems, one aspect of AI , have been successively developed in a variety of areas such as medical diagnosis, chemical compound identification, generative process planning, fault diagnosis etc.

The ability of expert systems to assimilate large chunks of information, suitably reformulate problem conditions, effective and efficient solution finding methodology and the pseudoability to reason makes them ideal and potential candidates to solve some of the problems in the scheduling area.

The idea of using expert systems in scheduling is to provide a computerized scheduler that has the knowledge and understanding of qualitative measures which the human scheduler possesses. An ideal expert system (knowledge-based system) consists of three components: a database, a knowledge base, and an inference engine.

The Database stores declarative knowledge about the goals, the current situation of the world, and the semi-finished goal. The Knowledge Base is the information portion of an expert system. It contains both facts and rules that can be used in arriving at a solution. Finally, the Inference Engine (sometimes called the Inference Mechanism) is the part of an expert system that selects and executes rules.

The major approaches to the design of expert scheduling systems are:

- the rule-driven approach and
- the pattern-directed approach

2.2.1 Rule-Driven Approach

The rule-driven approach is made up a collection of IF-THEN heuristic rules which contain facts or assertions about the problem. The Intelligent Scheduling and Information System (ISIS) (Fox et al. 1982) represents the first large scale scheduling system for a job-shop environment. ISIS is described later by Fox and Smith (1984) as a knowledge-based decision support system for factory scheduling.

A unique feature of the ISIS system is to consider a variety of constraints simultaneously which ensures that an operation is not begun until all required resources are available. In addition, the system is also able to select which machines are to be used to perform a given operation. The embedded inference engine uses a heuristic search procedure for generating alternate schedules. The search procedure described as a Beam Search procedure is discussed in Ow and Morton (1985).

Kusiak (1987b) proposed two new artficial intelligence based approaches, namely, the Goal-based Approach and the Model-based Approach, to designing expert scheduling systems in a flexible manufacturing system (FMS). Given the goal schedule, the objective of the Goal-based approach is to schedule resources such as parts, tools, machines, fixtures and pallets to minimize the deviation between the goal schedule and the current schedule subject to some resources availability and precedence constraints.

Application of an expert system for the generation of the solution for a scheduling problem is shown in Figure 1 (Kusiak 1988).

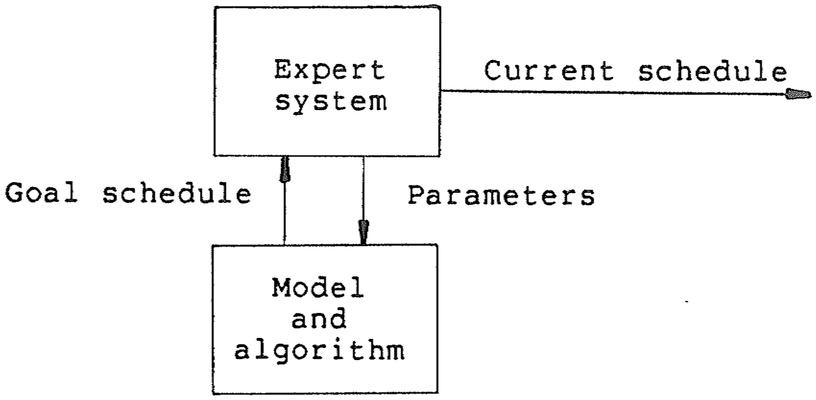


Figure 1: Application of an expert system for FMS scheduling

The goal schedule generated by the scheduling algorithm is evaluated by the expert system to generate the current production schedule. As a result of this evaluation the expert system provides the model solved by the algorithm with modified constraints or new set of parameters.

The Model-based approach for rule-based system is based on the single-model (Figure 2) and multi-model (Figure 3) tandem architecture proposed by Kusiak (1987a). Rules use input data to establish, correct the model by generating a new set of data, and select a new model in the case of the multi-model tandem architecture.

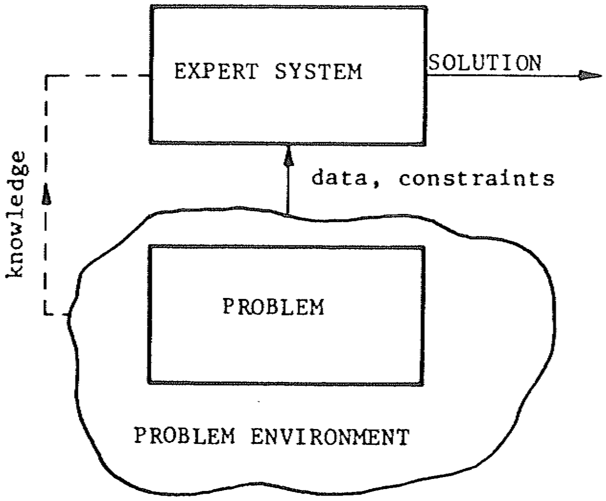


Figure 2: A stand-alone expert system (Kusiak 1987a)

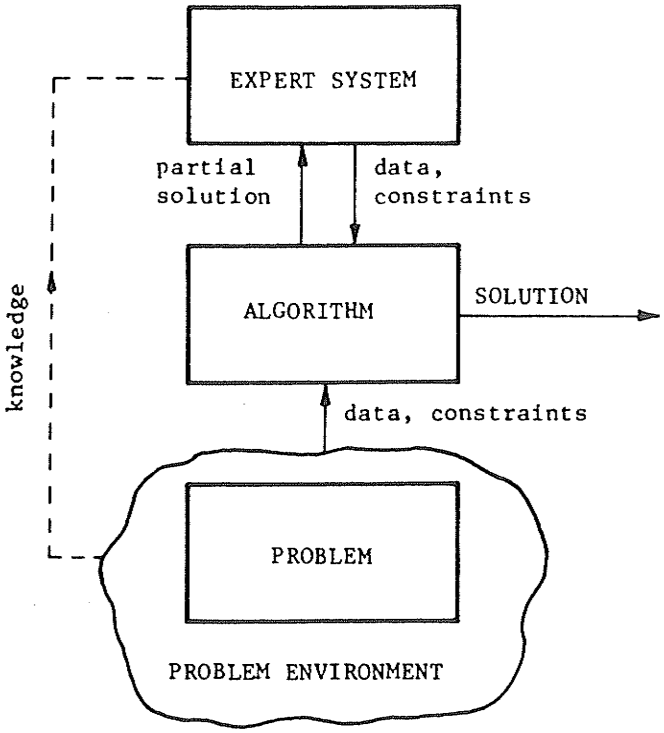


Figure 3: A tandem-mode expert system (Kusiak 1987a)

The tandem architecture handles artificial intelligence as well as optimization approach whereas an ordinary expert system called a stand-alone expert system (Kusiak 1987a) handles only artficial intelligence techniques. A unique feature of the tandem architecture (multi-model) is that the system selects the most appropriate model and then the expert system generates the required data. The expert system evaluates the solution generated by the algorithm. In case of no good solution it changes the model and the whole process is repeated.

2.2.2 Pattern-directed Approach

Shaw (1986) developed a pattern-directed approach to FMS scheduling in order to handle the dynamically changing environment and interactions between manufacturing processes. Within the pattern-directed scheduling framework, the manufacturing process corresponding to each job is modeled by state-changing transformations, represented by operators. Since operators change one state to another, they can be considered as functions whose domain (input) and range (output) are the set of states. Readers interested in more information of pattern-directed are referred to Hayes-Roth and Waterman (1978).

The approach is designed to fulfill the objective of minimizing the total completion time (makespan) of the jobs. A goal directed, nonlinear planning scheme developed in artificial intelligence is applied to generate a manufacturing plan for each part. The two most important steps of the scheme are: plan generation and plan-revision.

In the plan generation step, the inference engine calls upon a backward chaining procedure to search for the best planning steps in constructing the manufacturing plan for each part. In searching for applicable operators, a search procedure similar to the A* algorithm (Hart et al. 1968) (Pearl 1983) calls for an evaluation function $f(n) = g(n) + h(n)$.

Where:

$g(n)$ = Cumulative processing time.

$h(n)$ = The sum of shortest processing times for the remaining operations.

The objective of the algorithm is to minimize the function $f(n)$ to obtain an optimal plan.

After constructing a plan for each job, the next step is to identify conflicting interactions between jobs and to form precedence constraints to avoid these scheduling conflicts. The basic principle for establishing constraints is not to impose any constraint unless it is absolutely necessary, so that the makespan is minimized. The next step is to put the corresponding operator on a list called Alternate-list (Shaw 1986).

Finally, the plan revision procedure is used to improve the makespan as much as possible. The plan-revision procedure is described as follows:

Step 1. Select the first operator on the Alternate-list and identify the corresponding resource.

Step 2. Identify if consecutive operators in a subschedule share the same resource and call that section a critical section.

Step 3. Check if any alternate idle resource can reduce the waiting time. If not, exit with failure. Otherwise, go to step 4.

Step 4. Identify the initial and the goal conditions of the critical section found in step 2.

Step 5. Transform the initial conditions to the goal conditions using a forward chaining procedure.

Step 6. Replace the critical section of subschedule with the new plan generated from step 5.

Shaw (1988) also presented an integration approach to the FMS scheduling problem. This approach takes advantage of pattern-directed technique and heuristic search technique. The heuristic search procedure allows incorporation of heuristic knowledge to expedite the scheduling process and transforms the scheduling process into a graph search procedure guided by a heuristic function $f(n) = g(n) + h(n)$ explained earlier. He also proposed that a scheduling problem should be decomposed into subproblems to overcome the complexity of the searching procedure. The heuristic search procedure called an Operator-Search procedure (Shaw 1988) is applied to each subproblem to generate a schedule. Then the nonlinear planning algorithm, as explained earlier, is applied to establish constraints and the plan-revision technique to improve the makespan as much as possible.

2.3 SIMULATION APPROACH

Simulation can be defined as a procedure in which experiments are performed on a model of a system in order to determine how the system would respond to changes either in its structure or in its environment. Simulation modelling is the technique of building a computer model of a system so that its behavior may be studied without the need for building, disrupting the operation of, or destroying the real system.

Simulation is widely used in industry to determine the effectiveness of proposed scheduling strategies. Discrete simulation methods typically employ dispatch rule logic. Simulation enables the user to determine in advance which rules should be used in order to achieve desired changes in operating conditions (Melnyk et al. 1985). The material presented in the next subsection gives an idea of scheduling rules and how they are evaluated by simulation results.

2.3.1 Using Scheduling Rules

This is the most practical approach to scheduling parts to machines because of the simplicity of its implementation. In the scheduling literature, terms such as scheduling rule, dispatching rule, priority rule, heuristic are often used synonymously.

Many of the optimal and heuristic algorithms are discussed in Baker (1974) and French (1982). Panwalker and Iskander (1977) in their survey of scheduling rules present a summary of 113 such rules and cross-index them with 36 references. The study environment, the performance criteria, and the rules used in each of the references are stated. This survey might be useful for the reader who is interested in knowing more about the rules used and the environment in which they have been used. However, some well-known rules tested in the literature are discussed in the paragraphs that follow next paragraph.

Scheduling rules play a very important role in selecting the part type to be machined. When a priority scheduling rule is applied at a machine, all of the parts that are waiting to be processed at that machine are ranked according to a priority index assigned by the scheduling rule. Thus, the part having the highest scheduling priority is assigned to the machine when it becomes available to process another part. A typical objective in applying scheduling rules is to minimize the mean flow times, minimize makespan, minimize lateness or to minimize the number of tardy jobs (Co et al. 1988).

The objective of this thesis is to minimize the mean flow time of the parts processed in the flexible manufacturing system (FMS). Since the scheduling problem in FMS is like that of a dynamic job shop (Sarin, Dar-El, 1984), some of these rules have been applied to FMSs. They include, first-come first-served (FCFS), shortest processing time (SPT), longest processing time (LPT), fewest operations remaining (FOPR), most operations remaining (MOPR), shortest remaining processing time (SRPT), longest remaining processing time (LRPT), least total work content (TPT), and due date rules, such as the most imminent due time (MDT), least slack (LS), and least slack per operation. Most scheduling rules have been evaluated by computer simulation results under certain assumptions of running the simulation model.

The first-come first-served rule is considered to be the most equitable procedure, since it gives the highest priority to the part which has been in the system the longest. In most cases this rule has performed worst. But, according to William (1972), this rule results in a small manufacturing cycle time variance, since all parts wait approximately the same length of time to be processed at individual machines.

The shortest processing time (SPT) rule assigns priority on the basis of operation duration. The part requiring the least machine time receives the highest scheduling priority. The rule has been tested extensively in job shop scheduling and flexible manufacturing systems and has been shown to be effective in most cases. This rule results in a short average manufacturing cycle time, a low level of work-in-process, and high machine utilization. A disadvantage of this rule is that parts with a large operation time can be delayed for very long times waiting for the machine. This happens if parts with shorter operation times keep arriving at the machine before the bigger parts can capture it.

The rule opposite to SPT is the longest processing time (LPT). This rule, selecting the job with the largest operation time, of course has never been shown to be the best, but it proves to perform as well as the other rules in some cases. O'Gorman et al. (1986) have proved it.

The fewest operations remaining (FOPR) and the most operations remaining (MOPR) rules assign highest priority index to the part that has fewest and most operations remaining respectively. There are rare cases where they are tested in modern manufacturing systems but do not perform well. A good example is by Stecke and Solberg (1981).

The shortest remaining processing time (SRPT) rule derived from the SPT concept is based upon the fact that perhaps one should concentrate on finishing some jobs first in the hope that the later jobs may be speeded through a less cluttered system. It selects the part with the least processing time for all operations not yet performed. The longest remaining processing time (LRPT) stems from the contrary notion that it may be best not to get too far behind on a particular job, assigns opposite priority to the part to be processed next.

According to the least total work content (TPT) rule, first scheduling priority is given to the part with the least total processing time for all operations. This rule has not been tested very often. However, it has been tested indirectly in Stecke and Solberg (1981) and directly in Co et al. (1988).

Regarding due date, the most imminent due time (MDT) rule is established on the basis of the total work content (TPT) and computed by the following relationship

$$MDT = K*TPT + \text{Arrival time in the system}$$

Where, K is a safety factor to account for congestion in the system.

The slack rule, abbreviated LS gives first priority to the part which has the least slack time, where slack is the difference of the most imminent due time and the amount of manufacturing time to complete the part. Another rule derived from two other rules, the slack and remaining number of operations, is the slack per operation. According to this discipline, whichever waiting part has the least slack per operation is the part which gets the machine next.

Stecke (1978) investigated a number of scheduling rules using the simulation model developed by Mayer and Talavage (1976). She compared several rules that have been used in studies of the conventional job shop including SPT, LPT, and others that are related to unique features of the particular FMS on which her study was based. Her work did indicate that rules based on SPT favorably affect the performance of an FMS, just as they do in conventional job shops.

Next, Stecke and Solberg (1981) applied sixteen priority rules for scheduling a real flexible manufacturing system. Their simulation results indicated that a priority rule which is based on scheduling a next part with the smallest ratio obtained by dividing the shortest processing time for the operation by the total processing time (SPT/TPT) for the part produced results superior to those of the other priority rules, such as

SPT, LPT, FOPR, MOPR, SRPT, LRPT, and other related priority rules.

Carrie and Petsopoulos (1985) reported the results of simulation experiments to assess the dependence of the system's performance on the sequence in which jobs were launched and pointed out that none made any noticeable difference. They concluded that this was due to two factors.

Fistly, the operation sequences require parts to return to the load/unload area and the machines several times during processing, so that very soon after launching parts the initial priorities have little influence on the progress of parts.

Second reason was due to limited fixture availability. Since loading of subsequent parts depends on fixtures being released by previous parts of the same type, rather than by some externally determined priority.

Acree and Smith (1985) investigated effects and interactions of three types of scheduling rules on FMS performance. The rules included part scheduling, tool scheduling, and cart scheduling. The part scheduling rules on the machines include first-come first-served (FCFS), shortest processing time (SPT), longest processing time (LPT), and the first fit decreasing (FFD). The last rule FFD has been selected from the computer science literature. A simulation model for the FMS was developed and written in SLAM II to test scheduling rules to determine which gave the best results for a given performance criteria. The statistical Mann-Whitney test was used to test the simulation results and concluded that due to the availability of local storage at the machines the system performance measure (machine utilization) was insensitive to the part scheduling rules.

O'Gorman et al. (1986) experimented with four scheduling rules for a three machine flexible manufacturing system using the SLAM II simulation language. The rules which are tested include Johnson's algorithm, shortest processing time (SPT), longest processing time (LPT), and first-come first-served (FCFS). Johnson's algorithm determining the processing sequence of jobs in order to minimize the total throughput time gives an optimal solution by following a simple set of rules. From the simulation results, they concluded that all three rules, such as SPT, LPT, and FCFS performed as well as Johnson's algorithm.

Denzler and Boe (1987) divided part scheduling rules into two categories:

- Order file oriented loading rules
- System status oriented loading rules

An order file oriented loading rule considers only characteristics of parts in the order file. The rules selected for their purpose include shortest total processing time (TPT), smallest proportion of part requirement (SPJL), and Stecke and Solberg's (1981) best rule (SPT/TPT).

Alternatively, a system status oriented rule considers the status of the machines in the FMS and orders parts into an FMS so that high utilization of machines or the pallet fixtures can be achieved. The system status based rules tested in their investigation are: reload each pallet with a like product (NEP), load the first empty machine (FEM), and load machine with highest machine utilization first (HPEM).

The results obtained from their deterministic simulation model indicated that the SJPL and the NEP rules performed significantly better than the other part scheduling rules (or the SJPL and the NEP rules performed equally well).

Recently, Co et al. (1988) investigated the sensitivity of five scheduling rules, namely: first-come first-served (FCFS), shortest processing time (SPT), least processing time remaining (LPR), least total processing time (TPT), and next shortest queue length (NXQL) in situations of short-queue length flexible manufacturing systems. The simulation model developed to evaluate the impact of these rules has been written in SIMAN.

To test and compare performance of the rules, the simulation results are analyzed by using statistical tests: Analysis of Variance (ANOVA) and Scheffe's multiple comparison method. The analysis done by ANOVA test indicated that there is no significant difference in the five scheduling rules with respect to mean flow time. The Scheffe's test to determine the difference between mean flow times for different rules showed the SPT rule to be the best rule when the number of parts in the system is less than or equal the number of workstations/machines and when the the number of parts is greater than the number of workstation/machines, the NXQL rule's performance was much better than the other rules.

Next, Choi et al. (1988) evaluated seven part scheduling rules in a flexible manufacturing system using a physical simulator. Their computational results showed the SPT rule to be the best performer in terms of the total throughput time (makespan).

Simulation models written in different languages as described earlier in this section have been used to study scheduling and dispatching policies. They also have been used to study the performance of alternate operations (Gere 1966, Wilhelm and Shin 1985), but very little work has been done to evaluate scheduling rules using alternate operations in FMSs.

This thesis is also related to prior studies (Gere 1966,Wilhelm and Shin 1985), but the scheduling rule presented in chapter 3 following the next two sections and its performance in comparison to other rules using alternate machines in an FMS tested experimentally by GPSS modeling makes a big difference.

2.4 SIMULATION PROGRAMMING TOOL

The block-oriented GPSS/General Purpose Simulation System/language is the most widely used discrete-change simulation language. It is a very high level language which has most of its organizational structure and logic built in.

Writing a GPSS program is more or less equivalent to constructing a GPSS model or block diagram. A block diagram, a collection of characteristically shaped figures (blocks) can be visualized as a system flow diagram, since it describes the activities and indicates how they are interconnected. Moving through the system are entities that depend upon the nature of the system and each block can be thought as a point at which a subroutine can be called. The temporary entities that move through the system are represented by transactions. Whenever a transaction enters a block, it causes that block to execute its particular block-type subroutine and the transaction then (in particular) tries to move into another block.

In GPSS, a single instruction by the programmer causes the computer to execute a large number of machine-language instructions. In other words, one GPSS card usually causes the computer to execute one or more subroutines. Therefore, GPSS programs are usually far more compact than equivalent programs in other languages, such as FORTRAN.

The fact that most of the sequencing, cross-checking, statistical updating, and automatic output format specifications are built into GPSS rather than being specified by the programmer makes it simple to use and minimizes the opportunities for programming errors. Selected output may also be requested and displayed in the form of bar graphs or histograms. GPSS also rids the language of superfluous instructions which tend to obscure the relationship between the coded program and the modeled system. Thus GPSS is a very graphic language in that it tends to look like the model it represents.

2.5 INFORMATION-THEORETIC APPROACH

Information theory is a branch of probability theory with extensive potential applications to communication systems. Like several other branches of mathematics, information theory has a physical origin. It was initiated by communication scientists who were studying the statistical structure of electrical communication equipment.

In general, when a model is statistically defined, while there is no concrete assurance of its detailed performance, it is possible to describe its "over-all" or "average performance" in the light of its statistical description. In other words, a search for an amount of information is virtually a search for a statistical parameter associated with a probability scheme.

From a mathematical point of view, let

$x_1, x_2, \text{-------}, x_n$ be a finite number of events and

$P(x_1), P(x_2), \text{-------}, P(x_n)$ be their corresponding

probabilities. Assuming that the events occur randomly and successive occurences are statistically independent, the amount of information associated with the ocurrence of event x_k is defined as

$$I_k = - \log P(x_k) \quad \text{units of information}$$

where:

I_k is called the amount of self-information of event x_k.

The average information per event is defined as

$$I = - \sum_{k=1}^{n} P(x_k).\log(P(x_k))$$

The average information I is also referred to as the entropy and usually denoted by the letter H.

As Edwards (1964) has pointed out, the nomenclature of information theory has not been standardized. Different authors used different terms for it. Shannon (1948) who perhaps first originated information theory called it entropy. In certain applications of psychology, Garner (1962) prefers the term 'uncertainty'.

Moscato (1976) applied information theory in determining the degree of part commonality in a product line and called it commonality. He pointed out that parts with high commonality indicate the most broadly used parts in the product line and parts with low commonality can be considered as special purpose parts and can be replaced or eliminated by existing parts with a higher commonality.

In other attempts, the information-theoretic approach has been applied in measuring various types of flexibility related to manufacturing. Yao (1986) has used the average information (entropy) to flexibility in measuring routing flexibility for a part where the total number of possible routings available for the part are considered as number of options.

Kumar (1986) proposed information-theoretic measure of workstation loading flexibility where the relationship between flexibility and average information (entropy) is discussed. Flexibility of a transition probability matrix of markovian system is defined which is used to calculate the loading flexibility of a stochastic flexible manufacturing system. In the same paper, he introduced another measure of information theory to choose the next operation to be performed on the part through the use of least reduction of entropy (Yao,1986)

Next, Kumars (1987a) and Kumar (1987b) pointed out that the various types of flexibility defined in the literature are due to uncertainty associated with manufacturing systems and could be divided into four types of uncertainty: the uncertainty of, input materials, output, the manufacturing process, and the external environment. Based on this belief, they presented four information-theoretic measures to quantify flexibility. They are (Kumar, V. and Kumar, U. 1987a):

1) $$S_1(x_1,x_2,\text{-------},x_n) = -\sum_{i=1}^{n} x_i \ln x_i$$

2) $$S_2(x_1, x_2,\text{-------},x_n) = \frac{1}{1-\alpha} \ln (\Sigma\, x_i^{\alpha}) \;, \alpha \neq 1$$

3) $$S_3(x_1, x_2,\text{-------},x_n) = (1-e^{1-\alpha}) \,[1 - \Sigma\, x_i^{\alpha}], \; \alpha \neq 1$$

4) $$S_4(x_1, x_2, \text{-------}, x_n) = \frac{1}{1-\alpha} \ln \{\Sigma x_i^{\alpha+\beta-1} / \Sigma\, x_i^{\beta}\}, \quad \alpha \neq \beta$$

where:

x_i's are choices of selecting the various options.

S be the measure of flexibility.

The first measure of flexibility is the same which has been used as a measure of uncertainty or average information by Shannon (1948). The second expression is due to Renyi (1961) and approaches the first measure as α tends to 1. The third measure is the same expression which was used by Havrda and Charvat (1967) and also approaches the first measure due to Shannon(1948). The fourth measure of flexibility having two parameters α and β is due to Kapur (1986) and reduces to second measure for $\beta=1$ and to first measure for $\beta=1$ and $\alpha=1$ (Kumar 1987b).

Chapter III

METHODOLOGY

3.1 AN INFORMATION-BASED SCHEDULING RULE

From the available literature it can be seen that most of the priority rules developed and tested by different authors are based on processing times. But in flexible manufacturing systems, where machines could be used to perform alternate operations, there are some other factors which could be considered for scheduling. The uncertainty embedded in those operations which are allowed to be performed by alternate machines is one of them. Alternate machines are used only if original machines are either busy or not available. Initially, it is not known whether a particular operation of a part will be performed by the original machine or an alternate machine. Therefore, it is safer to say that with every alternate routing there is associated some kind of missing information.

Based on this belief, a new scheduling rule which handles uncertainty associated with alternate operations in flexible manufacturing systems is developed. It is assumed that

a) each of the operations on machines are random, and that
b) successive operations are statistically independent.

Mathematically, the rule which will be called information-based scheduling rule (LINF) henceforth, can be defined as follows:

Let

O_{ijk} be the operation j of part type i on machine k ,

T_{ijk} be the processing time of operation j for part type i on machine k ,

P_{ijk} the probability of operation O_{ijk} ocurring,

$$X_{ijk} = \begin{cases} 1 & \text{If operation j of part type i is assigned to machine k ,} \\ 0 & \text{Otherwise.} \end{cases}$$

such that,

$$0 \leq P_{ijk} \leq 1 \quad \text{and} \quad \sum_{k=1}^{m} \sum_{j=1}^{N} P_{ijk} = 1$$

for every i

where:

$$P_{ijk} = X_{ijk} \cdot \frac{T_{ijk}}{T_{i..}} \quad \text{and} \quad T_{i..} = \sum_{k=1}^{m} \sum_{j=1}^{N} X_{ijk} \quad T_{ijk}$$

for every i

Then, the amount of self-information associated with the ocurrence of an operation O_{ijk} is defined as

$$I(sinf)_{ijk} = - \log P(O_{ijk})$$
$$= - \log P_{ijk}$$

The total information for all operations of part type i is

$$I(sinf)_{i.k} = - \sum_{j=1}^{N} \log P_{ijk}$$

The parts on the alternate machine are scheduled and processed in ascending order of $I(sinf)_{i.k}$ and on original machine in ascending order of the difference between parts most imminent due time and processing time done so far. Later in the next chapter , the performance of the combination of these two rules is compared with that of the other scheduling rules available in the literature.

3.2 THE MODEL

The flexible manufacturing system to be modeled is described as follows:

1. There are n part types P_1, P_2, P_3,-------, P_n processed in the system.

2. The system is a network of m single-server S_1, S_2, S_3,-------, S_m stations (machines).

3. There are l pallets and t tools available in the system.

Parts are palletized at loading area and transported to machines, from one machine to the next, and from machines performing the last operation to the unloading area by an automated material handling cart. To perform operations on the various parts, required tools are stored on machines or may come from a storage area.

The main assumptions made in the operation of the system, are that:

1. Each CNC machining centre has one and only one machine.
2. The job arrival pattern is deterministic.
3. Processing time of each operation is deterministic.
4. No preemption is allowed. Once started, an operation continues until completed.
5. No machine break-down.
6. A part may visit a machine more than once for different operations.
7. An alternate machine is assumed to use the same number of tools as the corresponding original machine does.

8. Transport times between machines and the load/unload station are known.
9. Pallet loading/unloading takes 5 minutes.

The control of the system proceeds as follows:

If the original machine is free , parts are processed on first come first served basis. If the machine is not free and no alternate machine is available, then parts on the original machine are ordered according to some priority. Otherwise, the utilizations of original and alternate machines will be compared. If an alternate machine is less utilized, then parts will be scheduled and processed on that machine. Otherwise, the parts will wait for the original machine until other parts with higher priority arrive and which then move to the appropriate forward position in the queue.

3.3 EXPERIMENT DESIGN

After specifying the system to be studied , the next important step is to define objectives, goals, and performance criteria.

Objectives define the rationale of the modelling study. They allow to set the stage for the type of experiment required. The objective here is to compare the performance of different scheduling rules.

Goals define the transactions that must take place during the execution of the model and describe the conditions necessary for the simulation to end. The goals of this study are to produce 100 to 1000 parts.

Performance criteria are tied directly to the execution goals. Goals define when execution is complete; performance criteria define how well the model attains the goals to be considered successful. In other words, they describe the 'goodness' of the execution. The performance measure of this experiment is the mean flow time of parts in the system.

The data necessary for the manufacturing system are: the part types, the operations required for their complete production, processing time for each operation on the original as well as on alternate machines, the number of pallets, the number of tools, a material handling cart, and a number of operators at the load/unload area.

Selecting Scheduling Rules.

Eleven priority scheduling rules and ten combinations of these rules are examined in this study.
The following describes the eleven scheduling rules tested:

1. SPT - shortest processing time
2. LPT - longest processing time

3. LPD - least processing time done
4. MDT - most imminent due time
5. LPR - least total processing time not yet done
6. TPT - least total processing time
7. SPT/TPT - shortest processing time divided by the total processing time
8. EAT - first-come first-served
9. LS - least slack
10. MDT-LPD - smallest difference between most imminent due time and least processing done
11. LINF - least amount of total self-information

The most imminent due time (MDT), remaining processing time (LPR), processing done (LPD), and least slack (LS) used in the model are calculated using alternate operation times. The multiplier used in the calculation of most imminent due time is three. All rules, except rule numbers 10 and 11, have been found in the literature. Rule number 10 (MDT-LPD) is obtained from the other two rules which have been existed, while rule LINF, as presented earlier is new.

Table 1 contains a list of abbreviations and combinations of rules applied to original and alternate machines of the Flexible Manufacturing System.

Description	Combination of Rules
Highest priority is given to the part	
with the shortest processing time	SPTxSPT
with the longest processing time	LPTxLPT
with the least processing done	LPDxLPD
with the most imminent due time	MDTxMDT
having the least total processing time for all operations not yet performed	LPRxLPR
with the least total processing time for all operations	TPTxTPT
having the shortest processing time for the operation divided by the total processing time for the part	SPT/TPTxSPT/TPT (Stecke & Solberg's Best Rule)
which arrives first at the current machine	EATxEAT (Equivalent to FCFS)
with the least slack	LSxLS
having the smallest difference between most imminent due time and processing time done at original machines and the least ammount of total self information at alternate machines	(MDT-LPD)xLINF

TABLE 1

List of combinations of rules and abbreviations

The simulation model to test and compare the performance of the proposed rules with other nine most popular rules including Stecke and Solberg's (1981) recommended (SPT/TPT) rule is developed in GPSS version 360. The model requiring 256K core, is run on the AMDAHL 5870 mainframe computer at the University of Manitoba.

3.4 RUNNING AND DISCUSSION OF THE MODEL

The simulation is repeated several times using the same input and fixed number of parts each time. Only the scheduling rules are varied in order to focus on their different effects.

The flowchart (Figure 8), represents in general terms the control logic and various operations that have to be performed on the parts for complete production. The GPSS flowchart which gives a solid understanding of the model is shown in Figure 9 (Appendix B).

3.4.1 Correspondence Between System Elements and GPSS Entities

The time unit for the model is 1 minute. That is, part arrival, machining, and transport times are all expressed in minutes.

Parts are represented by transactions and machines in the system are represented by facilities.

The material handling cart, the operator responsible for loading pallets and another operator responsible for unloading pallets at the unloading/loading area are represented by storages. Pallets and tools in the system (also represented by storages) tell how many there are available to use. The load/unload area also represented by a storage gives information regarding the number of load/unload stations (i.e. capacity of load/unload area).

3.4.2 Standard Numerical Attributes (SNAs)

To fully understand the model one should explain the meaning and use of standard numerical attributes, especially msavevalues and parameters which have been used most in the model.

Fullword Msavevalues.

Fullword matrix savevalues 1, 2, 4, and 5 contain routing information and operation times on machines. Msavevalue 3 displays information for required tools and fullword msavevalues 7 through 9 are used for transport times information (i.e. from load/unload area to machines, from one machine to the next, and from machines to unload/load). It is important to note that since GPSS handles only integer values, the self-information represented by msavevalue six is multiplied by 100 to make it integer.

Parameters.

P1 : Part type.
P2 : Total number of operations.
P3 : Generation Time.
P4 : Sum of operation times already performed.
P5 : Sum of all alternate operation times for the part.
P6 : Very first operation number.
P7 : For computation purposes.
P8 : The most imminent due time.
P9 : Remaining processing time.
P10 : Job slack.

P11 : Used for shortest processing time on original machine.

P12 : Shortest processing time on alternate machine.

P13 : Specify when the first operation began.

P14 : Machine number used to correspond to user chain number.

P15 : Longest processing time on original machine.

P16 : Shortest processing time divided by total processing time on alternate machine.

P17 : Arrival time at original machine.

P18 : Arrival time at alternate machine.

P19 : Total self-information.

P20 : Not used.

P21 : Sum of all original operation times for the part.

P22 : Not used.

P23 : First original machine.

P24 ,P25 : Original and alternate machines to compare utilizations.

P26 : Transit time from loading area to very first original machine.

P27 : Not used.

P28 : Transit time from load/unload to corresponding alternate machine (If exists).

P29 : Not used.

P30 : Current alternate machine number used to point to transport time from alternate to original machine.

P31 : Transport time from alternate machine to the next original machine.

P32 : Next original machine number.

P33 : Transit time from one original machine to the next original machine.

P34 : Current original machine used to point to transport time from this machine to the next.

P35 : Not used.

P36 : Next original machine number used to point to transport time from current alternate to the next original.

P37 : Transport time from current alternate machine to current original machine (Required for utilization comparisons).

P38 : Last machine number.

P39 : Transit time from last machine to unload/load area.

P40 : Not used.

P41 : Last alternate machine (If different from original)

P42 : Transit time from that machine to load/unload.

P44 : Longest processing time on alternate machine.

P45 : Difference of the most imminent due time and operation times performed so far.

P46 : Shortest processing time divided by total processing time on original machine.

3.4.3 Control Logic:

3.4.3.1 Part Generation at Loading Area

The following code segment illustrates the logic required to move parts from loading area to the machines.

```
1               GENERATE   15,,,100,,46
           *
2               ASSIGN     1,FN$PTYP
3               ASSIGN     2,FN$MACH
           *
4               ASSIGN     23,MX1(P1,P2)
           *
5               ASSIGN     26,MX7(1,P23)
6               MARK       3
7               ASSIGN     4,0
8               ASSIGN     6,P2
9               ASSIGN     5,0
           *
10              ASSIGN     7,P2
11         TOTL ASSIGN     5+,MX5(P1,P7)
           *
12              LOOP       7,TOTL
           *
13              ASSIGN     19,0
14              ASSIGN     20,P2
15         ADDT ASSIGN     19+,MX6(P1,P20)
16              LOOP       20,ADDT
           *
           *
17              ASSIGN     21,0
           *
18              ASSIGN     22,P2
19         SUM  ASSIGN     21+,MX2(P1,P22)
           *
20              LOOP       22,SUM
           *
21              ASSIGN     8,V2
           *
22              PRIORITY   FN$PRIR
23              QUEUE      OPPL
           *
24              TEST E     BV$COND,1
           *
25              ENTER      OPRT
26              ENTER      PALT
27              DEPART     OPPL
```

```
28              ADVANCE     5
29              LEAVE       OPRT
30              GATE SNF    CART
        *
31              ENTER       CART
32              ADVANCE     P26
        *
        *
33              LEAVE       CART
```

This is the segment which brings parts into the model and each part transaction is assigned the number of operations corresponding to its type (Block 3). All the necessary information, such as transit time (Block 5) from loading area to original and to alternate machines (Block 4), total processing time (Blocks 11 & 19) , total self-information for the part (Block 15), most imminent due time (Block 21), and priority (Block 22) is given by this section of the model. Each part transaction waits in queue (Block 23) until a pallet, operator, and cart become available (Blocks 24 & 25). Then, the cart delivers part to the original machine (Block 32).

3.4.3.2 Scheduling and Processing of Parts on Original Machines

a) Processing on original machines

As explained in section 3.2, if parts find the original machine not busy, they are machined as soon as they arrive at this machine.

The model code which presents this kind of processing follows.

```
34      CONT  GATE NU    MX1(P1,P2),CHCK
35            ENTER      TOOL,MX3(P1,P2)
36            SEIZE      MX1(P1,P2)
37            TEST E     BV$FRST,1,HOSE
38            MARK       13
       *
       *
39      HOSE  ADVANCE    MX2(P1,P2)
40            ASSIGN     4+,MX2(P1,P2)
41            ASSIGN     9,V4
       *
42            ASSIGN     10,V3
43            LEAVE      TOOL,MX3(P1,P2)
44            RELEASE    MX1(P1,P2)
```

The Block number 34 checks whether or not the primary machine is free. If it is, the control proceeds to the next blocks in sequences. Next, block 37 tests for operation number, since the flow time is measured from the first operation to the last operation of the part. After capturing the machine and the required tools by executing Blocks SEIZE and ENTER (35 and 36), machining takes place by the ADVANCE Block (39). The LEAVE and RELEASE Blocks (43 and 44) tell the model that the machine and tools used are now ready to perform another operation. Processing time finished so far, remaining processing time, and job slack are calculated by the variables given in the variable definitions part of the model (Figure 10) and assigned to the parameters corresponding to the block numbers 40, 41, and 42 respectively.

If parts arriving at the original machine find it busy, then they have to be scheduled before actual processing. To do this, one must find out whether or not an equivalent machine (alternate machine) to perform the operation which the original machine was supposed to perform, exists. The following segment code is responsible for this task.

```
67        CHCK  ASSIGN     24,MX1(P1,P2)
68              ASSIGN     25,MX4(P1,P2)
69              TEST E     P24,P25,AVAL
```

The Block numbers 67 and 68 simply assign parameters, but the real work is done by the block number 69 where equality of parameters is tested for the availability. If the condition is met, then the part transaction moves to the next block. Otherwise, it branches to the block labeled AVAL (to alternate machine).

b) Scheduling and Processing on Original Machines

The procedure used for representing how part transactions should be scheduled and machined on original machines follows.

```
71              ASSIGN     11,MX5(P1,P2)
          *
72              ASSIGN     14,MX4(P1,P2)
73              ASSIGN     45,V8
```

```
74              ASSIGN     15,V5
75              ASSIGN     46,V10
76              MARK       17
77              LINK       V6,P11,PLAY
         *
         *
         *
78        PLAY  SEIZE      MX4(P1,P2)
79              ENTER      TOOL,MX3(P1,P2)
80              TEST E     BV$FRST,1,PROC
81              MARK       13
         *
82        PROC  ADVANCE    MX5(P1,P2)
83              ASSIGN     4+,MX5(P1,P2)
84              ASSIGN     9,V4
         *
85              ASSIGN     10,V3
86              PRIORITY   PR,BUFFER
         *
87              RELEASE    MX4(P1,P2)
88              LEAVE      TOOL,MX3(P1,P2)
89              UNLINK     V6,PLAY,1
         *
90              TRANSFER   ,GONP
```

Scheduling rules applied at the original machine are SPT (P11, Block 71), LPT (P15, Block 74), EAT (P17, Block 76), MDT (P8, Block 21 of Part Generation Section), TPT (P21, Part Generation code, Block 19), SPT/TPT (P46, Block 75), MDT-LPD (P45, Block 73), LPD (P4), LPR (P9), and LS (P10) used at various places after each operation. Once the parameters are set for scheduling rules, the actual scheduling is done by the block labeled LINK (Block 77) where parts waiting for the machine are put onto the user chain V6 (corresponding to machine number) and arranged in ascending order of the values of the parameter placed at the B operand of the LINK Block (may be P11,P15,P4, etc.).

After scheduling, the parts are sent to the next blocks where machining on parts takes place. A part which has seized the machine at Block SEIZE needed to get the necessary tools for processing, executes an ENTER Block (79). It is notable that the msavevalues corresponding to original machines and processing times are four and five instead of one and two. These do not make any difference because original and alternate machines are the same in the case when no alternate machine exists. The block labeled TEST tests the operation number condition, since we are interested in measuring flow time (from the beginning of first operation to the last). The sole purpose of the MARK Block subroutine is to measure the time that has elapsed.

After being processed at the block marked ADVANCE, the Block 83 (ASSIGN) updates the processing time by adding current processing time to the total operation time finished right before this stored in parameter P4. The other two ASSIGN Blocks 84 and 85 compute remaining processing time and job slack for the part. After completing an operation, the part transaction informs the model at the UNLINK Block that a machine has been freed and next scheduled part is then processed.

3.4.3.3 Operation Updating and Flow Time

Every time a part completes processing at a machine, it enters the model code given below.

```
45      GONP  ASSIGN     34,MX1(P1,P2)
46            ASSIGN     2-,1
        *
47            TEST E     P2,0,CONP
48            ASSIGN     2+,1
49            TABULATE   FLOW
        *
50            TABULATE   COMP
51            TABULATE   P1
        *
52            ASSIGN     38,MX1(P1,P2)
53            ASSIGN     39,MX9(P38,1)
        *
54            GATE SNF   CART,HOLD
55       USE  ENTER      CART
56            ADVANCE    P39
```

The first ASSIGN Block number 45 is used just for logic. The actual work starts at the second ASSIGN Block where the parameter number two is decremented, and compared with the number zero (TEST Block). Note that the GPSS reads matrix values from right to left, so the parameter P2 was initialized to the total number of operations required for each part (Loading Segment, Block 3).

Next, If all operations have been done, the part proceeds to the next sequential block. Again the ASSIGN Block number 48 is used just for computational purposes, so it points to the last operation. By executing the block assigned TABULATE (Block 49), the mean flow time of the parts since first to last operation is measured and displayed by the INCLUDE statement coded in the Report section (Figure 10, Appendix C).

One may also measure mean completion time (makespan) and mean completion time for each part type by the next two TABULATE Blocks repectively. In general, the rule which minimizes mean flow time also minimizes makespan.

Executing the remaining blocks of this submodel (Blocks 52 through 56) parts are taken to the unloading area. The part uses a refusal-mode GATE (Block 54) to test for the availability of the material handling cart. If it is available, then part delivery to the unloading area takes place by executing the ENTER and ADVANCE Blocks where parameter number 39 corresponds to the transport time from the machine to unloading area. Otherwise, the part branches to the block labeled HOLD to be linked on the User Chain WAIT.

3.4.3.4 Depalletizing Parts at the Unloading Area

Depalletizing procedure at the unloading area is very straight forward.

The following code segment illustrates the logic required to depalletize parts and leave the unloading area.

```
57              ENTER       UNLD
58              LEAVE       CART
59              ENTER       OPR2
60              ADVANCE     5
61              LEAVE       PALT
62              LEAVE       OPR2
63              LEAVE       UNLD
          *
          *
          *
64              UNLINK      WAIT,USE,1
          *
65              TERMINATE   1
66         HOLD LINK        WAIT,FIFO
```

Execution of two ENTER Blocks (Blocks 57 and 59) indicates the presence of the part at the unloading station which has to be depalletized by the operator by executing the Block named ADVANCE. Two LEAVE Blocks (Blocks 61 and 63) cause the part transaction to leave the pallet and unloading area. This means that there has been one pallet available for reloading another part and one station available at unloading area. Another LEAVE Block 62 in between these two blocks indicates the availability of the operator for next part to be depalletized.

The main task of two interrelated Blocks LINK and UNLINK is to put parts on User Chain named WAIT and to tell the model that the cart has been freed to pick up the next part and deliver it to the unloading area. It is the

TERMINATE Block that causes the simulation to stop after completing the number of parts specified by the START card just before Report Section of the model (Figure 10, Appendix C).

3.4.3.5 Testing Machine Utilization

A parameter must be kept for each machine to record the machine's most recent utilization. To examine which machine (original or alternate) is least utilized is done by means of the following code.

```
139       DOT1  TEST LE     FR*24,FR*25,ALTN
         *
         *
         *
140             ASSIGN      37,MX8(P25,P24)
         *
         *
         *
141             ENTER       CART
142             ADVANCE     P37
         *
         *
143             LEAVE       CART
144             TRANSFER    ,PTOP
         *
         *
145       ALTN  GATE NU     MX4(P1,P2)
```

The point where the machine selection is made, is the Block TEST. The Parameters 24 and 25 containing utilization of original and alternate machines are tested for less than or equal to condition. The machine which has the minimum value of that parameter is selected (i.e. the machine which has been idle the longest). If the less-than or-equal to condition is met, the part moves to the next sequential block. Otherwise, the part branches to the Block named ALTN for alternate machine where scheduling and processing take place.

A similar control logic for scheduling and processing on alternate machines, operation updating, and depalletizing parts is applied. Only the parameters, matrix numbers, and User Chain names are different.

Chapter IV

APPLICATION AND EVALUATION OF SCHEDULING RULES

4.1 DEMONSTRATION EXAMPLE

A hypothetical example is devised to test and compare the performance of the combination of scheduling rules (MDT-LPD) at original machines and LINF at alternate machines with other most popular rules. Our model FMS comprises 6 machining centers, each of which is a single server station. The FMS is to process 3 part types with highest priority given to part type 3.

Table 2 shows the appearance of the visitation sequence along with operation times. Machines considered as alternates and corresponding operation times are enclosed in parentheses. The tool requirement for each part type on machines is shown in Table 3. Table 4 gives the transport times matrix. The percentage of parts of each type to be produced is also given in Table 2 (Row 6). The self-information for alternate operations and summary of the simulation results are presented in Tables 5 and 6 respectively.

Operation sequence	Part 1		Part 2		Part 3	
	Mach.	Time	Mach.	Time	Mach.	Time
1	1 (3)	20 (25)	3 (4)	20 25	1	24
2	4	25	2	15	5 (4)	20 (25)
3	3	22	6	12	4	15
4	5	15	5	17	3	12
5	6	10	4	22	2	10
%age	20%		20%		60%	

TABLE 2

Operation (routing) sequence

Operation sequence	Part 1	Part 2	Part 3
1	5	6	7
2	2	3	6
3	4	3	3
4	2	3	5
5	5	4	2

TABLE 3

Tool requirement

		To						
		Load/Unload	MH1	MH2	MH3	MH4	MH5	MH6
	Load/Unload	0	3	7	3	5	6	6
	MH1	3	0	3	3	1	5	2
F	MH2	7	3	0	6	3	3	4
R	MH3	3	3	6	0	3	2	3
O	MH4	5	1	3	3	0	2	3
M	MH5	6	5	3	2	2	0	3
	MH6	6	2	4	3	3	3	0

TABLE 4

Transport times matrix

Operation Number	Self-Information		
	Part type 1	Part type 2	Part type 3
1	.59	.56	.55
2	.59	.78	.53
3	.64	.87	.75
4	.78	.73	.85
5	.98	.61	.93

TABLE 5

Self-Information of alternate operations

No. of part types	Parts in system	Machines	Scheduling Rules on		Mean Flow time (Minutes)
			Original Machines	Alternate Machines	
3	100	6	SPT	SPT	375.189
			LPT	LPT	426.589
			LPD	LPD	404.109
			SPT/TPT	SPT/TPT	417.419
			MDT	MDT	402.129
			LPR	LPR	411.049
			TPT	TPT	402.129
			EAT	EAT	417.419
			LS	LS	430.789
			MDT-LPD	LINF	354.789
	200		SPT	SPT	394.294
			LPT	LPT	407.569
			LPD	LPD	397.559
			SPT/TPT	SPT/TPT	409.214
			MDT	MDT	433.754
			LPR	LPR	438.104
			TPT	TPT	433.754
			EAT	EAT	409.214
			LS	LS	414.359
			MDT-LPD	LINF	341.314
	300		SPT	SPT	403.929
			LPT	LPT	415.166
			LPD	LPD	406.703
			SPT/TPT	SPT/TPT	427.099
			MDT	MDT	445.679
			LPR	LPR	435.006
			TPT	TPT	445.679
			EAT	EAT	427.099
			LS	LS	420.233
			MDT-LPD	LINF	323.809
	400		SPT	SPT	411.567
			LPT	LPT	400.569
			LPD	LPD	413.452
			SPT/TPT	SPT/TPT	429.067
			MDT	MDT	441.364
			LPR	LPR	442.562
			TPT	TPT	441.364
			EAT	EAT	429.067
			LS	LS	422.959
			MDT-LPD	LINF	350.727

TABLE 6

The performance of selected scheduling rules

Table 6 continued

No. of part types	Parts in system	Machines	Scheduling Rules on Original Machines	Scheduling Rules on Alternate Machines	Mean Flow time (Minutes)
3	500	6	SPT	SPT	397.475
			LPT	LPT	429.391
			LPD	LPD	429.183
			SPT/TPT	SPT/TPT	433.861
			MDT	MDT	448.135
			LPR	LPR	451.537
			TPT	TPT	448.135
			EAT	EAT	433.861
			LS	LS	430.901
			MDT-LPD	LINF	334.653
	600		SPT	SPT	427.936
			LPT	LPT	400.628
			LPD	LPD	441.866
			SPT/TPT	SPT/TPT	432.393
			MDT	MDT	442.369
			LPR	LPR	430.501
			TPT	TPT	442.369
			EAT	EAT	432.393
			LS	LS	436.213
			MDT-LPD	LINF	322.928
	700		SPT	SPT	413.389
			LPT	LPT	388.812
			LPD	LPD	421.725
			SPT/TPT	SPT/TPT	421.458
			MDT	MDT	447.158
			LPR	LPR	445.429
			TPT	TPT	447.158
			EAT	EAT	421.458
			LS	LS	419.832
			MDT-LPD	LINF	327.692
	800		SPT	SPT	421.487
			LPT	LPT	393.276
			LPD	LPD	431.244
			SPT/TPT	SPT/TPT	418.571
			MDT	MDT	450.133
			LPR	LPR	445.125
			TPT	TPT	450.133
			EAT	EAT	418.571
			LS	LS	438.866
			MDT-LPD	LINF	325.381

Table 6 continued

No. of part types	Parts in system	Machines	Scheduling Rules on Original Machines	Scheduling Rules on Alternate Machines	Mean Flow time (Minutes)
3	900	6	SPT	SPT	423.420
			LPT	LPT	403.314
			LPD	LPD	430.422
			SPT/TPT	SPT/TPT	429.076
			MDT	MDT	457.126
			LPR	LPR	445.091
			TPT	TPT	457.126
			EAT	EAT	429.076
			LS	LS	430.496
			MDT-LPD	LINF	318.270
	1000		SPT	SPT	417.396
			LPT	LPT	393.142
			LPD	LPD	433.967
			SPT/TPT	SPT/TPT	420.906
			MDT	MDT	453.681
			LPR	LPR	448.146
			TPT	TPT	453.681
			EAT	EAT	420.906
			LS	LS	436.344
			MDT-LPD	LINF	333.246

The GPSS Graphical Output.

As pointed out earlier, the GPSS can produce graphical output. The histogram produced for 100 parts with the application of the MDT-LPD rule at the original and the LINF rule at the alternate machine is shown in Figure 4. The histogram is produced from the Table FLOW (shown below) in the model.

```
TABLE   FLOW
ENTRIES IN TABLE            MEAN ARGUMENT
             100                  354.789
           UPPER        OBSERVED
           LIMIT       FREQUENCY
              10               0
              20               0
              30               0
              40               0
              50               0
              60               0
              70               0
              80               0
              90               0
             100               0
             110               1
             120               1
        OVERFLOW              98
```

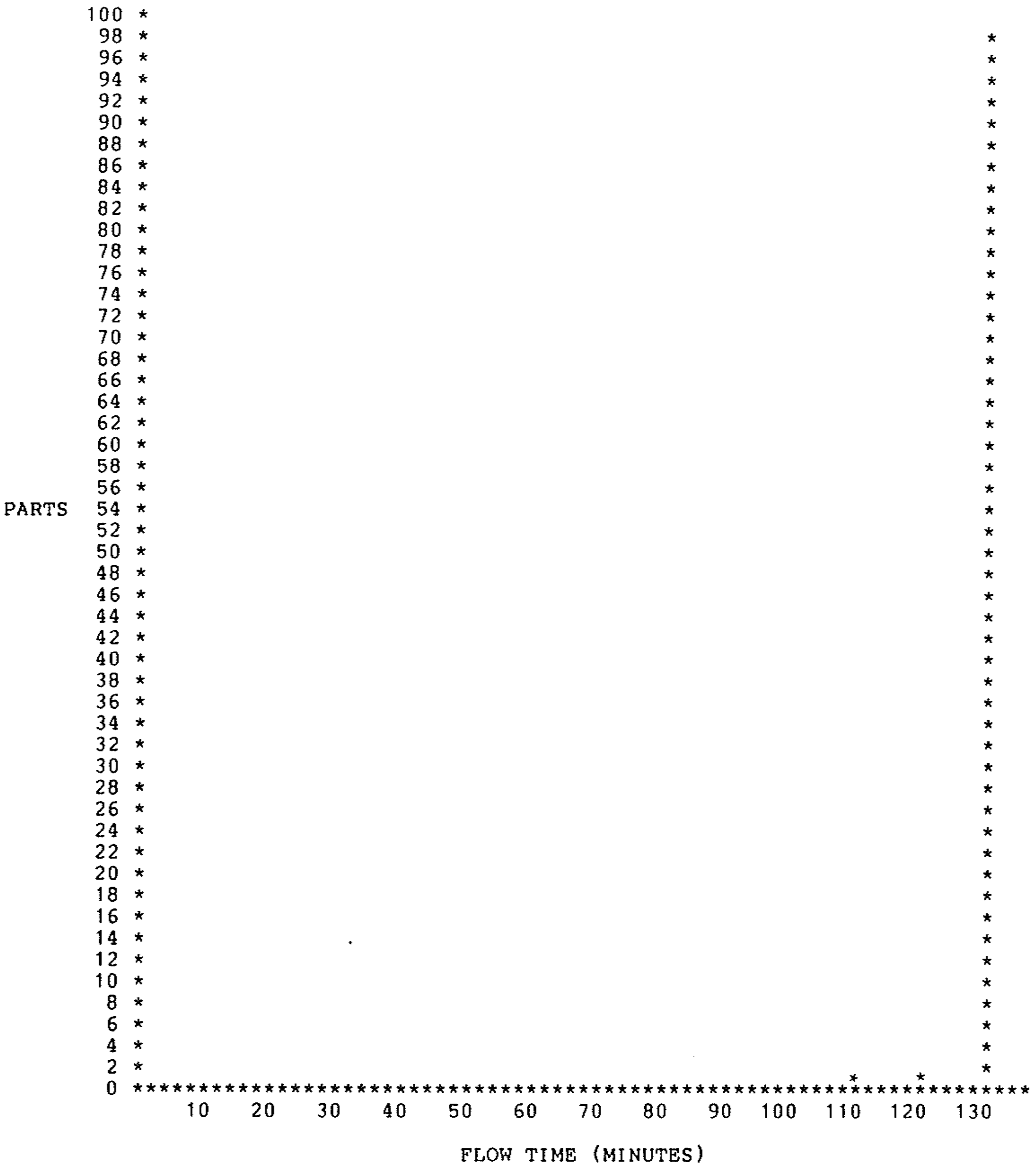


Figure 4: Flow time vs. No. of parts for (MDT-LPD)x(LINF)

Note that the values in a GPSS Table range from "minus infinity" to "plus infinity". This means there is no part (observed frequency 0) whose flow time is less than or equal 10 minutes (UPPER LIMIT 10). The observed frequencies 1 for UPPER LIMITs 110 and 120 show that there was only one part whose flow time is less than or equal to 110 minutes and one part whose flow time is less than or equal to 120 minutes. OVERFLOW on the right-most interval indicates that the flow time of 98 parts is greater than 120 minutes (may be infinity). That is, we have no idea what the flow times were. The reason of showing 130 minutes in the graph is because we requested 13 points in the Table FLOW.

```
*
FLOW  TABLE     MP13,10,10,13        TABLE FOR PART FLOW TIME.
*
```

If we increase the number of points in the Table, the flow time might be greater than 130 minutes. The GPSS is restricted to produce histograms only from Tables for each individual run. Therefore, it does not allow to compare scheduling rules in a single graph. From this point on, the scheduling rules will be compared using SAS bar graphs.

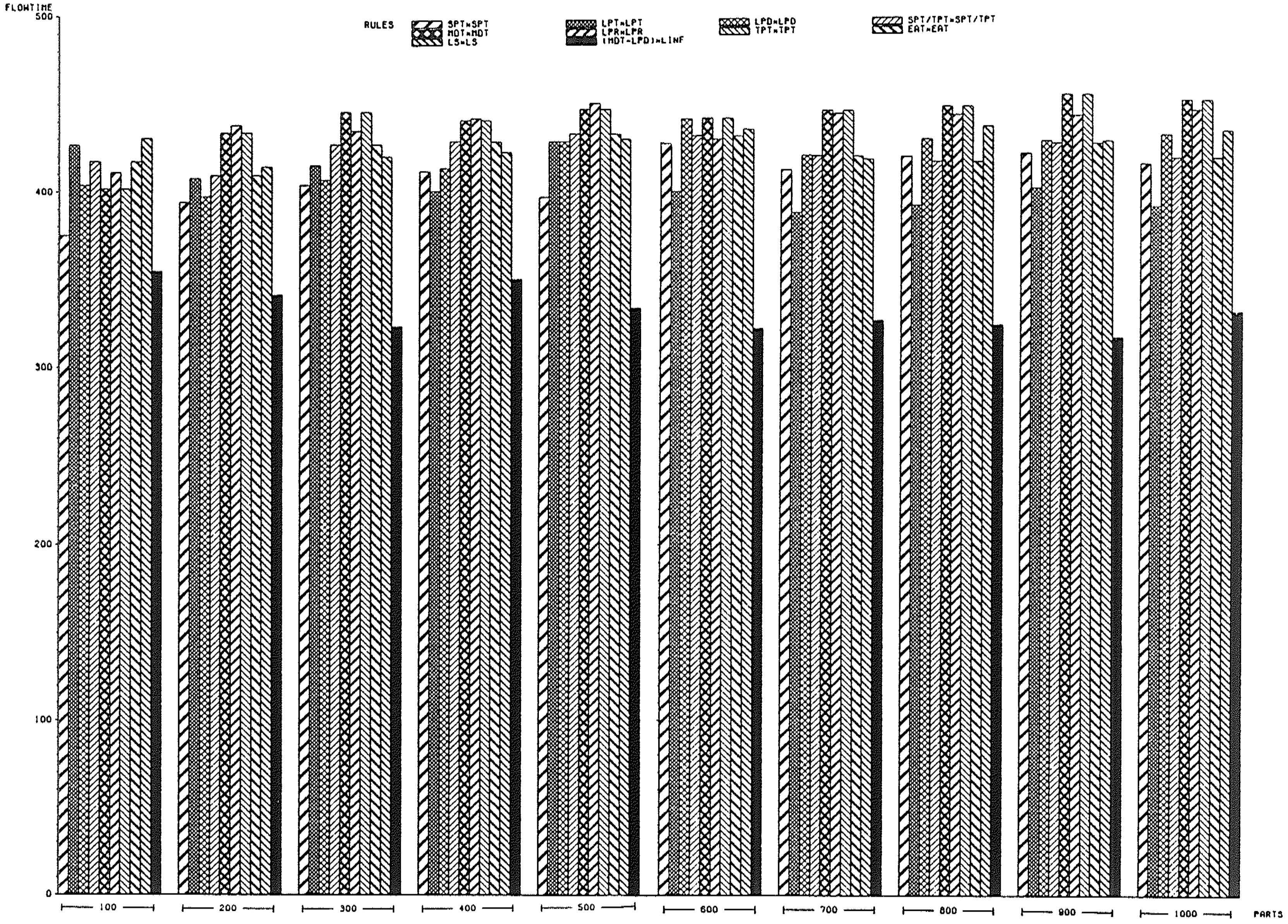


Figure 5: Comparison of scheduling rules for the example problem

4.2 APPLICATION TO WILHELM AND SARIN (1985)

The operation sequence and operation times for alternate operations directed dynamically (AD) scheme from Wilhelm and Sarin (1985) are shown in Table 7 . The number of tools used and transport times are given in Tables 8 and 9 respectively. Tables 10 and 11 show the calculated self-information and summarized simulation results for the problem.

Operation sequence	Part 1		Part 2		Part 3	
	Mach.	Time	Mach.	Time	Mach.	Time
1	1 (2)	20 (25)	2 (3)	20 25	1	20
2	3	25	1	15	4 (3)	20 (10)
3	2	20	3	15	3	10
4	4	10	4	30	2	10
%age	33%		33%		34%	

TABLE 7

Operation (routing) sequence (Wilhelm and Sarin 1985)

Operation seuence	Part 1	Part 2	Part 3
1	5	4	2
2	2	3	5
3	4	3	3
4	2	3	6

TABLE 8

Tool requirement

		To			
		Load/Unload	MH1	MH2	MH3	MH4

		To Load/Unload	MH1	MH2	MH3	MH4
	Load/Unload	0	1	2	1	2
F	MH1	1	0	1	2	3
R	MH2	2	1	0	1	2
O	MH3	1	2	1	0	1
M	MH4	2	3	2	1	0

TABLE 9

Transport times matrix

Operation Number	Self-Information Part type 1	Part type 2	Part type 3
1	.50	.53	.40
2	.50	.75	.70
3	.60	.75	.70
4	.90	.45	.70

TABLE 10

Self-Information of alternate operations

No. of part types	Parts in system	Machines	Scheduling Rules on Original Machines	Scheduling Rules on Alternate Machines	Mean Flow time (Minutes)
3	100	4	SPT	SPT	271.539
			LPT	LPT	379.729
			LPD	LPD	387.519
			SPT/TPT	SPT/TPT	344.869
			MDT	MDT	300.750
			LPR	LPR	367.439
			TPT	TPT	300.750
			EAT	EAT	344.869
			LS	LS	383.669
			MDT-LPD	LINF	198.729
	200		SPT	SPT	288.774
			LPT	LPT	399.679
			LPD	LPD	417.769
			SPT/TPT	SPT/TPT	355.214
			MDT	MDT	308.199
			LPR	LPR	401.024
			TPT	TPT	308.199
			EAT	EAT	355.214
			LS	LS	411.929
			MDT-LPD	LINF	189.859
	300		SPT	SPT	302.126
			LPT	LPT	400.473
			LPD	LPD	425.889
			SPT/TPT	SPT/TPT	368.449
			MDT	MDT	314.569
			LPR	LPR	411.006
			TPT	TPT	314.569
			EAT	EAT	368.449
			LS	LS	416.676
			MDT-LPD	LINF	192.143
	400		SPT	SPT	308.889
			LPT	LPT	409.897
			LPD	LPD	427.052
			SPT/TPT	SPT/TPT	371.927
			MDT	MDT	310.627
			LPR	LPR	412.299
			TPT	TPT	310.627
			EAT	EAT	371.927
			LS	LS	423.597
			MDT-LPD	LINF	171.584

TABLE 11

The performance of selected scheduling rules for the example problem from Wlihelm and Sarin (1985)

Table 11 continued

No. of part types	Parts in system	Machines	Scheduling Rules on Original Machines	Scheduling Rules on Alternate Machines	Mean Flow time (Minutes)
3	500	4	SPT	SPT	307.813
			LPT	LPT	417.113
			LPD	LPD	432.595
			SPT/TPT	SPT/TPT	366.587
			MDT	MDT	312.889
			LPR	LPR	418.993
			TPT	TPT	312.889
			EAT	EAT	366.587
			LS	LS	423.863
			MDT-LPD	LINF	169.961
	600		SPT	SPT	309.753
			LPT	LPT	422.891
			LPD	LPD	429.494
			SPT/TPT	SPT/TPT	379.108
			MDT	MDT	318.184
			LPR	LPR	422.784
			TPT	TPT	318.184
			EAT	EAT	379.108
			LS	LS	424.254
			MDT-LPD	LINF	167.174
	700		SPT	SPT	308.024
			LPT	LPT	417.876
			LPD	LPD	426.817
			SPT/TPT	SPT/TPT	374.339
			MDT	MDT	314.371
			LPR	LPR	424.192
			TPT	TPT	314.371
			EAT	EAT	374.339
			LS	LS	421.288
			MDT-LPD	LINF	169.555
	800		SPT	SPT	311.103
			LPT	LPT	425.871
			LPD	LPD	435.212
			SPT/TPT	SPT/TPT	375.591
			MDT	MDT	319.803
			LPR	LPR	426.279
			TPT	TPT	319.803
			EAT	EAT	375.591
			LS	LS	429.378
			MDT-LPD	LINF	167.002

Table 11 continued

No. of part types	Parts in system	Machines	Scheduling Rules on Original Machines	Scheduling Rules on Alternate Machines	Mean Flow time (Minutes)
3	900	4	SPT	SPT	310.490
			LPT	LPT	415.537
			LPD	LPD	432.123
			SPT/TPT	SPT/TPT	375.405
			MDT	MDT	319.307
			LPR	LPR	420.264
			TPT	TPT	319.307
			EAT	EAT	375.405
			LS	LS	426.295
			MDT-LPD	LINF	166.269
	1000		SPT	SPT	308.215
			LPT	LPT	425.024
			LPD	LPD	432.881
			SPT/TPT	SPT/TPT	378.138
			MDT	MDT	322.803
			LPR	LPR	425.411
			TPT	TPT	322.803
			EAT	EAT	378.138
			LS	LS	427.807
			MDT-LPD	LINF	166.910

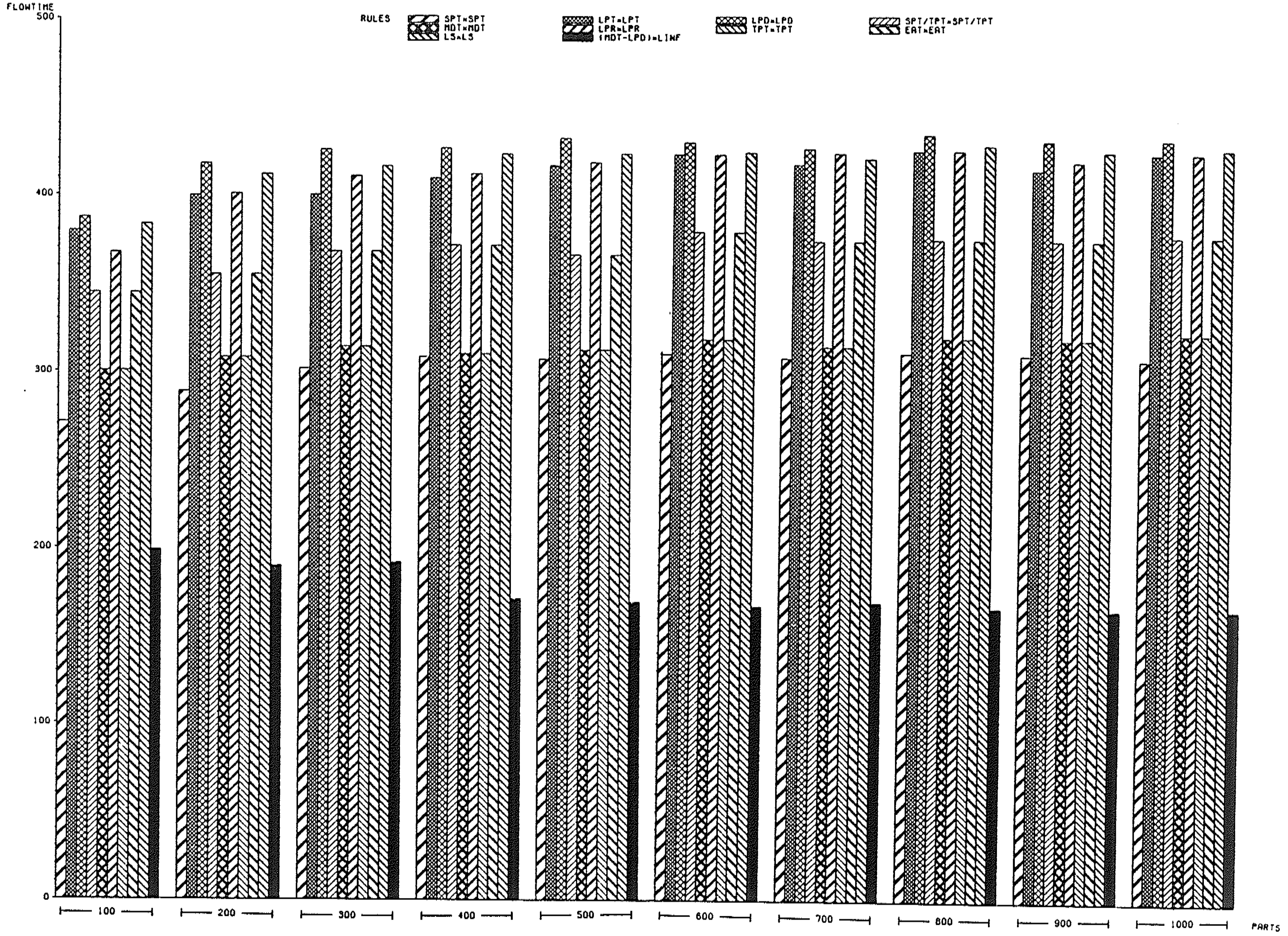


Figure 6: Comparison of scheduling rules for Wilhelm and Sarin (1985)

4.3 APPLICATION TO DOULGERI AND HIBBERD (1985)

The input data from this paper to be tested is shown in Tables 12 and 14. Tables 13 and 15 give the number of tools used on each machine for each operation of four part types and information matrix respectively.

Operation sequence	Part 1		Part 2		Part 3		Part 4	
	Mach.	Time	Mach.	Time	Mach.	Time	Mach.	Time
1	6	1.0	5	2.0	6	0.9	3 (4)	2.5
2	5	2.5	6	0.7	5	3.3	5	3.0
3	3 (4)	4.0	3 (4)	5.0	1 (2)	2.0	1 (2)	3.6
4	1 (2)	3.0	1 (2)	3.3	3 (4)	6.0	6	1.2
5	6	10	4	22	2	10		
%age	25%		25%		25%		25%	

TABLE 12

Operation (routing) sequence (Doulgeri and Hibberd 1985)

Operation sequence	Part 1	Part 2	Part 3	Part 4
1	5	4	3	3
2	2	3	6	6
3	4	3	5	5
4	2	3	4	4

TABLE 13

Tool requirement

		To					
	Load/Unload	MH1	MH2	MH3	MH4	MH5	MH6
Load/Unload	0	0.3	0.7	0.3	0.7	0.9	0.9
MH1	0.3	0	0.3	0.3	0.7	0.7	0.9
F MH2	0.7	0.3	0	0.7	0.3	0.3	0.3
R MH3	0.3	0.3	0.7	0	0.3	0.7	0.3
O MH4	0.7	0.7	0.3	0.3	0	0.7	0.3
M MH5	0.9	0.7	0.3	0.9	0.7	0	0.3
MH6	0.9	0.9	0.7	0.7	0.3	0.3	0

TABLE 14

Transport times matrix (Doulgeri and Hibberd 1985)

Operation Number	Self-Information			
	Part type 1	Part type 2	Part type 3	Part type 4
1	.102	.74	.113	.61
2	.62	.119	.57	.53
3	.42	.34	.78	.45
4	.54	.52	.31	.93

TABLE 15

Self-Information matrix

No. of part types	Parts in system	Machines	Scheduling Rules on		Mean Flow time (Minutes)
			Original Machines	Alternate Machines	
4	100	6	SPT	SPT	12.581
			LPT	LPT	12.581
			LPD	LPD	12.581
			SPT/TPT	SPT/TPT	12.581
			MDT	MDT	12.581
			LPR	LPR	12.581
			TPT	TPT	12.581
			EAT	EAT	12.581
			LS	LS	12.581
			MDT-LPD	LINF	12.581
	200		SPT	SPT	12.629
			LPT	LPT	12.629
			LPD	LPD	12.629
			SPT/TPT	SPT/TPT	12.629
			MDT	MDT	12.629
			LPR	LPR	12.629
			TPT	TPT	12.629
			EAT	EAT	12.629
			LS	LS	12.629
			MDT-LPD	LINF	12.629
	300		SPT	SPT	12.603
			LPT	LPT	12.603
			LPD	LPD	12.603
			SPT/TPT	SPT/TPT	12.603
			MDT	MDT	12.603
			LPR	LPR	12.603
			TPT	TPT	12.603
			EAT	EAT	12.603
			LS	LS	12.603
			MDT-LPD	LINF	12.603
	400		SPT	SPT	12.580
			LPT	LPT	12.580
			LPD	LPD	12.580
			SPT/TPT	SPT/TPT	12.580
			MDT	MDT	12.580
			LPR	LPR	12.580
			TPT	TPT	12.580
			EAT	EAT	12.580
			LS	LS	12.580
			MDT-LPD	LINF	12.580

TABLE 16

The performance of scheduling rules for Doulgeri and Hibberd (1985) with no time penalty

Table 16 continued

No. of part types	Parts in system	Machines	Scheduling Rules on Original Machines	Alternate Machines	Mean Flow time (Minutes)
4	500	6	SPT	SPT	12.587
			LPT	LPT	12.587
			LPD	LPD	12.587
			SPT/TPT	SPT/TPT	12.587
			MDT	MDT	12.587
			LPR	LPR	12.587
			TPT	TPT	12.587
			EAT	EAT	12.587
			LS	LS	12.587
			MDT-LPD	LINF	12.587
	600		SPT	SPT	12.593
			LPT	LPT	12.593
			LPD	LPD	12.593
			SPT/TPT	SPT/TPT	12.593
			MDT	MDT	12.593
			LPR	LPR	12.593
			TPT	TPT	12.593
			EAT	EAT	12.593
			LS	LS	12.593
			MDT-LPD	LINF	12.593
	700		SPT	SPT	12.602
			LPT	LPT	12.602
			LPD	LPD	12.602
			SPT/TPT	SPT/TPT	12.602
			MDT	MDT	12.602
			LPR	LPR	12.602
			TPT	TPT	12.602
			EAT	EAT	12.602
			LS	LS	12.602
			MDT-LPD	LINF	12.602
	800		SPT	SPT	12.600
			LPT	LPT	12.600
			LPD	LPD	12.600
			SPT/TPT	SPT/TPT	12.600
			MDT	MDT	12.600
			LPR	LPR	12.600
			TPT	TPT	12.600
			EAT	EAT	12.600
			LS	LS	12.600
			MDT-LPD	LINF	12.600

Table 16 continued

No. of part types	Parts in system	Machines	Scheduling Rules on Original Machines	Scheduling Rules on Alternate Machines	Mean Flow time (Minutes)
4	900	6	SPT	SPT	12.593
			LPT	LPT	12.593
			LPD	LPD	12.593
			SPT/TPT	SPT/TPT	12.593
			MDT	MDT	12.593
			LPR	LPR	12.593
			TPT	TPT	12.593
			EAT	EAT	12.593
			LS	LS	12.593
			MDT-LPD	LINF	12.593
	1000		SPT	SPT	12.593
			LPT	LPT	12.593
			LPD	LPD	12.593
			SPT/TPT	SPT/TPT	12.593
			MDT	MDT	12.593
			LPR	LPR	12.593
			TPT	TPT	12.593
			EAT	EAT	12.593
			LS	LS	12.593
			MDT-LPD	LINF	12.593

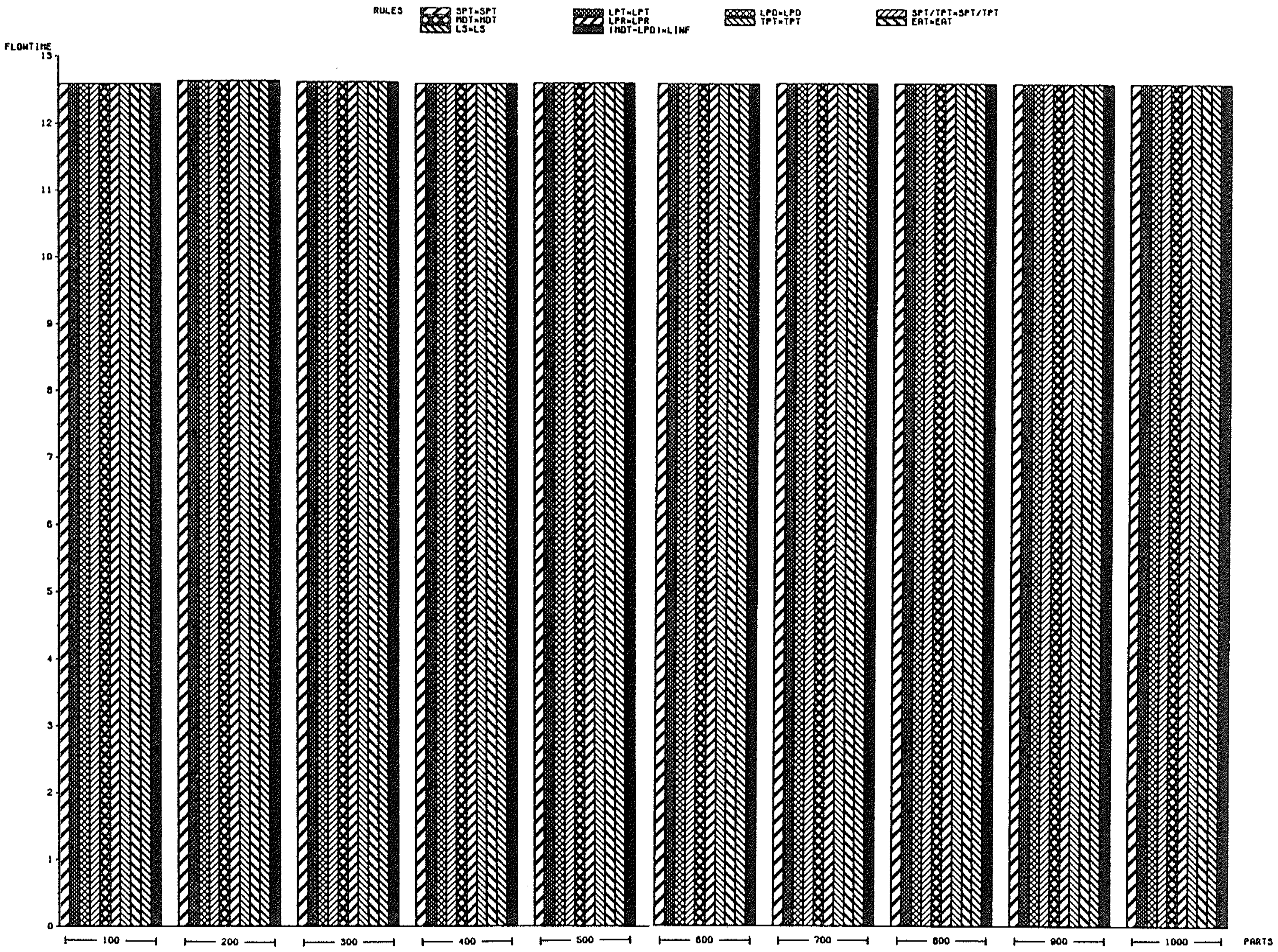


Figure 7: Comparison of scheduling rules for Doulgeri and Hibberd (1985)

4.4 EVALUATING SCHEDULING RULES

Tables 6, 11, and 16 summarize the simulation results of three problems and are displayed graphically in Figures 5, 6, and 7. The CPU time and SRB (Block Subroutine) time depending mainly upon the number of parts released and scheduling rules used, for three problems are reported in Table 17. For each problem, different simulation runs are made for 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1000 parts in total. For each fixed number of parts there are ten different runs to compare, each representing a different combination of scheduling rules on the original and alternate machines. In all, 300 simulation runs, 100 (10x10) for each problem were performed.

Observing Tables 6 and 11, and Figures 5 and 6 which display the mean flow times of the ten combinations of rules, the SPT/TPTxSPT/TPT combination (Stecke and Solberg 1981) did not perform well. Even the other rules, such as LPD for lower volumes and LPT for higher volumes performed better. The SPTxSPT combination which has been proved to be the best in most studies (Conway and Maxwell 1962, Jones 1973, Co et al. 1988, and Choi et al. 1988), and for some scheduling problems SPT produces the optimum solution (Conway 1965) takes second and third positions depending upon the type of the problem and number of parts released. Referring to Table 16 and Figure 7 , all combinations SPTxSPT, LPTxLPT, LPDxLPD, SPT/TPTxSPT/TPT etc. performed equally well when no time penalty was associated with processing times using alternate machines.

In the illustrative example, the most imminent due time (MDTxMDT) and TPTxTPT combinations exhibited very poor results for higher volumes (See Table 6 and Figure 5). Referring to Table 11 and Figure 6, the combination LPDxLPD produced the highest mean flow times for all volumes in the problem two. The combination of the difference of the MDT and LPD applied at original machines and the information-based scheduling rule LINF at alternate machines drastically reduces the mean flow time in the first two problems as well as in problem three when there is no time penalty in using alternate machines (Table 16 and Figure 7).

Problems	Range of CPU Time (Seconds)	Range of SRB Time (Seconds)
Example problem	1.21 to 59.06	0.12 to 0.21
Wilhelm and Sarin (1985)	1.07 to 47.21	0.12 to 0.18
Doulgeri and Hibberd (1985)	0.85 to 2.32	0.12 to 0.20

TABLE 17

CPU and SRB time for three problems

Chapter V

CONCLUSION

This thesis evaluated the effectiveness of heuristic scheduling rules for scheduling a flexible manufacturing system. The most important result of this study was the discovery of the information-based scheduling rule which carefully handles the uncertainty associated with the operations in a flexible manufacturing environment. Also the MDT-LPD rule obtained from two other rules has, of course, never been tested before in the literature. The combination of these two rules, MDT-LPD at original and information-based scheduling rule LINF at alternate machines is tested and compared with other well-known and popular rules such as: shortest processing time (SPT), longest processing time (LPT), and other priority rules including Stecke and Solberg's (1981) SPT/TPT suggested rule in a flexible manufacturing system where the operations of a part can be accomplished by routing the part through alternate machine sequences.

To compare and evaluate the mean flow times of the different combinations of rules at original and alternate machines, the GPSS model was developed. The logic used in the model is not only responsible for minimizing the mean flow times, but also maximizes the utilization of machines of the manufacturing system. Ten combinations of scheduling rules were tested with varying number of parts with and without time penalty incurred for alternate operations. The results obtained from the simulation runs indicate that the (MDT-LPD)xLINF combination yielded substantial reductions in mean flow times. Although this combination of rules performed equally well in case of no time penalty associated with alternate processing times, there was no time when it was even at second place. Therefore, the overall performance of the combination of these two rules is superior when compared with other scheduling rules both directly and across varying number of parts in the system.

It is interesting to note that the part priority rule that Stecke and Solberg (1981) reported as performing best in their study did not perform as well as the (MDT-LPD)xLINF. This may be because of the configuration of their flexible manufacturing system is significantly different from ours and each FMS tends to have its own individual characteristics. Therefore, the results related to one system may not be generally valid (Carrie and Perera 1986).

In summary, this study has shown that (MDT-LPD)xLINF is a viable combination of two scheduling rules for the flexible manufacturing environment and should be included in future studies comparing sequencing and scheduling rule performance.

REFERENCES

1. Acree, E. S., and Smith, M. L., "Simulation of a Flexible Manufacturing System - Applications of Computer Operating System Techniques" , Annual Simulation Symposium 1985.

2. Baker, K. R., "Introduction to Sequencing and Scheduling, Wiley, New York 1974.

3. Browne, J., Dubois, D., Rathmill, K., Sethi, S. P., and Stecke, K. E., "Classification of Flexible Manufacturing Systems" , FMS Magazine 2, 114, 1984.

4. Carrie, A. S., "The Role of Simulation in FMS" , Flexible Manufacturing Systems: Methods and Studies edited by A. Kusiak, North-Holland, Amsterdam. New York. Oxford, 1986.

5. Carrie, A.S., and Perera, D.T.S., "Work Scheduling in FMS under Tool Availability Constraints" , IJPR, Vol. 24, No. 6, 1986, pp. 1299-1308.

6. Carrie, A. S. and Petsopoulos, "Operations Sequencing in an FMS" , Robotica Vol. 3, No. 4, 1985, pp. 259-264.

7. Chang, Y. L. and Sullivan, R. S., "Real-Time Scheduling of Flexible Manufacturing Systems - A Conceptual and Mathematical Formulations" , Research Report, Graduate School of Business, The University of Texas at Austin, 1984.

8. Choi, R. H., "An analysis of Traditional Work Scheduling Rules for a Flexible Manufacturing System" , Ph.D. Dissertation, Department of Industrial Engineering, Iowa State University, Ames, Iowa 1985.

9. Choi, R. H. and Malstrom, E. M., "Evaluation of Traditional Work Scheduling Rules in a Flexible Manufacturing System with a Physical Simulator" , Journal of Manufacturing Systems, Vol. 7, No. 1, 1988, pp. 33-45.

10. Co, H. C., Jaw, T. J., and Chen, S. K., "Sequencing in Flexible Manufacturing Systems and Other Short Queue-Length Systems" , Journal of Manufacturing Systems, Vol. 7, No. 1, 1988, pp. 1-9.

11. Conway, R.W., and Maxwell, W.L., "Network Dispatching by the Shortest Operation Discipline" , Operations research, 10, 51, 1962.

12. Conway, R.W., "Priority Dispatching and Work-In-Process Inventory in a Job Shop" , Journal of Industrial Engineering, 16(2), 1965.

13. Denzler, D. R. and Boe, W. J., "Experimental Investigation of Flexible Manufacturing Systems Scheduling Decision Rules" , International Journal of Production Research, 1987, Vol. 25, No. 7, pp. 979-994, 1987.

14. Doulgeri, Z. and Hibberd, R. D., "A Simulation to develop and Assess Control Algorithm for FMS" , Proceeding of the 1st International Conference on Simulation in Manufacturing edited by W. B. Heginbotham, March 1985, Stratford-upon-Avon, UK, pp. 185-194.

15. Edward, E., Information Transmission, London: Chapman & Hall 1964.

16. Edward, J. P., "Flexible Manufacturing Systems: An Overview" , Fall Industrial Engineering Conference Nov. 13-16, 1983, pp. 639-645.

17. Erschler, J., Roubellat, F., and Thuriot, C., "Periodic Release Strategies for FMS" , presented at the TIMS/ORSA Meeting, San Francisco, CA. 1984.

18. Fazlollah, M. R., An Introduction to Information Theory, McGraw-Hill Book Company, Inc., New York, Toronto, London, 1961.

19. Finke, G. and Kusiak, A., "Network Approach to Modelling of Flexible Manufacturing Modules and Cells" , Revue Francoise d'Automatique, d'Informatique et de Recherche Operationnelle (RAIRO-APII), 1985, Vol. 19, No. 4, pp.359-370.

20. Fox, M. S., Allen, B. and Strohm, G., "Job-Shop Scheduling-An Investigation in Constraint-Directed Reasoning" , Proceedings NCAI (Pittsburgh, 1982) pp. 155-158.

21. Fox, M. S. and Smith, S. W., "ISIS-A Knowledge-Based System for Factory Scheduling" , Expert Systems, 1984, Vol. 1, No. 1, pp. 25-49.

22. French, S., "Sequencing and Scheduling, Wiley, New York 1982.

23. Garner, W. Uncertainty and Structure as Psychological Concepts, New York, John Willey, 1962.

24. Gere, W. S., "Heuristics in Job Shop Scheduling" , Management Science, 1966, 13.

25. Hart, P., Nillson, N., and Raphael, B., "A Formal Basis for the Heuristic Determination of Minimum Cost Paths" , IEEE Trans. System Science Cybernet, 1968 Vol. 4, No. 2, pp. 100-107.

26. Havrda, J.H. and Charvat, F., "Quantification Method of Classification Processes: Concept of Structural α Entropy" , Kybernetika, 1967, 3, pp. 30-35.

27. Hayes-Roth, F. and Waterman, D., Principles of Pattern-directed Inference Systems in Pattern-Directed Inference Systems, Waterman, D. and Hayes-Roth, F. (Editors), New York: Academic Press, 1978.

28. Hildebrant, R. R. and Suri, R., "Methodology and Multilevel Algorithm Structure for Scheduling and Real-Time Control of Flexible Manufacturing Systems" , Proceedings 3rd International Symposium on Large Engineering Systems, Memorial University of Newfoundland, Canada, July 1980.

29. Hildebrant, R. R., "Scheduling Flexible Machining Systems using Mean Value analysis" , IEEE Conference on decision and Control, 1980.

30. Hitz, K. L., "Scheduling of Flexible Flow Shops" , Report # LIDS-R-879, Laboratory for Information and Decision Systems, MIT, Cambridge, MA., 1979.

31. Jones, C.H., "An Economic Evaluation of Job Shop Dispatching Rules" , Management Science, 20(3), 1973.

32. Kapur, J. N., "Four Families of Measures of Entropy" , Indian Journal of Pure and Applied Mathematics, 1986, 17, pp. 429-449.

33. Kimemia, J. and Gershwin, S. B., "Network Flow Optimization in Flexible Manufacturing systems" , Proceedings of the IEEE Conference on Decision and Control, 1979.

34. Kimemia, J. and Gershwin, S. B., "An Algorithm for the Computer Control of a Flexible Manufacturing System" , IEEE Trans., 1983, Vol. 15, No. 4, pp. 353-362.

35. Kumar, V., " On Measurement of Flexibility in Flexible Manufacturing Systems: An Information-Theoretic Approach" , Proceedings of the 2nd ORSA/TIMS Conference on Flexible Manufacturing Systems: Operations Research Models and Applications (The Netherland: Elsevier Publications) edited by Kathryn E. Stecke and R. Suri, 1986, pp. 131-143.

36. Kumar, V. and Kumar. U.,(a) "Manufacturing Flexibility: A New Approach to its Measurement" , World Productivity Forum & 1987 International Industrial Engineering Conference Proceedings, 1987.

37. Kumar, V.,(b) "Entropic Measures of Manufacturing Flexibility" , IJPR, 1987 Vol. 25, No. 7, pp. 957-966.

38. Kumar, V., (b), "Entropic Measures of Manufacturing Flexibility" , IJPR, 1987, Vol. 25, No. 7, pp. 957-966.

39. Kusiak, A., "Loading Models in Flexible Manufacturing Systems" , Proceedings of VIIth International Conference on Production Research, Windsor, Canada, 1983.

40. Kusiak, A., "Flexible Manufacturing Systems: A Structural Approach" , IJPR, 1985.

41. Kusiak, A., "Scheduling Flexible Machining and Assembly Systems" , Proceedings of the Second ORSA/TIMS Conference on Flexible Manufacturing Systems: Operations Research Models and Applications, edited by K. E. Stecke and R. Suri, Elsevier Science Publishers B.V., Amsterdam, 1986.

42. Kusiak, A., (a), "Artificial Intelligence and Operations Research in Flexible Manufacturing Systems" , Information Systems and Operational research (INFOR), 1987, Vol. 25, No. 1, pp. 2-12.

43. Kusiak, A., (b), "Designing Expert Systems for Scheduling of Automated Manufacturing" , Industrial Engineering, 1987, Vol. 19, No. 7, pp. 42-46.

44. Kusiak, A., "Artificial Intelligence and CIM Systems" , in Artificial Intelligence: Computer Integrated Manufacture, edited by A. Kusiak, IFS (Publications) Ltd., Kempston, Bedford, U.K., and Springer Verlag, New York, NY, 1988.

45. Mayer, R. J. and Talavage, J. J., "Simulation of a Computerized Manufacturing Systems" , Report No. 4, NSF Grant No. APR74-15256, (November, 1976).

46. Melnyk, S.A. et al., Shop Floor Control, Dow Jones-Irvin, Homewood, Illinois, 1985.

47. Moscato, D. R., "The Application of the Entropy Measure to the Analysis of Part Commonality in a Product Line" , IJPR, 1976, Vol. 14, No. 3, pp. 401-406.

48. Newman, P. A., "Scheduling in CIM Systems" , Artificial Intelligence Implications for CIM edited by A. Kusiak, IFS (Publications) Ltd. UK, Springer-Verlag, Berlin, Heidelberg, New York, London, Tokyo, 1988.

49. Nof, S. Y., Whinston, A. B., and Bullers, W. I., "Control and Decision Support in Automatic Manufacturing Systems" , AIIE Trans., 1980, Vol. 12, No. 2, pp. 156-169.

50. O'Gorman, P., Gibbons, J., and Browne, J., "Evaluation of Scheduling Systems for a Flexible Transfer Line using a Simulation Model" , Flexible Manufacturing Systems: Methods and Studies edited by A. Kusiak, North-Holland Amsterdam, New York, Oxford, 1986.

51. Ow, P. S. and Morton, T. E., "An Investigation of Beam Search for Scheduling" , Carnegie-Mellon University, Pittsburgh, PA, 1985.

52. Panwalker, S.S. and Iskander, W., "A Survey of Scheduling Rules" , Operations Research, 1977, Vol. 25, pp. 45-61.

53. Pearl, J., "Knowledge vs. Search: A Quantitative Analysis using A*" , Artificial intelligence, 1983, 20, pp.1-13.

54. Renyi, A., "On Measures of Entropy and Information" , Proceedings of the 4th Berkeley Symposium on Mathematics, Statistics and Probability, 1961, Vol. 1, pp. 547-561

55. Sarin, S. C. and Dar-El, E. M., "Approaches to the Scheduling Problem in FMS" , 1984 Fall Industrial Engineering Conference Proceedings.

56. Shannon, C. E., "A Mathematical Theory of Communication" , Bell System Technical Journal, 1948, Vol. 27, pp. 379-423.

57. Shaw, M. J., "A Pattern-Directed Approach to FMS Scheduling" , Proceedings of the Second ORSA/TIMS Conference on Flexible Manufacturing Systems edited by Stecke, K. and Suri, R., Elsevier Science Publishers, Amsterdam, 1986.

58. Shaw, M. J., "Knowledge-Based Scheduling in Flexible Manufacturing Systems: An Integration of Pattern-Directed Inference and Heuristic Search" , IJPR, 1988, Vol. 26, No. 5, pp. 821-844.

59. Stecke, K. E., "Experimental Investigation of a Computerized Manufacturing Systems" , Unpublished M. S. Thesis, Purdue University, 1978.

60. Stecke, K. E. and Solberg, J. J., "Loading and Control Policies for a Flexible Manufacturing System" , IJPR, 1981, Vol. 19, No. 5, pp. 481-490.

61. Stecke, K. E., "Formulation and Solution of Nonlinear Integer Production Planning Problems for Flexible Manufacturing Systems" , Management Science, 1983, Vol. 29, No. 3, pp. 273-288.

62. Stecke, K. E., "Design, Planning, Scheduling and Control Problems of Flexible Manufacturing Systems" , Proceedings of TIMS-ORSA Conference on FMS (August 1984), 2-7.

63. Thomas, J. Schriber, Simulation using GPSS, John Wiley & Sons, New York, London, Sydney, Toronto, 1974.

64. Wiener, N., "Cybernetics, New York, John Willey, 1948.

65. Wilhelm, W. E. and Shin, Hyun-Myung, "Effectivness of Alternate Operations in a Flexible Manufacturing System" , IJPR, 1985, Vol. 23, No. 1, pp. 65-79.

66. William L. B., "Priority Scheduling and Inventory Control in Job Lot Manufacturing Systems" , IEEE Trans., 1972, pp. 267-276.

67. William, E. and Newman J., "Model to Evaluate the Benefits of FMS Pallet Flexibility" , Proceedings of the Second ORSA/TIMS Conference on Flexible Manufacturing Systems: Operation Research Models and Applications edited by K. E. Stecke and R. Suri, Elsevier Science Publishers B.V., Amsterdam, 1986.

68. Yao, D. D., "Material and Information Flow in Flexible Manufacturing Systems" , Material Flow (Special Issue in Flexible Manufacturing Systems), 1986.

Appendix A

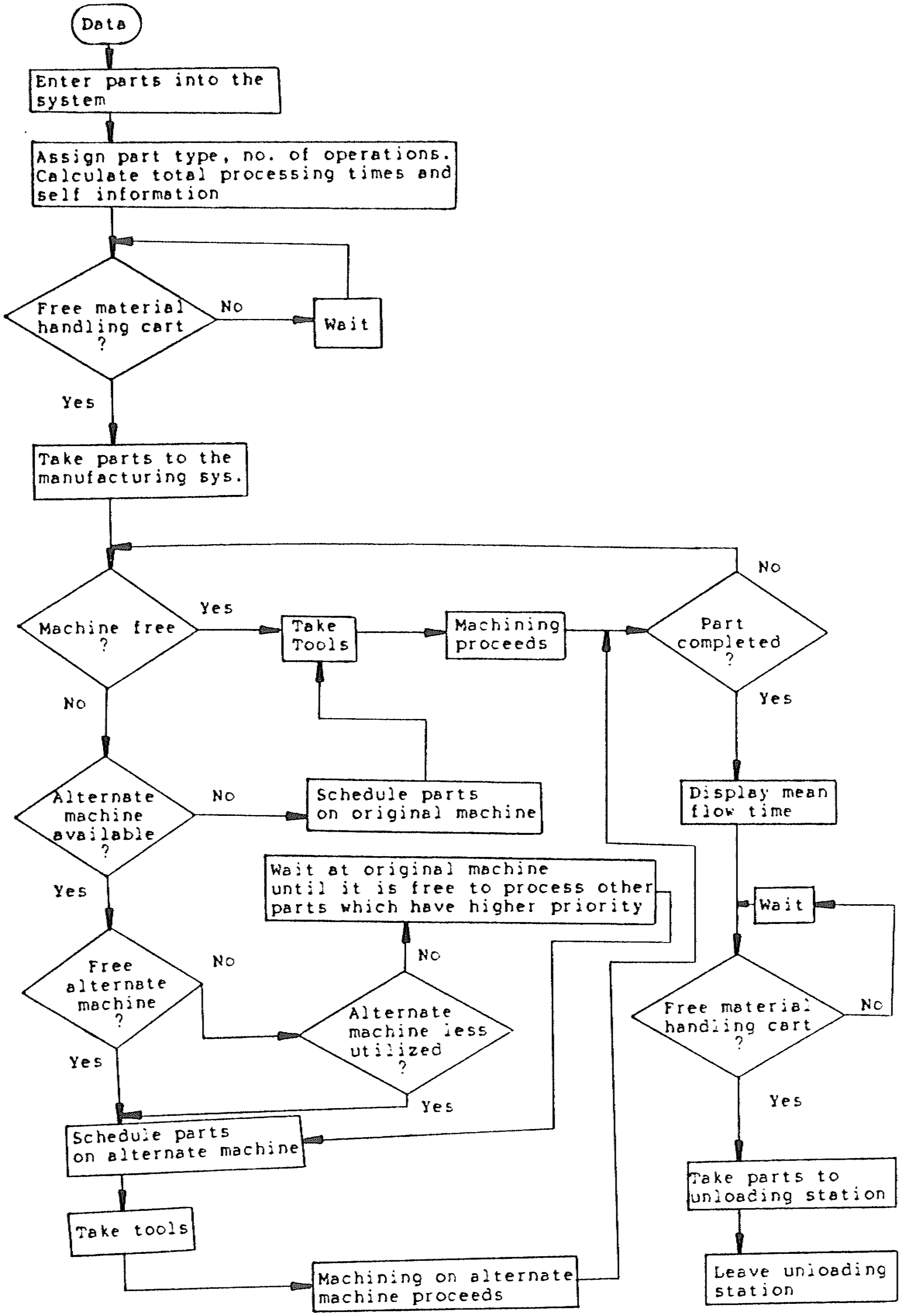
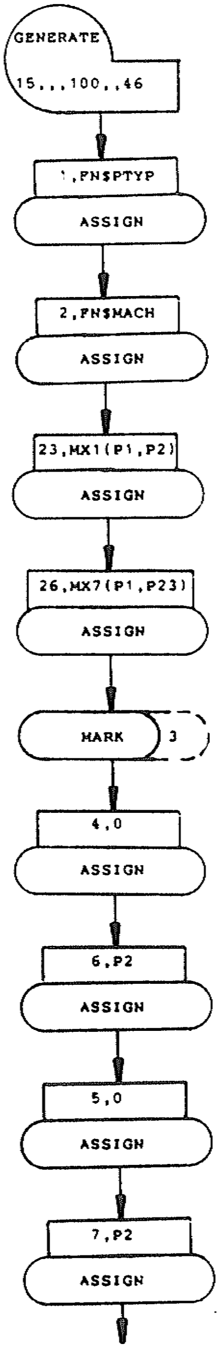


Figure 8: Flow Diagram of the model control

Appendix B

Loading section



PARTS ENTER LOAD/UNLOAD AREA EVERY 15 MINUTES

P1 CARRIES PART TYPE

P2 STORES TOTAL NO. OF OPERATIONS

PUT FIRST MACHINE NO. INTO PARAMETER P23

STORE TRANSPORT TIME FROM LOADING AREA TO THAT MACHINE IN PARAMETER P26

GENERATION TIME

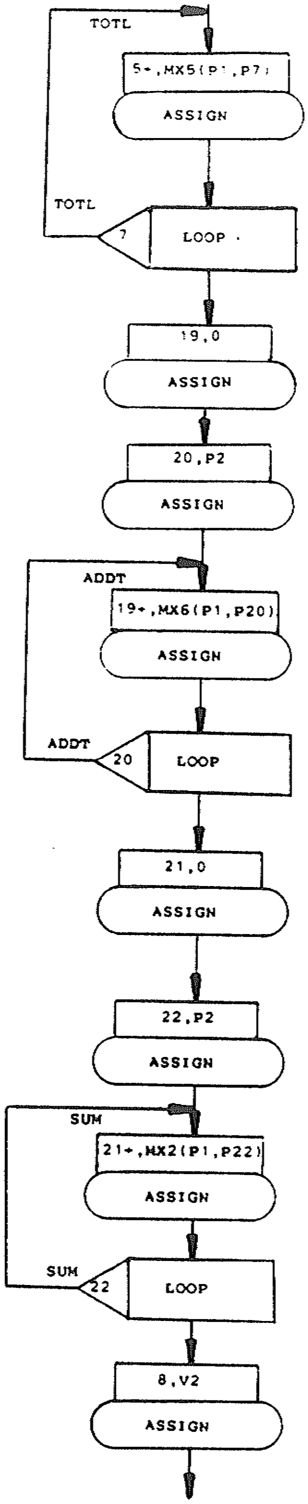
INITIALIZE P4=0

SET P6=P2

INITIALIZE TOTAL ALTERNATE PROCESSING TIME TO ZERO

SET P7=P2 FOR COMPUTATION

Figure 9: The GPSS Block Diagram of the model



SUM ALTERNATE PROCESSING TIMES AND

REPEAT UNTIL IT'S DONE FOR ALL OPERATIONS

TOTAL SELF-INFORMATION=0

SET P20=P2 FOR COMPUTATION PURPOSES

P19 CARRIES TOTAL SELF-INFORMATION

LOOP BACK TO ADD SELF-INFORMATION FOR NEXT OPERATION (IF ANY)

INITIALIZATION OF TOTAL

PROCESSING TIME ON ORIGINAL MACHINES

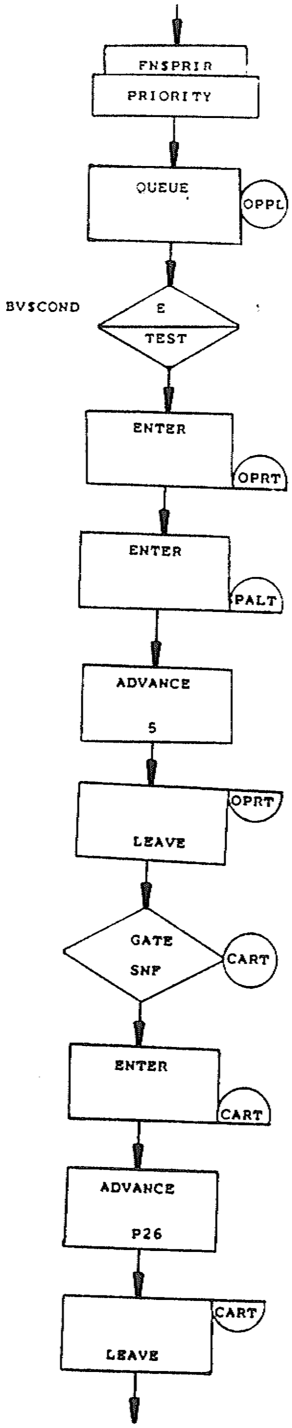
PUT NO. OF OPERATIONS IN PARAMETER P22

START ADDING ORIGINAL PROCESSING TIMES

GO BACK TO ADD PROCESSING FOR NEXT OPERATION (IF ANY)

COMPUTE THE MOST IMMINENT DUE TIME

Figure 9 continued



GIVE PRIORITY TO PARTS

GET INTO LINE

HOLD UNTIL OPERATOR AND
PALLET ARE AVAILABLE

OPERATOR IS READY TO
LOAD PART ON PALLET

PALLET IS ALSO AVAILABLE

THE OPERATOR TAKES 5 MINUTES
TO LOAD PART ON A PALLET

OPERATOR HAS DONE HIS/HER
DUTY

HOLD THE PART AT ITS LOADING
STATION UNTIL CART IS READY
TO DELIVER IT

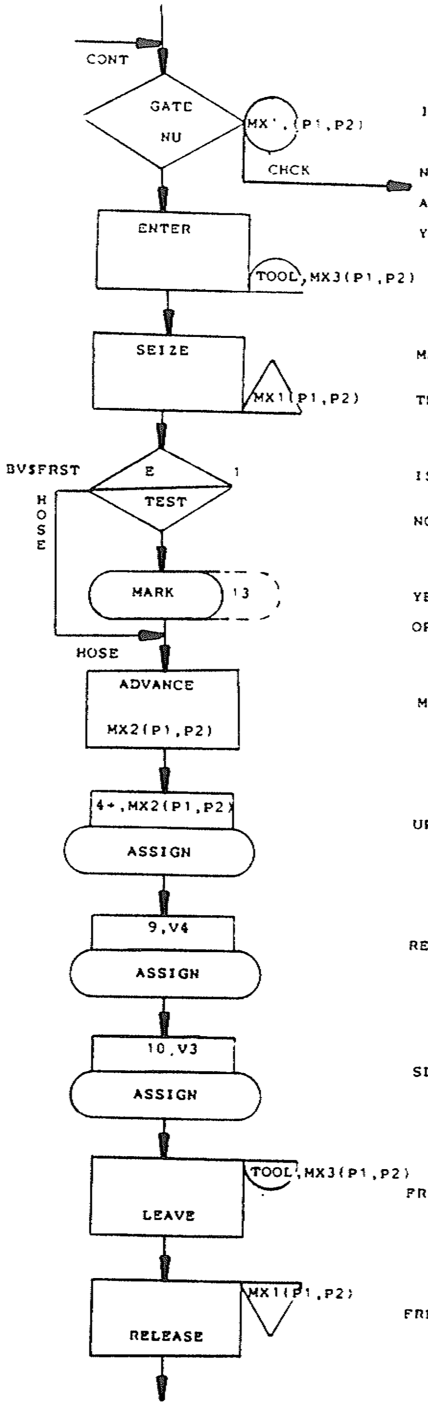
CART TAKES PART TO DELIVER IT

THIS TAKES TIME STORED IN
PARAMETER P26

CART CAN DELIVER NEXT PART
WAITING TO BE DELIVERED

Figure 9 continued

Processing on original machines



IS MACHINE FREE ?

NO, CHECK IF ALTERNATE IS AVAILABLE

YES, TAKE TOOLS

MACHINE IS READY TO PERFORM THE OPERATION

IS THIS FIRST OPERATION ?

NO, PROCESS THE PART

YES, MARK TIME WHEN FIRST OPERATION BEGINS

MACHINING TAKES PLACE

UPDATE PROCESSING TIME

REMAINING PROCESSING TIME

SLACK TIME

FREE THE TOOLS

FREE THE MACHINE

Figure 9 continued

Updating operations (Testing segment)

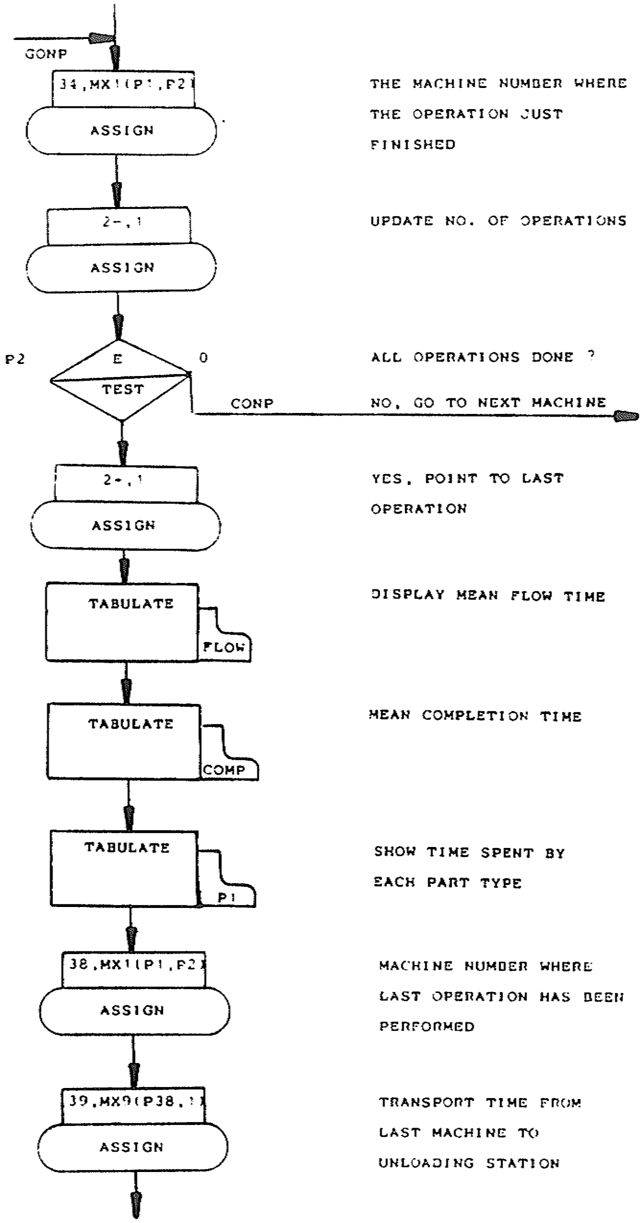
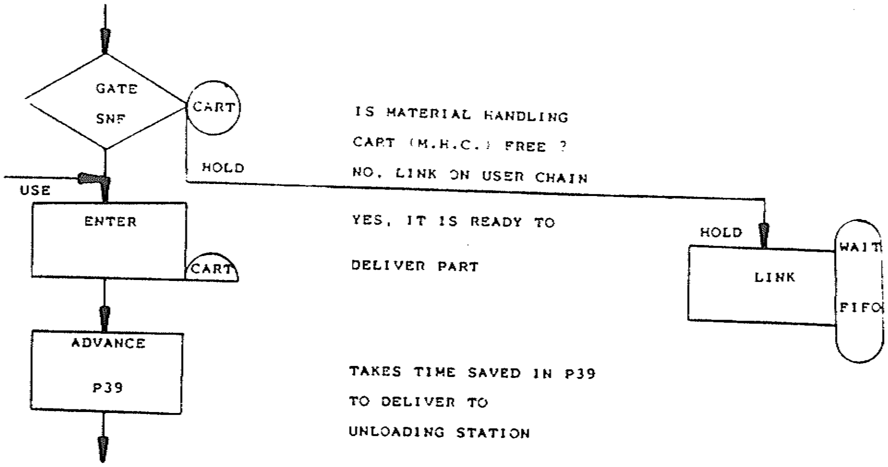


Figure 9 continued

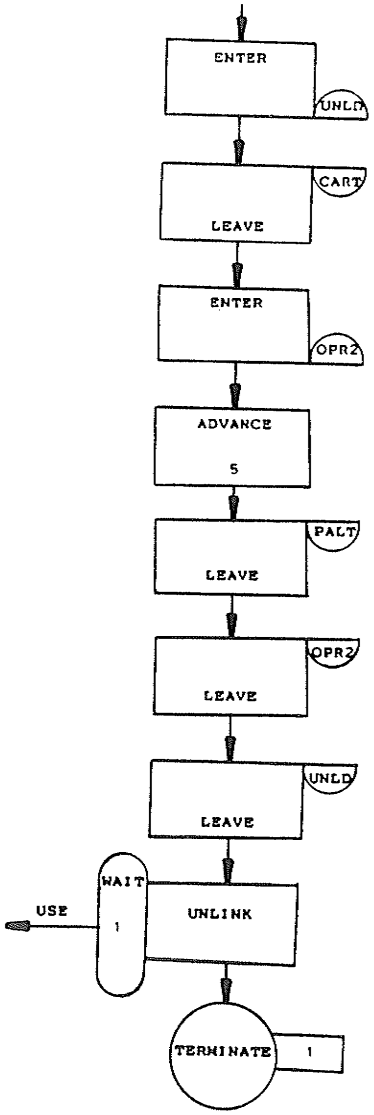


IS MATERIAL HANDLING CART (M.H.C.) FREE ?
NO, LINK ON USER CHAIN
YES, IT IS READY TO DELIVER PART

TAKES TIME SAVED IN P39 TO DELIVER TO UNLOADING STATION

Figure 9 continued

Depalletizing parts at unloading area



CART WITH PART ON PALLET
REACHED AT UNLOADING
STATION AND READY TO BE
UNLOADED FROM CART

CART IS FREE TO DELIVER
MORE PARTS

OPERATOR IN UNLODING
SECTION IS READY TO
REMOVE PART FROM PALLET

TAKES 5 MINUTES TO
REMOVE IT

THAT PALLET IS FREE
FOR RELOADING

OPERATOR NOW CAN REMOVE
NEXT PART

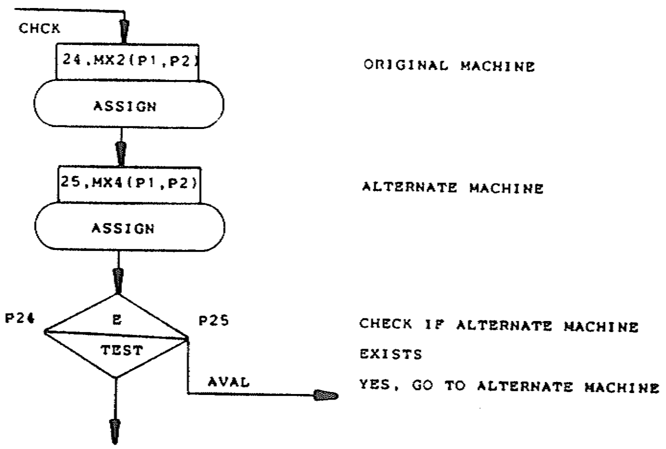
PART LEAVES ITS UNLOADING
STATION

NEXT WAITING PART (IF ANY)
CAPTURES THE CART

LEAVE THE SYSTEM

Figure 9 continued

Existence of alternate machines



Scheduling and processing on original machines

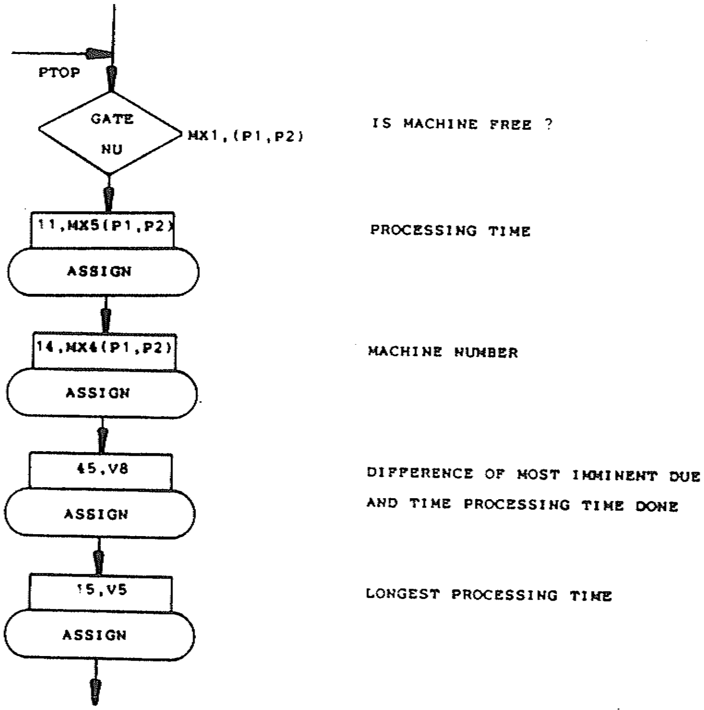


Figure 9 continued

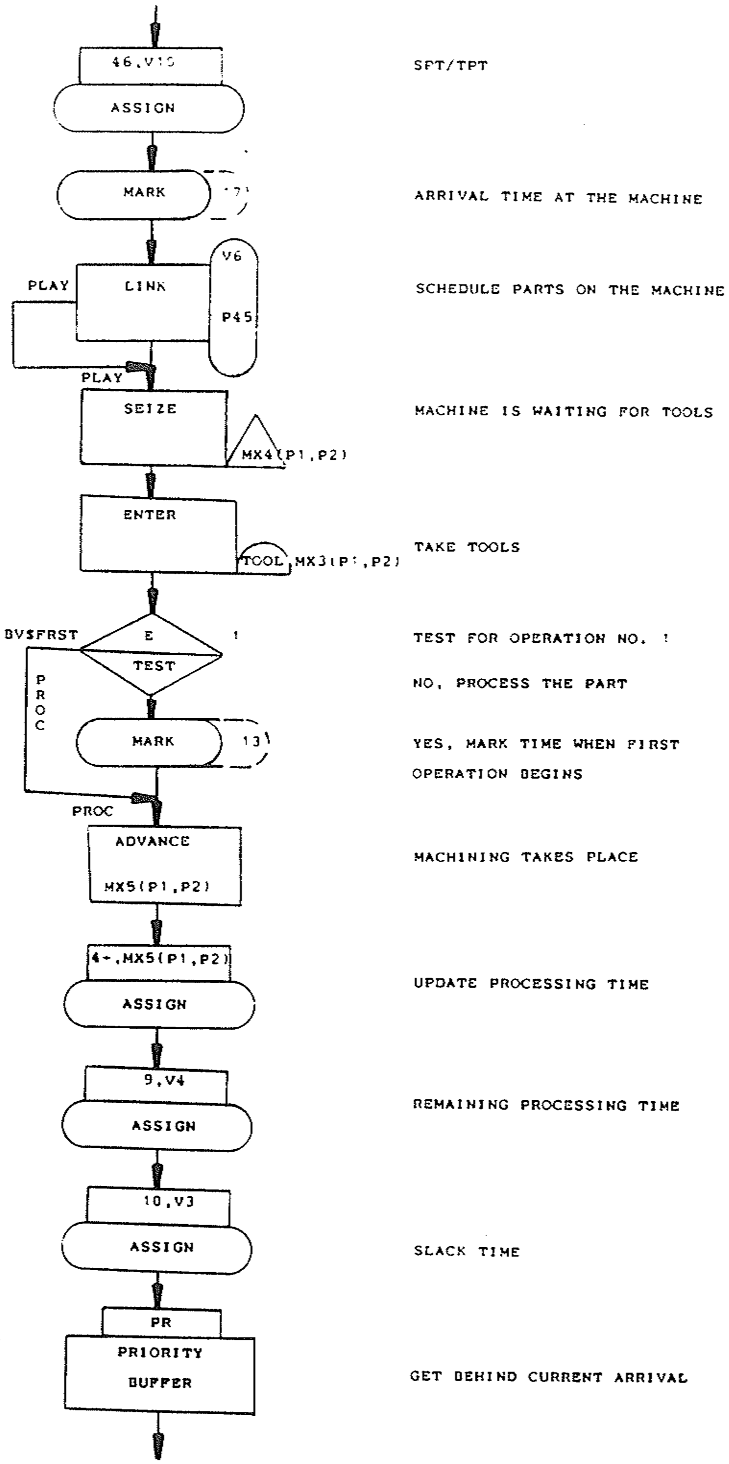
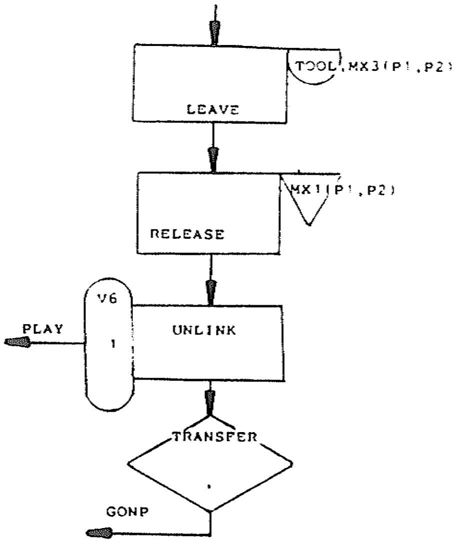


Figure 9 continued



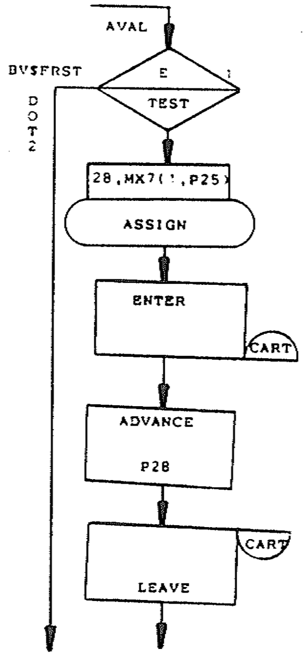
FREE THE TOOLS

FREE THE MACHINE

PROCESS NEXT SCHEDULED PART (IF ANY)

RETURN TO UPDATING SECTION

Part delivery from loading area to alternate machines



TEST FOR OPERATION NUMBER ONE

TRANSIT TIME FROM LOADING STATION TO ALTERNATE MACHINE

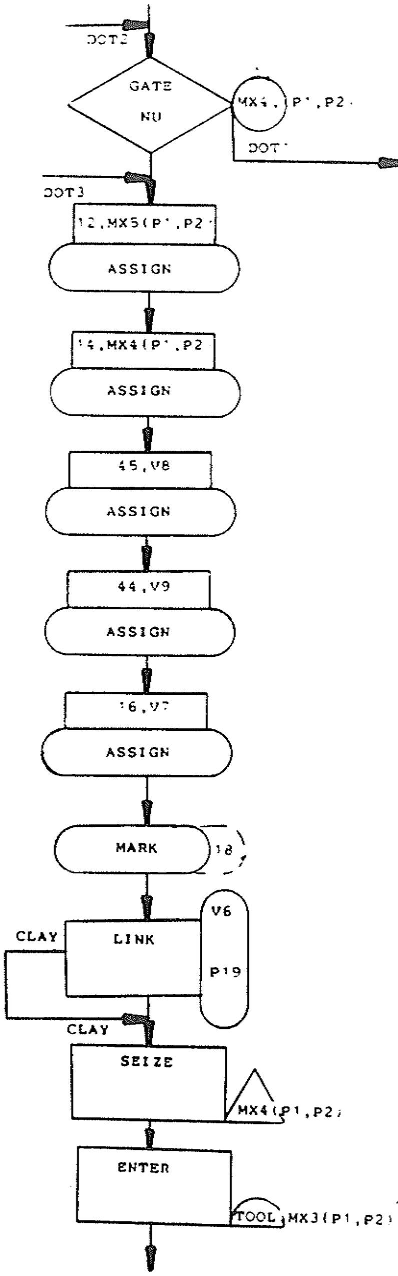
ENGAGE MATERIAL HANDLING CART

TAKES TIME STORED IN PARAMETER P28

FREE THE CART

Figure 9 continued

Scheduling and processing on alternate machines



IS ALTERNATE MACHINE FREE ?

NO, TEST UTILIZATION

YES, POINT TO CURRENT PROCESSING TIME

MACHINE NUMBER

DIFFERENCE OF MOST IMMINENT DUE TIME AND PROCESSING TIME DONE

LONGEST PROCESSING TIME

SPT/TPT

ARRIVAL TIME AT ALTERNATE MACHINE

SCHEDULE PARTS ON THAT MACHINE

MACHINE IS WAITING FOR TOOLS

TAKE TOOLS

Figure 9 continued

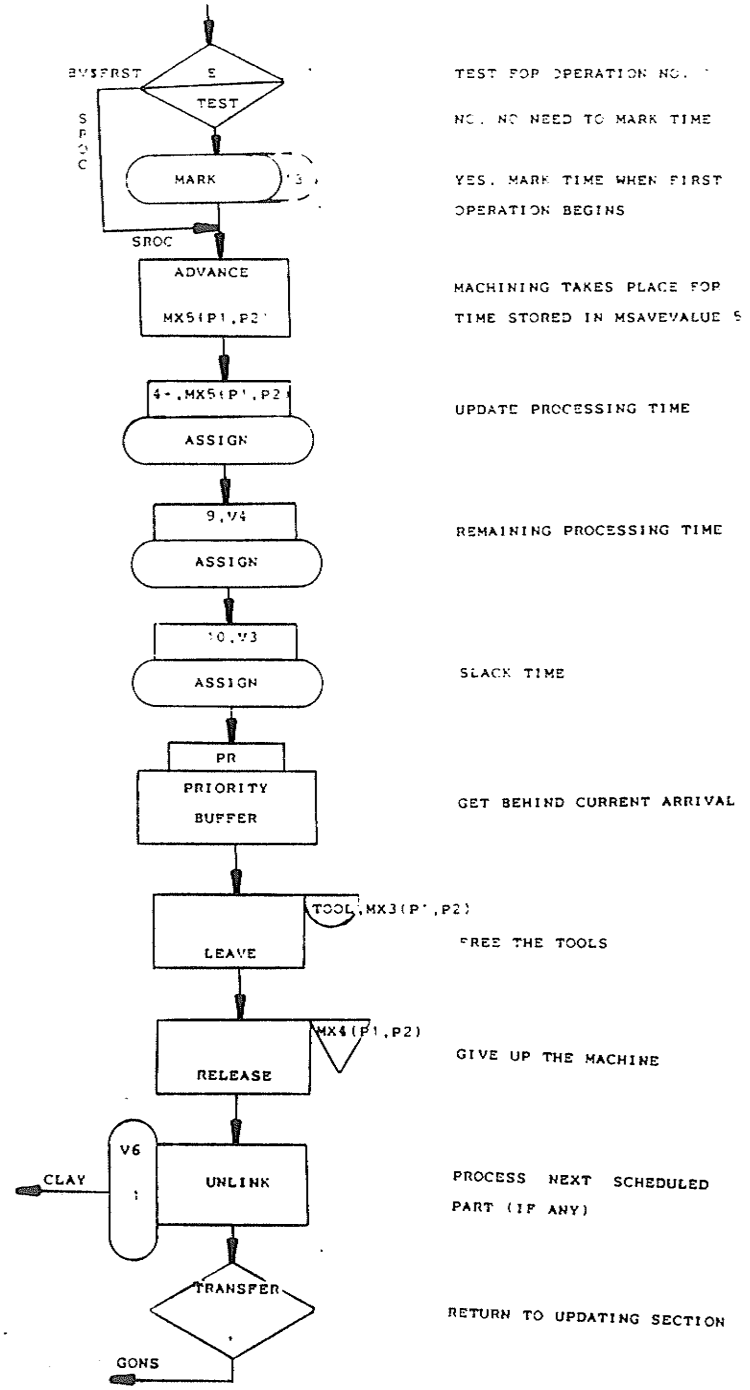


Figure 9 continued

Operation updating for parts coming from alternate machines

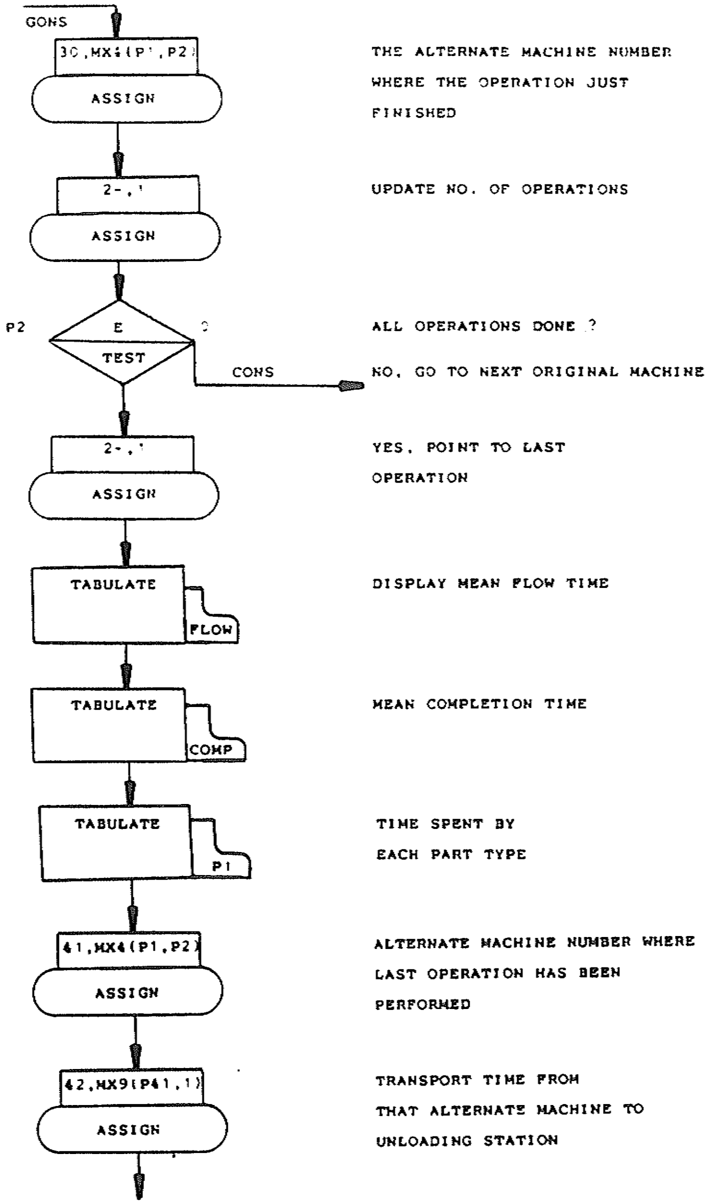
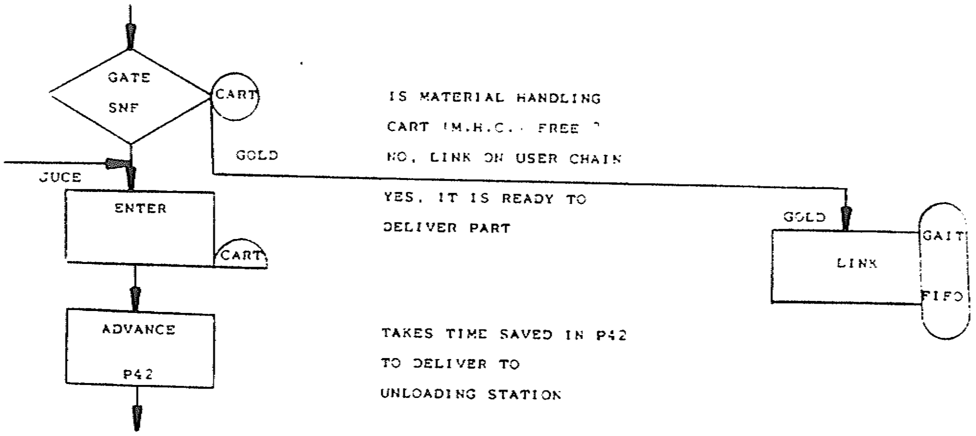


Figure 9 continued



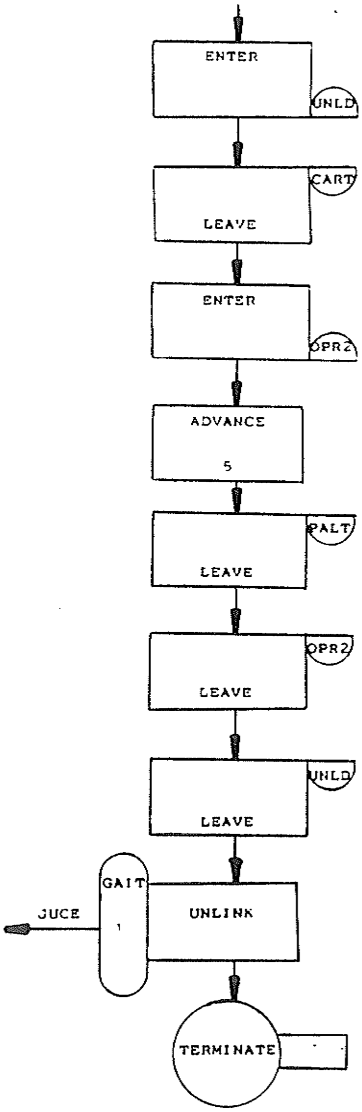
IS MATERIAL HANDLING
CART (M.H.C.) FREE ?
NO, LINK ON USER CHAIN

YES, IT IS READY TO
DELIVER PART

TAKES TIME SAVED IN P42
TO DELIVER TO
UNLOADING STATION

Figure 9 continued

Depalletizing of parts coming from alternate machines



CART WITH PART ON PALLET
REACHED AT UNLOADING
STATION AND READY TO BE
UNLOADED FROM CART
CART IS FREE TO DELIVER
MORE PARTS

OPERATOR IN UNLODING
SECTION IS READY TO
REMOVE PART FROM PALLET

TAKES 5 MINUTES TO
REMOVE IT

THAT PALLET IS FREE
FOR RELOADING

OPERATOR IS FREE TO DEPALLETIZE
OTHER WAITING PARTS

PART LEAVES ITS UNLOADING
STATION

NEXT WAITING PART (IF ANY)
CAPTURES THE CART

LEAVE THE SYSTEM

Figure 9 continued

Utilization section

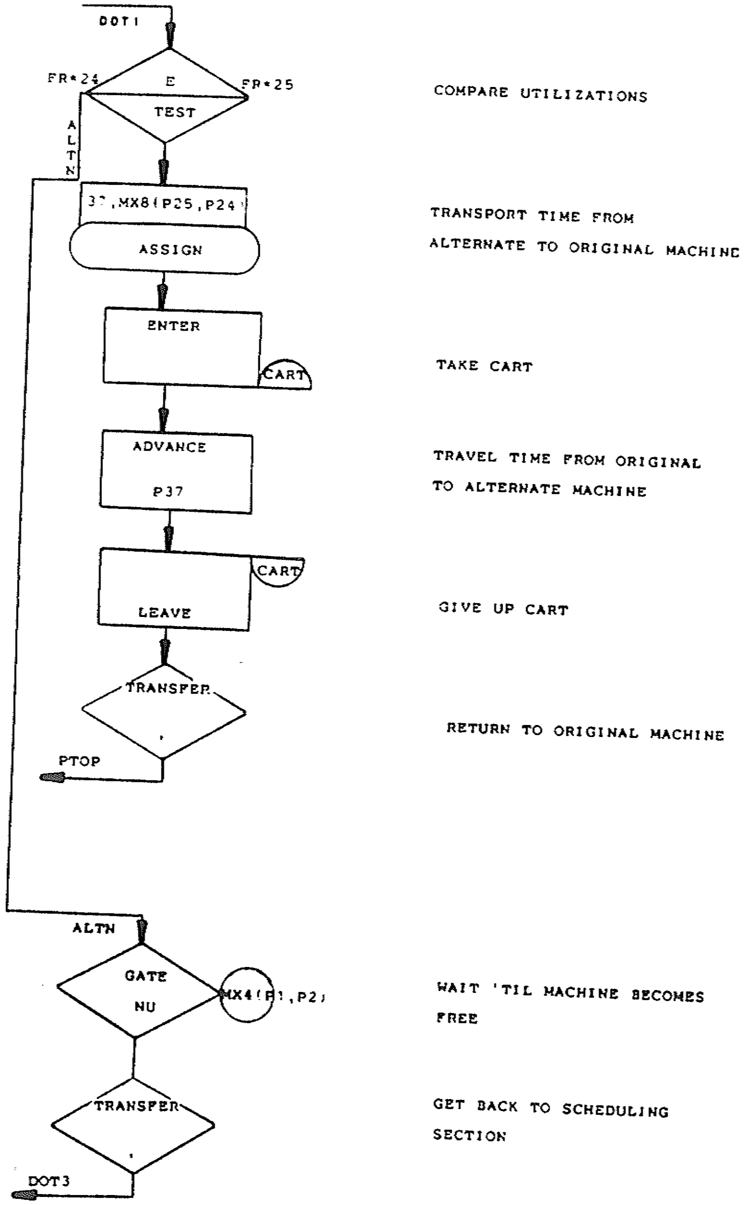
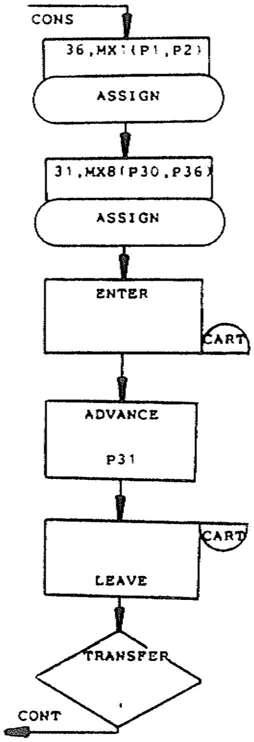


Figure 9 continued

Part delivery from alternate to next original machine



ORIGINAL MACHINE NUMBER

TRANSPORT TIME FROM CURRENT ALTERNATE TO NEXT ORIGINAL MACHINE

CAPTURE THE MATERIAL HANDLING CART

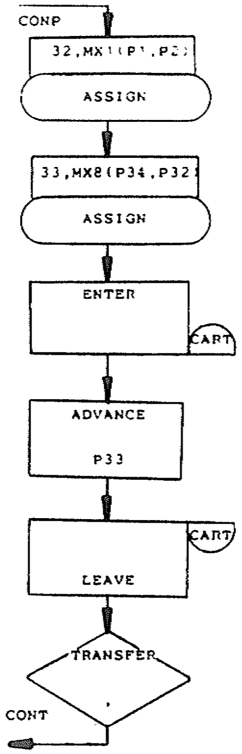
GO TO NEXT MACHINE

FREE THE CART

CHECK IF THAT MACHINE IS FREE

Figure 9 continued

Part delivery from current original to next original machine



CURRENT ORIGINAL MACHINE NUMBER

TRANSPORT TIME FROM CURRENT ORIGINAL TO NEXT ORIGINAL MACHINE

ENGAGE THE MATERIAL HANDLING CART

DELIVER PART TO NEXT MACHINE

FREE THE CART

CHECK IF THAT MACHINE IS NOT BUSY

Figure 9 continued

Appendix C

```
       REALLOCATE FAC,6,STO,8,QUE,1
       REALLOCATE XAC,1000,CHA,20,FUN,10,FSV,1
       REALLOCATE LOG,20,BLO,200,HMS,1
       REALLOCATE HSV,1,TAB,6,VAR,20,BVR,5,COM,123522
BLOCK                                                                                              CARD
NUMBER  *LOC   OPERATION  A,B,C,D,E,F,G             COMMENTS                                       NUMBER
                                                                                                        5
        ******************************************************************                              6
        *                                                                *                              7
        *                                                                *                              8
        *      SIMULATION OF SCHEDULING RULES IN FMS                     *                              9
        *                                                                *                             10
        *                                                                *                             11
        ******************************************************************                             12
        *                                                                                              13
        *                                                                                              14
               SIMULATE                                                                                15
        *****************************************************************                              16
        *                                                               *                              17
        *      FUNCTION DEFINITIONS                                     *                              18
        *                                                               *                              19
        *****************************************************************                              20
        *                                                                                              21
         MACH  FUNCTION   P1,D3                 NO. OF OPERATIONS FOR EACH                             22
        1,5/2,5/3,5                             PART TYPE .                                            23
        *                                                                                              24
         PTYP  FUNCTION   RN1,D3                PART TYPE DISTRIBUTION .                               25
        .20,1/.40,2/1,3                                                                                26
        *                                                                                              27
         PRIR  FUNCTION   RN1,D3                PART PRIORITY DISTRIBUTION .                           28
        .20,1/.40,2/1,3                                                                                29
        *                                                                                              30
        *                                                                                              31
        *****************************************************************                              32
        *                                                               *                              33
        *      STORAGE CAPACITY DEFINITIONS                             *                              34
        *                                                               *                              35
        *****************************************************************                              36
        *                                                                                              37
        *                                                                                              38
               STORAGE    S$CART,1              PROVIDE 1 MATERIAL HANDELING                           39
        *                                       CART .                                                 40
        *                                                                                              41
               STORAGE    S$OPRT,1              PROVIDE 1 OPERATOR AT                                  42
        *                                       LOADING SECTION OF LOAD/UNLOAD                         43
        *                                       AREA .                                                 44
```

Figure 10: Program Listing for the model

```
*
       STORAGE    S$OPR2,1             PROVIDE 1 OPERATOR AT
*                                      UNLOADING SECTION .
*
       STORAGE    S$PALT,20            PROVIDE 20 PALLETS .
*
*
       STORAGE    S$TOOL,20            20 TOOLS AVAILABLE .
*
*
       STORAGE    S$UNLD,10            PROVIDE 10 LOADING/UNLOADING
*                                      STATIONS .
*
*
******************************************************************
*                                                                *
*      MATRIX SAVEVALUE DECLERATIONS/INITIALIZATIONS             *
*                                                                *
******************************************************************
*
*
 1     MATRIX     X,3,5                MATRIX OF OPERATION SEQUENCES .
*
       INITIAL    MX1(1,1),6/MX1(1,2),5/MX1(1,3),3/MX1(1,4),4
       INITIAL    MX1(1,5),1
       INITIAL    MX1(2,1),4/MX1(2,2),5/MX1(2,3),6/MX1(2,4),2
       INITIAL    MX1(2,5),3
       INITIAL    MX1(3,1),2/MX1(3,2),3/MX1(3,3),4/MX1(3,4),5
       INITIAL    MX1(3,5),1
*
 2     MATRIX     X,3,5                MATRIX OF MACHINING TIMES .
*
       INITIAL    MX2(1,1),10/MX2(1,2),15/MX2(1,3),22/MX2(1,4),25
       INITIAL    MX2(1,5),20
       INITIAL    MX2(2,1),22/MX2(2,2),17/MX2(2,3),12/MX2(2,4),15
       INITIAL    MX2(2,5),20
       INITIAL    MX2(3,1),10/MX2(3,2),12/MX2(3,3),15/MX2(3,4),20
       INITIAL    MX2(3,5),24
*
 3     MATRIX     X,3,5                TOOL MATRIX .
*
       INITIAL    MX3(1,1),5/MX3(1,2),2/MX3(1,3),4
       INITIAL    MX3(1,4),2/MX3(1,5),5
       INITIAL    MX3(2,1),4/MX3(2,2),3/MX3(2,3),3
       INITIAL    MX3(2,4),3/MX3(2,5),6
       INITIAL    MX3(3,1),2/MX3(3,2),5/MX3(3,3),3/MX3(3,4),6
       INITIAL    MX3(3,5),7
```

Figure 10 continued

```
*
 4      MATRIX      X,3,5                   ALTERNATE OPERATION
*                                           SEQUENCES MATRIX .
        INITIAL     MX4(1,1),6/MX4(1,2),5/MX4(1,3),3/MX4(1,4),4
        INITIAL     MX4(1,5),3
        INITIAL     MX4(2,1),4/MX4(2,2),5/MX4(2,3),6/MX4(2,4),2
        INITIAL     MX4(2,5),4
        INITIAL     MX4(3,1),2/MX4(3,2),3/MX4(3,3),4/MX4(3,4),4
        INITIAL     MX4(3,5),1
*
 5      MATRIX      X,3,5                   ALTERNATE OPERATION TIME
*                                           MATRIX .
        INITIAL     MX5(1,1),10/MX5(1,2),15/MX5(1,3),22/MX5(1,4),25
        INITIAL     MX5(1,5),25
        INITIAL     MX5(2,1),22/MX5(2,2),17/MX5(2,3),12/MX5(2,4),15
        INITIAL     MX5(2,5),25
        INITIAL     MX5(3,1),10/MX5(3,2),12/MX5(3,3),15/MX5(3,4),25
        INITIAL     MX5(3,5),24
*
 6      MATRIX      X,3,5                   INFORMATION MATRIX FOR
*                                           ALTERNATE MACHINING TIMES.
*
        INITIAL     MX6(1,1),98/MX6(1,2),78/MX6(1,3),64
        INITIAL     MX6(1,4),59/MX6(1,5),59
        INITIAL     MX6(2,1),61/MX6(2,2),73/MX6(2,3),87
        INITIAL     MX6(2,4),78/MX6(2,5),56
        INITIAL     MX6(3,1),93/MX6(3,2),85/MX6(3,3),75
        INITIAL     MX6(3,4),53/MX6(3,5),55

*
 7      MATRIX      X,1,6                   TRANSPORT TIMES FROM LOADING
*                                           SECTION TO MACHINES .
*
        INITIAL     MX7(1,1),3/MX7(1,2),7/MX7(1,3),3
        INITIAL     MX7(1,4),5/MX7(1,5),6/MX7(1,6),6
*
 8      MATRIX      X,6,6                   TRANSPORT TIMES BETWEEN
*                                           MACHINES .
*
        INITIAL     MX8(1,1),0/MX8(1,2),3/MX8(1,3),3
        INITIAL     MX8(1,4),1/MX8(1,5),5/MX8(1,6),2
        INITIAL     MX8(2,1),3/MX8(2,2),0/MX8(2,3),6
        INITIAL     MX8(2,4),3/MX8(2,5),3/MX8(2,6),4
        INITIAL     MX8(3,1),3/MX8(3,2),6/MX8(3,3),0
        INITIAL     MX8(3,4),3/MX8(3,5),2/MX8(3,6),3
        INITIAL     MX8(4,1),1/MX8(4,2),3/MX8(4,3),3
```

Figure 10 continued

```
       INITIAL    MX8(4,4),0/MX8(4,5),2/MX8(4,6),3
       INITIAL    MX8(5,1),5/MX8(5,2),3/MX8(5,3),2
       INITIAL    MX8(5,4),2/MX8(5,5),0/MX8(5,6),3
       INITIAL    MX8(6,1),2/MX8(6,2),4/MX8(6,3),3
       INITIAL    MX8(6,4),3/MX8(6,5),3/MX8(6,6),0
*
*
 9     MATRIX     X,6,1                TRAVEL TIME FROM MACHINES
*                                      TO UNLOADING SECTION .
*
       INITIAL    MX9(1,1),3/MX9(2,1),7/MX9(3,1),3
       INITIAL    MX9(4,1),5/MX9(5,1),6/MX9(6,1),6
*
*******************************************************************
*                                                                 *
*      VARIABLE DEFINITIONS                                       *
*                                                                 *
*******************************************************************
*
*
*
 1     VARIABLE   3                    FACTOR FOR DUE TIME.
 2     VARIABLE   MP3+P5*V1            THE MOST IMMINENT DUE TIME.
 3     VARIABLE   P8-P9                JOB SLACK.
*
 4     VARIABLE   P5-P4                REMAINING PROCESSING TIME.
 5     VARIABLE   0-P11                LONGEST PROCESSING TIME ON
*                                      ORIGINAL MACHINES.
 6     VARIABLE   6+P14                USER CHAIN FOR EACH MACHINE.
 7     VARIABLE   P12/P5               SPT/TPT (STECKE & SOLEBERG'S
*                                      BEST RULE ON ALTERNATE MACHINES.
 8     VARIABLE   P8-P4                DIFFERENCE BETWEEN THE MOST
*                                      IMMINENT DUE TIME & PROCESSING
*                                      TIME DONE.
 9     VARIABLE   0-P12                LONGEST PROCESSING TIME ON
*                                      ALTERNATE MACHINES.

 10    VARIABLE   P11/P21              SPT/TPT (STECKE & SOLEBERG'S
*                                      BEST RULE ON ORIGINAL MACHINES.
*
*
```

Figure 10 continued

```
*****************************************************************
*                                                               *
*      BOOLEAN VARIABLE DEFINITIONS                             *
*                                                               *
*****************************************************************
*
*
 COND  BVARIABLE  SNF$PALT*SNF$OPRT    LOADING CONDITION AT LOADING
*                                      SECTION .
*
 FRST  BVARIABLE  P2'E'P6              TEST FOR OPERATION# 1.
*
*
*
****************************************************************
*                                                              *
*      TABLE DEFINITIONS                                       *
*                                                              *
****************************************************************
*
*
 1     TABLE      M1,50,10,10          PART TYPE 1'S RESIDENCE TIME.*
*
 2     TABLE      M1,50,10,10          PART TYPE 2'S RESIDENCE TIME.*
*
 3     TABLE      M1,50,10,10          PART TYPE 3'S RESIDENCE TIME.*
*
 4     TABLE      M1,50,10,10          PART TYPE 4'S RESIDENCE TIME.*
*
*                                      [* COMPLETION TIME FOR EACH PART
*                                         TYPE (ARRIVAL + MANUF.TIME) ]
*
 FLOW  TABLE      MP13,10,10,13        TABLE FOR PART FLOW TIME.
*
*
 COMP  TABLE      MP3,10,10,13         TABLE FOR COMPLETION TIME.
*
```

Figure 10 continued

```
            *
            *
            ******************************************************************
            *                                                                *
            *       LOADING SEGMENT                                          *
            *                                                                *
            ******************************************************************
            *
  1                GENERATE   15,,,100,,46          PARTS ARRIVE AT LOADING SECTION
            *                                       EVERY 15 MINUTES.
  2                ASSIGN     1,FN$PTYP             SET P1=PART TYPE.
  3                ASSIGN     2,FN$MACH             SET P2=TOTAL # OF OPERATIONS
            *                                       FOR EACH PART TYPE.
  4                ASSIGN     23,MX1(P1,P2)         SET P23=VERY FIRST ORIGINAL MACH.
            *                                       TO PERFORM 1ST OPERATION.
  5                ASSIGN     26,MX7(1,P23)         TRANSIT TIME FROM LOADING STATION
            *                                       TO THE FIRST ORIGINAL MACHINE.
  6                MARK       3                     GENERATION TIME.
  7                ASSIGN     4,0                   INITIALIZE PROCESSING TIME DONE.
  8                ASSIGN     6,P2                  P6=P2 (TO CHECK FOR IST OPER.).
  9                ASSIGN     5,0                   INITIALIZE TOTAL PROCESSING TIME
            *                                       FOR ALTERNATE ROUTE.
 10                ASSIGN     7,P2                  SET P7=P2 (FOR COMPUTATIONS).
 11         TOTL   ASSIGN     5+,MX5(P1,P7)         ADD PROCESSING TIME FOR ALTERNATE
            *                                       ROUTING SEQ. REQUIRED BY A PART.
 12                LOOP       7,TOTL                REPEAT FOR ALL OPERATIONS
            *                                       REQUIRED BY THAT PART.
 13                ASSIGN     19,0                  INITIALIZE SELF INFORMATION.
 14                ASSIGN     20,P2                 SET P20=P2 (FOR COMPUTATIONS).
 15         ADDT   ASSIGN     19+,MX6(P1,P20)       ADD SELF-INFORMATION OF A PART.
 16                LOOP       20,ADDT               REPEAT FOR ALL OPERATIONS TO
            *                                       CALCULATE TOTAL INFORMATION OF
            *                                       A PART.
 17                ASSIGN     21,0                  INITIALIZE TOTAL PROCESSING
            *                                       TIME ON ORIGINAL MACHINES.
 18                ASSIGN     22,P2                 FOR COMPUTATIONS.
 19         SUM    ASSIGN     21+,MX2(P1,P22)       ADD PROCESSING TIME ON ORIGINAL
            *                                       MACHINES.
 20                LOOP       22,SUM                REPEAT FOR ALL OPERATIONS
            *                                       REQUIRED BY THAT PART.
 21                ASSIGN     8,V2                  CALCULATE PARTS MOST IMMINENT
            *                                       DUE TIME.
 22                PRIORITY   FN$PRIR               PART PRIORITY.
 23                QUEUE      OPPL                  GET IN LINE & WAIT FOR A PALLET
            *                                       AND  OPERATOR .
 24                TEST E     BV$COND,1             WAIT 'TIL A PALLET AND OPERATOR
            *                                       BECOME AVAILABLE .
```

Figure 10 continued

```
25            ENTER     OPRT                CAPTURE THE OPERATOR .
26            ENTER     PALT                CAPTURE A PALLET .
27            DEPART    OPPL                LEAVE THE WAITING LINE OPPL .
28            ADVANCE   5                   LOAD PART ON THE PALLET .
29            LEAVE     OPRT                FREE THE OPERATOR .
30            GATE SNF  CART                WAIT 'TIL MATERIAL HANDELING
        *                                   CART IS AVAILABLE .
31            ENTER     CART                TAKE A CART .
32            ADVANCE   P26                 PUT PALLET ON CART AND GO TO
        *                                   THE MACHINE TO PERFORM
        *                                   VERY FIRST OPERATION.
33            LEAVE     CART                FREE THE CART.
        *
        *
        *
        ************************************************************
        *                                                          *
        *     ORIGINAL MACHINING SEGMENT                           *
        *                                                          *
        ************************************************************
        *
        *
        *
34       CONT GATE NU   MX1(P1,P2),CHCK     IS MACHINE FREE ?
35            ENTER     TOOL,MX3(P1,P2)     YES, GET REQUIRED TOOLS .
36            SEIZE     MX1(P1,P2)          CAPTURE THE CNC MACHINE .
37            TEST E    BV$FRST,1,HOSE      TEST FOR OPER.#1.
38            MARK      13                  IF IT IS, START MEASURE TIME
        *                                   IN THE MANUFACTURING SYSTEM
        *                                   ( FLOW TIME ).
39       HOSE ADVANCE   MX2(P1,P2)          MACHINING PROCEEDS .
40            ASSIGN    4+,MX2(P1,P2)       PROCESSING TIME DONE SO FAR.
41            ASSIGN    9,V4                CALCULATE REMAINING PROCESSING
        *                                   TIME & SET IT EQUAL TO P9.
42            ASSIGN    10,V3               COMPUTE JOB SLACK.
43            LEAVE     TOOL,MX3(P1,P2)     RETURN THE TOOLS .
44            RELEASE   MX1(P1,P2)          FREE THE CNC MACHINE .
        *
        *
        *
        ************************************************************
        *                                                          *
        *     TESTING SEGMENT  FOR PARTS COMING FROM ORIGINAL MACHINES *
        *                                                          *
        ************************************************************
        *
        *
45       GONP ASSIGN    34,MX1(P1,P2)       THE CURRENT MACHINE NUMBER.
```

Figure 10 continued

```
46            ASSIGN     2-,1                UPDATE NO. OF OPERATIONS YET TO
         *                                   COMPLETE .
47            TEST E     P2,0,CONP           PART COMPLETED ?
48            ASSIGN     2+,1                YES, POINT TO LAST MACHINE.
49            TABULATE   FLOW                RECORD TIME SINCE MACHINING
         *                                   BEGAN ( FLOW TIME ).
50            TABULATE   COMP                RECORD MEAN COMPLETION TIME.
51            TABULATE   P1                  RECORD TIME SPENT BY EACH PART
         *                                   TYPE.
52            ASSIGN     38,MX1(P1,P2)       THE LAST MACHINE.
53            ASSIGN     39,MX9(P38,1)       TRANSIT TIME FROM THE LAST
         *                                   MACHINE TO UNLOADING STATION.
54            GATE SNF   CART,HOLD           IS CART AVAILABLE ?
55        USE ENTER      CART                YES ; CAPTURE THE CART .
56            ADVANCE    P39                 GO TO UNLOADING STATION
         *                                   ( TRANSIT TIME ) .
         *
         *
         ***************************************************************
         *                                                             *
         *    UNLOADING SEGMENT  FOR PARTS COMING FROM ORIGINAL MACHINES *
         *                                                             *
         ***************************************************************
         *
         *
57            ENTER      UNLD                ENTER UNLOADING SECTION .
58            LEAVE      CART                FREE THE CART .
59            ENTER      OPR2                CAPTURE THE OPERATOR .
60            ADVANCE    5                   REMOVE PART FROM THE PALLET .
61            LEAVE      PALT                FREE THE PALLET .
62            LEAVE      OPR2                FREE THE OPERATOR .
63            LEAVE      UNLD                PART LEAVES THE LOADING/
         *                                   UNLOADING STATION AND GOES
         *                                   FOR INSPECTION OR FOR PACK-
         *                                   ING .
64            UNLINK     WAIT,USE,1          SEND NEXT WAITING PART (IF ANY)
         *                                   TO CAPTURE THE CART.
65            TERMINATE  1                   LEAVE THE  SYSTEM .
66       HOLD LINK       WAIT,FIFO           LINK PARTS ON USER CHAIN ON
         *                                   FIFO BASIS PROVIDED THE CART
         *                                   IS NOT FREE.
         *
         *
         *
```

Figure 10 continued

```
        ****************************************************************
        *                                                              *
        *      TEST FOR THE EXISTENCE OF ALTERNATE MACHINE             *
        *                                                              *
        ****************************************************************
        *
67       CHCK  ASSIGN     24,MX1(P1,P2)       SET P24=ORIGINAL MACHINE.
68             ASSIGN     25,MX4(P1,P2)       SET P25=ALTERNATE MACHINE.
69             TEST E     P24,P25,AVAL        IS AN ALTERNATE MACHINE
        *                                     AVAILABLE ?
        *
        *
        ****************************************************************
        *                                                              *
        *      SCHEDULING AND PROCESSING OF PARTS ON ORIGINAL MACHINES *
        *                                                              *
        ****************************************************************
        *
70       PTOP  GATE NU    MX1(P1,P2)          IF NOT, WAIT 'TIL ORIGINAL
        *                                     MACHINE BECOMES FREE.
71             ASSIGN     11,MX5(P1,P2)       PROCESSING TIME OF PARTS ON
        *                                     THAT MACHINE.
72             ASSIGN     14,MX4(P1,P2)       MACHINE NUMBER.
73             ASSIGN     45,V8               DIFFERENCE OF THE MOST IMMINENT
        *                                     DUE TIME & PROCESSING TIME DONE.
74             ASSIGN     15,V5               LONGEST PROCESSING TIME.
75             ASSIGN     46,V10              COMPUTE SPT/TPT.
76             MARK       17                  ARRIVAL TIME AT THE MACHINE
77             LINK       V6,P45,PLAY         SCHEDULE PARTS ACCORDING TO
        *                                     INCREASING VALUE OF THE B
        *                                     OPERAND OF THE LINK BLOCK
        *                                     (P45 HERE)
78       PLAY  SEIZE      MX4(P1,P2)          CAPTURE THE MACHINE .
79             ENTER      TOOL,MX3(P1,P2)     GET REQUIRED TOOLS .
80             TEST E     BV$FRST,1,PROC      TEST FOR OPER.#1.
81             MARK       13                  START MEASURE TIME IN THE
        *                                     MANUFACTURING SYSTEM.
82       PROC  ADVANCE    MX5(P1,P2)          MACHINING PROCEEDS .
83             ASSIGN     4+,MX5(P1,P2)       SUM PROCESSING TIME DONE.
84             ASSIGN     9,V4                COMPUTE REMAINING PROCESSING
        *                                     TIME.
85             ASSIGN     10,V3               COMPUTE JOB SLACK.
86             PRIORITY   PR,BUFFER           GET BEHIND CURRENT ARRIVAL
        *                                     (IF ANY) AND RESTART THE SCAN.
87             RELEASE    MX4(P1,P2)          FREE THE MACHINE .
88             LEAVE      TOOL,MX3(P1,P2)     RETURN THE TOOLS .
89             UNLINK     V6,PLAY,1           SEND NEXT SCHEDULED PART (IF
        *                                     ANY) TO CAPTURE THE MACHINE .
```

Figure 10 continued

```
90              TRANSFER   ,GONP                GO TO TESTING SEGMENT AND
        *                                       CHECK IF PART IS COMPLETED.
        *
        *********************************************************************
        *                                                                   *
        *      DELIVERY OF PARTS FROM LOADING STATION TO ALTERNATE MACHINES *
        *                                                                   *
        *********************************************************************
        *
91       AVAL   TEST E     BV$FRST,1,DOT2       TEST IF IT'S 1ST OPERATION.
92              ASSIGN     28,MX7(1,P25)        IF IT IS, SET P28=TRANSIT TIME
        *                                       FROM LOADING STATION TO THE
        *                                       ALTERNATE MACHINE.
93              ENTER      CART                 ENGAGE THE CART.
94              ADVANCE    P28                  THE CART GOES TO THE ALTERNATE
        *                                       MACHINE WHERE 1ST OPERATION IS
        *                                       TO BE PERFORMED.
95              LEAVE      CART                 FREE THE CART.
        *
        *
        *
        ********************************************************************
        *                                                                  *
        *      SCHEDULING AND PROCESSING OF PARTS ON ALTERNATE MACHINES    *
        *                                                                  *
        ********************************************************************
        *
96       DOT2   GATE NU    MX4(P1,P2),DOT1      IS THE ALTERNATE MACHINE FREE ?
97       DOT3   ASSIGN     12,MX5(P1,P2)        YES, SET P12= PROCESSING TIME
        *                                       ON THAT MACHINE.
98              ASSIGN     14,MX4(P1,P2)        THE ALTERNATE MACHINE.
99              ASSIGN     45,V8                P8-P4
100             ASSIGN     44,V9                LONGEST PROCESSING TIME (LPT).
101             ASSIGN     16,V7                COMPUTE SPT/TPT.
102             MARK       18                   ARRIVAL TIME AT THE ALTERNATE
        *                                       MACHINE.
103             LINK       V6,P19,CLAY          SCHEDULE PARTS ACCORDING TO
        *                                       INCREASING VALUE OF THE B
        *                                       OPERAND OF THE LINK BLOCK
        *                                       (SELF-INFORMATION (P19) HERE)
104      CLAY   SEIZE      MX4(P1,P2)           SCHEDULED PART CAPTURES THE
        *                                       ALTERNATE MACHINE.
105             ENTER      TOOL,MX3(P1,P2)      GET REQUIRED TOOLS.
106             TEST E     BV$FRST,1,SROC       TEST FOR OPERATRION # 1.
107             MARK       13                   START MEASURE TIME IN THE
        *                                       MANUFACTURING SYSTEM.
108      SROC   ADVANCE    MX5(P1,P2)           MACHINING ON ALTERNATE MACHINE
        *                                       PROCEEDS.
```

Figure 10 continued

```
109          ASSIGN      4+,MX5(P1,P2)       SUM PROCESSING TIME DONE.
110          ASSIGN      9,V4                COMPUTE REMAINING PROCESSING
       *                                     TIME.
111          ASSIGN      10,V3               COMPUTE JOB SLACK.
112          PRIORITY    PR,BUFFER           GET BEHIND CURRENT ARRIVAL
       *                                     (IF ANY) AND RESTART THE SCAN.
113          LEAVE       TOOL,MX3(P1,P2)     FREE THE TOOLS.
114          RELEASE     MX4(P1,P2)          GIVE UP THE ALTERNATE MACHINE.
115          UNLINK      V6,CLAY,1           SEND NEXT SCHEDULED PART (IF ANY)
       *                                     TO CAPTURE THE MACHINE.
116          TRANSFER    ,GONS               CHECK IF PART IS COMPLETED ?
       *
       *
       *
       ****************************************************************
       *                                                              *
       *     UPDATING SEGMENT FOR PARTS COMING FROM ALTERNATE MACHINES *
       *                                                              *
       ****************************************************************
       *
117     GONS ASSIGN      30,MX4(P1,P2)       THE CURRENT ALTERNATE MACHINE.
118          ASSIGN      2-,1                UPDATE NO. OF OPERATIONS YET
       *                                     TO COMPLETE.
119          TEST E      P2,0,CONS           PART COMPLETED ?
120          ASSIGN      2+,1                YES, PTR LAST MACHINE.
121          TABULATE    FLOW                RECORD TIME SINCE MACHINING
       *                                     BEGAN (FLOW TIME) .
122          TABULATE    COMP                RECORD COMPLETION TIME.
123          TABULATE    P1                  RECORD  TIME SINCE PARTS WERE
       *                                     GENERATED ( MEAN COMPLETION TIME
       *                                     OF EACH PART TYPE ).
124          ASSIGN      41,MX4(P1,P2)       THE LAST MACHINE.
125          ASSIGN      42,MX9(P41,1)       TRANSIT TIME FROM LAST MACHINE
       *                                     TO UNLOADING STATION.
126          GATE SNF    CART,GOLD           IS CART AVAILABLE ?
127     JUCE ENTER       CART                YES, ENGAGE THE CART.
128          ADVANCE     P42                 AND GO TO UNLOADING STATION.
       *
       *
       *
       ****************************************************************
       *                                                              *
       *     UNLOADING SEGMENT FOR PARTS COMING FROM ALTERNATE MACHINES *
       *                                                              *
       ****************************************************************
       *
       *
129          ENTER       UNLD                ENTER UNLOADING STATION.
```

Figure 10 continued

```
130         LEAVE      CART                 FREE THE CART.
131         ENTER      OPR2                 CAPTURE THE OPERATOR.
132         ADVANCE    5                    REMOVE PART FROM THE PALLET
133         LEAVE      PALT                 GIVE UP THE PALLET.
134         LEAVE      OPR2                 FREE THE OPERATOR.
135         LEAVE      UNLD                 PARTS LEAVE THE UNLOADING
      *                                     STATION AND GO FOR INSPECTION
      *                                     OR FOR PACKING.
136         UNLINK     GAIT,JUCE,1          SEND NEXT WAITING PART (IF ANY)
      *                                     TO CAPTURE THE CART.
137         TERMINATE  1                    LEAVE THE SYSTEM.
138    GOLD LINK       GAIT,FIFO            LINK PARTS ON FIFO BASIS IF
      *                                     THE CART IS NOT FREE.
      *
      *
      ***************************************************************
      *                                                             *
      *     UTILIZATION SEGMENT                                     *
      *                                                             *
      ***************************************************************
      *
      *                                                             *
139    DOT1 TEST LE    FR*24,FR*25,ALTN     COMPARE THE UTILIZATIONS OF
      *                                     ORIGINAL & ALTERNATE MACHINES.
      *                                     THE PART GOES TO LESS
      *                                     UTILIZED MACHINE.
140         ASSIGN     37,MX8(P25,P24)      IF ORIGINAL MACHINE IS LESS
      *                                     UTILIZED, THEN SET P37=TRANSIT
      *                                     TIME FROM ALTERNATE MACH. TO
      *                                     THE ORIGINAL MACHINE.
141         ENTER      CART                 ENGAGE THE CART.
142         ADVANCE    P37                  THE CART DELIVERS PART FROM
      *                                     ALTERNATE MACHINE TO
      *                                     ORIGINAL MACHINE.
143         LEAVE      CART                 FREE THE CART.
144         TRANSFER   ,PTOP                RETURN TO ORIGINAL MACHINE
      *
      *
145    ALTN GATE NU    MX4(P1,P2)           WAIT 'TIL MACHINE BECOMES
      *                                     FREE.
146         TRANSFER   ,DOT3                RETURN TO SCHEDULING SEGMENT
      *                                     WHERE PARTS WILL BE SCHEDULED
      *                                     & PROCESSED ON ALTERNATE MACH.
      *
      *
```

Figure 10 continued

```
              **************************************************************
              *                                                            *
              *      DELIVERY FROM ALTERNATE TO THE NEXT ORIGINAL MACHINE  *
              *                                                            *
              **************************************************************
              *
              *
 147           CONS  ASSIGN     36,MX1(P1,P2)        SET P36=THE ORIGINAL MACH.
 148                 ASSIGN     31,MX8(P30,P36)      SET P31= TRANSIT TIME FROM
              *                                      ALTERNATE MACHINE TO THE NEXT
              *                                      ORIGINAL MACHINE.
 149                 ENTER      CART                 CAPTURE THE CART.
 150                 ADVANCE    P31                  THE CART DELIVERS PART TO
              *                                      THE NEXT ORIGINAL MACHINE.
 151                 LEAVE      CART                 FREE THE CART.
 152                 TRANSFER   ,CONT                GO AND CHECK IF THAT MACHINE
              *                                      IS FREE.
              *
              *
              *************************************************************
              *                                                           *
              *      DELIVERY FROM ONE ORIGINAL MACH. TO THE NEXT MACHINE *
              *                                                           *
              *************************************************************
              *
              *
 153           CONP  ASSIGN     32,MX1(P1,P2)        THE CURRENT ORIGINAL MACHINE.
 154                 ASSIGN     33,MX8(P34,P32)      TRANSIT TIME FROM THE CURRENT
              *                                      MACH. TO THE NEXT ORIGINAL MACH.
 155                 ENTER      CART                 TAKE THE CART.
 156                 ADVANCE    P33                  DELIVER PART TO THE NEXT ORIGINAL
              *                                      MACHINE.
 157                 LEAVE      CART                 THE CART IS FREE TO DELIVER MORE
              *                                      PARTS.
 158                 TRANSFER   ,CONT                CHECK IF THAT MACHINE IS FREE.
              *
              *************************************************************
              *                                                           *
              *     CONTROL     CARDS                                     *
              *                                                           *
              *************************************************************
                     START      100                  PROCESSING OF 100 PARTS.
              *
                     REPORT     PRINT REQUESTED OUTPUT
              *
                     EJECT      ON A NEW PAGE.
```

Figure 10 continued

```
       TEXT       NUMBER OF PARTS AND MEAN COMP. & FLOW TIME
       SPACE      1
TAB    INCLUDE    T1-T6/1,2,3,4,10,11
       EJECT      SKIP TO A NEW PAGE AND
       GRAPH      TF,FLOW               DRAW GRAPH FOR FLOW TIME.
       ORIGIN     52,20
       X          ,1,4,10,1,13,FLOW
       Y          0,1,50,1
25     STATEMENT  1,36,GRAPH OF FLOW TIME VS. NO. OF PARTS
10     STATEMENT  25,5,PARTS
45     STATEMENT  55,20,FLOW TIME (MINUTES)
       ENDGRAPH
       END        RETURN CONTROL TO O.P. SYS.
```

Figure 10 continued