

DISCRETE SIMULATION OF FLEXIBLE  
MANUFACTURING SYSTEM



by  
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## ABSTRACT

A Flexible Manufacturing System is an integration of machine tools, material handling devices and computers into a system designed to improve productivity in the mid-volume production.

Although a number of such systems have been designed, relatively little is known about the managing and optimal operating conditions of such systems. Even less is known about how future systems should be designed for optimal efficiency. The main objective here is to develop a user-oriented general purpose simulator which can be used as an experimental tool to gain insight into the problems posed by such complex systems.

The developed FMSSIM simulator uses the discrete event simulation approach, incorporating the philosophy of the GASP simulation package in event monitoring. It is capable of simulating different configurations and topology including bidirectional tracks. It can check blockage of route due to interference of carts. It can also simulate random failures and repairs of the various components in the system. It provides the user with a wide range of priority rules to select from. It also allows the user to define his own priority rules.

The main features of this simulator are:

- (1) Ease of use: FMSSIM is a user-oriented package where simulation is transparent to the user. Only a set of input data needs to be supplied. The program will perform the simulation and produce a report on various

vital system performance statistics.

- (2) Graphical Output: The program produces a graphical output on a visual display terminal showing the movement of parts through the system.
- (3) Data Input: The program has a systematically organised data structure where information can be easily modified and retrieved.

A series of experiments were conducted using this simulator to test its versatility and study the behaviour of a hypothetical Flexible Manufacturing System when various design parameters are changed. The response of the system to changes in transporter speed, in- and out-shuttles capacity and number of pallets was studied. Two different types of material handling systems viz. the cart and the conveyor were compared. The effects of introducing an additional machine and changing the system topology were also examined. The general trends of results obtained from the case study are in agreement with the findings reported in other published literature.

The ability to simulate a wide range of systems with varied design parameters has made the FMSSIM simulator a very useful design aid which enables the system designer to analyse various parameters and arrive at a more efficient system.

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## CHAPTER 1

### INTRODUCTION

#### 1.1 Definition of Flexible Manufacturing System

A Flexible Manufacturing System or FMS is an integrated system of work stations and material handling equipments for the automatic random processing of palletized parts.

A workpiece or part is mounted on a pallet which has the appropriate fixture to hold and carry the part through its machining processes. The station can be a machine tool or other auxiliary equipment for washing or inspection. The stations generally have shuttles that move the parts to and from the material handling system and serve as a buffer for both the machine and material handling system.

The processing of the parts is determined by a process routing (an ordered list of operations that must be performed). The operations identify the stations that can do the operation, the part program, the necessary tools and the processing time required by the station for the operation. The processes that the part goes through define the part type. Associated with each part type is the kind of pallet with the appropriate fixture for that particular part type. To provide effective control and overall management, these systems are controlled by a common computer. All stations are digitally controlled

(such as NC machines) to allow for the most efficient operation.

## 1.2 Areas of Application of FMS

FMS have emerged in many parts of the industrialised world in response to the need to increase productivity in mid-volume batch production where the parts are made in quantities of 50-10,000 parts per year [1]\*. The traditional choice faced by a firm with a group of parts to manufacture was between job shop and transfer line.

For low volume production, the job shop approach would normally be adopted. Job shops are highly versatile and involve relatively little investments in machine and tooling. Many different parts can be processed concurrently. The shop can be expanded as required to meet increasing demands. On the other hand, the productivity in job shops tends to be relatively low and the in-process inventory is usually high.

For high volume production, the job shop approach will be too inefficient and transfer lines would be preferred. In a transfer line, machines are specially tooled up to make a single part type or with change-overs, a limited variety of very similar parts. They are however severely limited in their versatility to meet engineering and product mix changes. The initial capital investment is very high and it requires a steady production rate to ensure good utilization of machines.

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\* Numbers between square brackets indicate reference number.

For mid-volume production, neither of these approaches has been completely satisfactory. There arises a need for a new manufacturing concept which will have both the flexibility of the job shop and the high productivity of the transfer line. FMS shows the promise of meeting this challenge. It can have a significant impact on the manufacturing scenario since 50-75% of parts manufacturing expenditures fall in this range [2].

### 1.3 Benefits of FMS

The existing FMS have demonstrated many benefits compared to conventional production methods. Fig. 1.1 shows the comparison of various types of manufacturing systems [3].

#### 1.3.1 Cost reduction

In a typical FMS, loading and unloading are the only manual processes involved. Direct labour cost is therefore considerably lower than ordinary job shop. Cost reductions as much as 70% have been achieved by some FMS in operation [4]. The use of automated material handling equipment and palletization of parts significantly reduce the waiting and set-up time attributable to refixturing and handling inherent in standard machine tool operation.

#### 1.3.2 Flexibility

Another benefit provided by FMS in many situations is the substantial flexibility it offers. A number of different

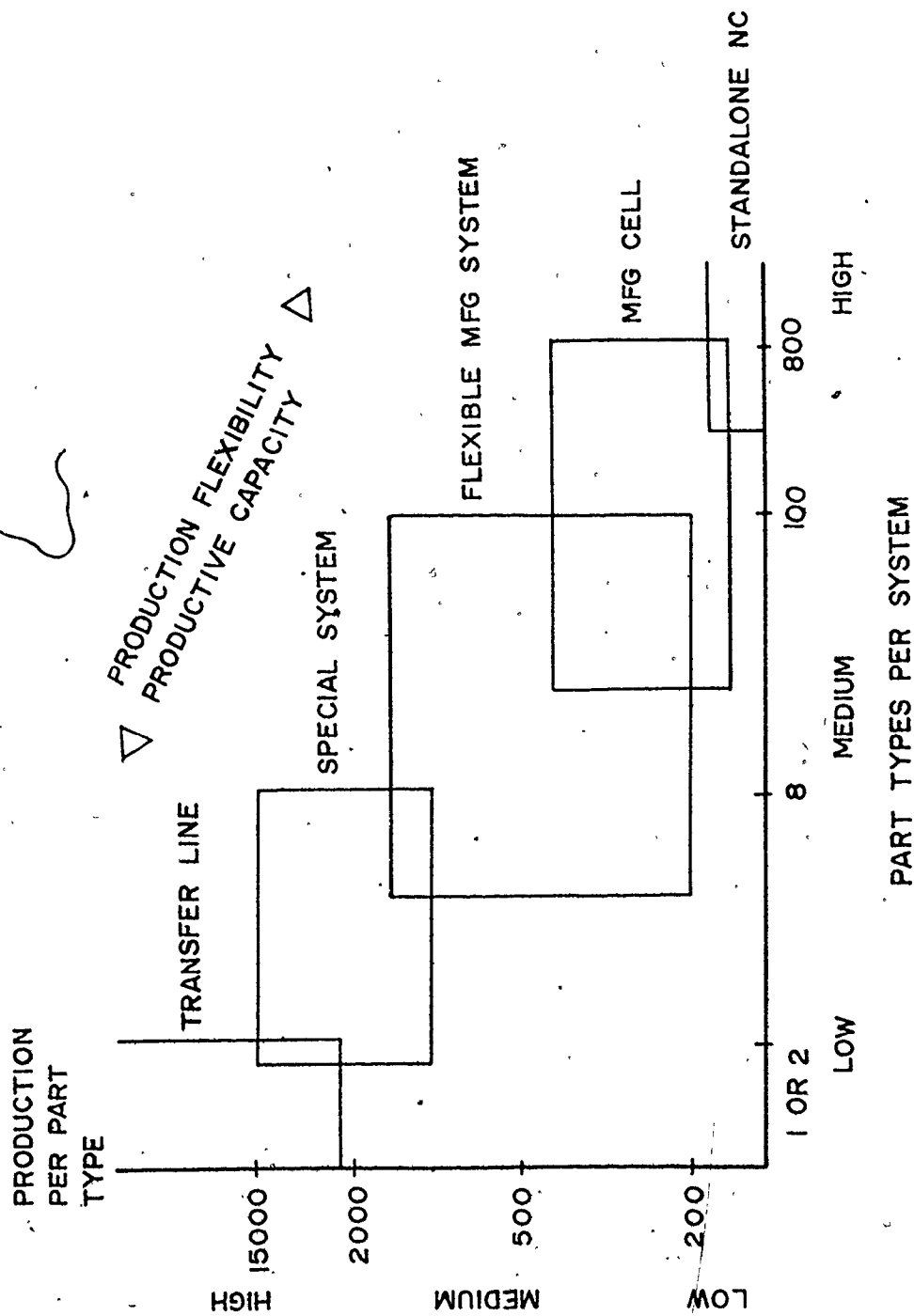


Fig. 1.1 Comparison of Various Manufacturing Systems [4].

parts may be handled in a system simultaneously. It also permits engineering changes and part mix changes without major production losses for re-tooling. The inherent flexibility of the system also allows the parts to be automatically rescheduled when part of the system breaks down.

### 1.3.3 Ease of expansion

A distinct advantage of FMS lies in its expandability. The modular nature of the system provides phased production capacity. The number of work stations and the size of the material handling system can be altered easily to meet changing demand. Phased installation also leads to further cost reduction due to delayed investment and retention of capital. Depending on a number of factors such as variable cost ratio, capital ratio and interest rate, FMS can operate economically in production volumes close to those normally suitable for transfer lines.

Associated with these major benefits are many advantages which motivate the acquisition of FMS. These advantages are reduced work in process, improved flow times, improved machine utilisation, rapid adaptation to changes in part design or work load, improved production control and scheduling and risk avoidance.

## 1.4 Characteristics of FMS

FMS are essentially automated job shops and have all

the traditional problems associated with the control of job shop including dispatching, work station assignment and task sequencing. The major differences between job shops and FMS are that human functions are automated. The design of the components in the FMS is aimed at achieving an optimal production.

#### 1.4.1 Work stations

The automated processing of parts is achieved almost without exception with the use of NC machine tools or machining centers. Auxiliary work stations such as automatic washing, assembly and inspection stations may also be included.

Due to the absence of operators to attend to these work stations, automatic tool changers and chip flushing are commonly used. Additional monitoring units have to be incorporated to cover potential problems that would normally be corrected by an operator.

Another common feature often found in FMS is the pallet shuttle arrangement which allows the interfacing between work stations and the material handling system. It provides a buffer for parts queuing before and after processing by the station.

#### 1.4.2 Material handling system

The optimal work flow in an FMS is achieved by means of an automated material handling system. Many types of material handling systems have been used in actual FMS, such

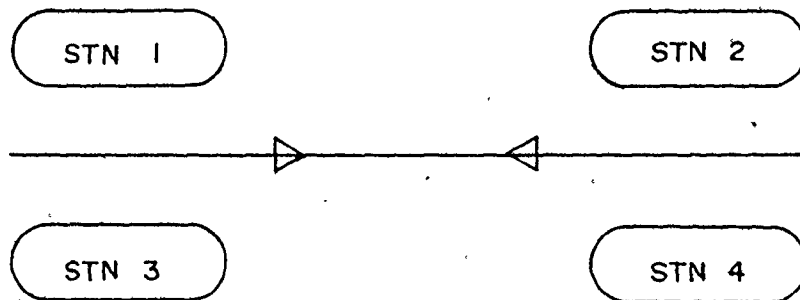
as roller conveyor, tow-cart, overhead cart, guided vehicle, stacker crane and combination. They all share a common characteristic, i.e., they are capable of transporting the workpieces among work stations along a route that is most appropriate for the individual processing requirements all under computer control.

#### 1.4.3 Topology

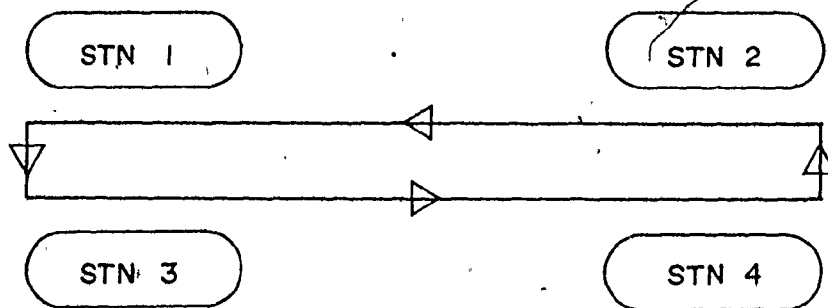
There are three basic types of topology that can be used for laying out the material handling system. They are straight line, loop and network. [Fig. 1.2] The choice depends very much on the physical constraints such as floor space, working height of transportation system, size of workpiece and type of processes involved. In the network system, zone control is sometimes used to control the traffic of the transporter (cart or other carriers) [5]. The entire route is divided into a number of zones which is equivalent to a short section of cart tracks. Only one cart is permitted in a zone at any one time. Before a cart can be moved through a zone, the computer will check if the cart can move through that zone.

#### 1.4.4 Pallet and fixture

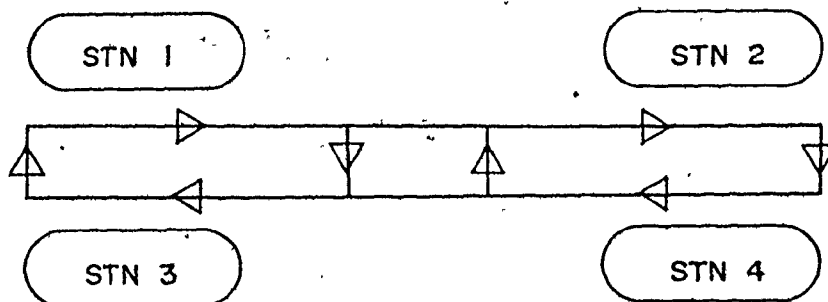
Central loading and unloading stations are used to prepare the workpieces on fixtured pallets before they are introduced into the system. Refixturing may be necessary when a change of fixture is required such as after roughing



1-2a STRAIGHT LINE TOPOLOGY



1-2b LOOP TOPOLOGY



1-2c NETWORK TOPOLOGY

Fig. 1.2 Basic Types of Topology Used in FMS.

operation and for some inspection operations.

#### 1.4.5 Computer control

The three main functions of the computers in an FMS are data distribution, workpiece scheduling and movement, and system status monitoring. Tape data are distributed to the appropriate machines for the control of machine functions. This is usually done by the DNC computer. Another computer called the FMS computer is usually needed to control the entire system including the DNC computer, material handling system and all movement of fixtures and parts. It also maintains statistical data and system status such as tool life, machine utilization, etc. [5].

#### 1.4.6 Buffering

Buffering is usually necessary for the work stations to have high utilisation. This buffering can be centralised by having an internal storage station or they can be provided locally at each station in the form of a shuttle (in-shuttle for parts coming into the machine and out-shuttle for parts leaving the stations and waiting for the transporter). A common or non-dedicated shuttle can also be used which can serve both functions of in- and out-shuttle.

### 1.5 Review of Some Existing Systems

Many FMS are already in operation in Europe, Japan and the United States. The operating and control rationales

will be briefly discussed to indicate the design parameters which seem to have major impacts on their performances.

A summarized description of existing systems is given in Appendix A [2].

#### 1.5.1 Kearney and Trecker system at Allis Chalmers [6, 7]

The system shown in Fig. 1.3 was installed in 1971 and contains 10 machine tools. Five of these are standard Milwaukee-Matic Traveling Column Modu-Line Machining Centers for miscellaneous operations, 1 Traveling Column Milling Machine for heavy duty rough milling, 4 Duplex Multiple Spindle Head Indexing Machines each of which can store up to 20 heads for drilling, tapping, boring and grooving.

The system employs a tow-line concept with zone control configuration for the material handling. The towing chain is installed below floor level in a network fashion, a computer activated mechanism located at each station disengages and engages the tow pin that connects the cart to the chain. The advantage of such a system is that it can be expanded easily if new machines or other stations are added to the system. It employs up to 23 carts to carry fixtured pallets to the stations destined to perform the required operations. If a station is not available the part floats around the system until a position is open. Both local, multiple position queue at work station and carts, serve as a buffer pool.

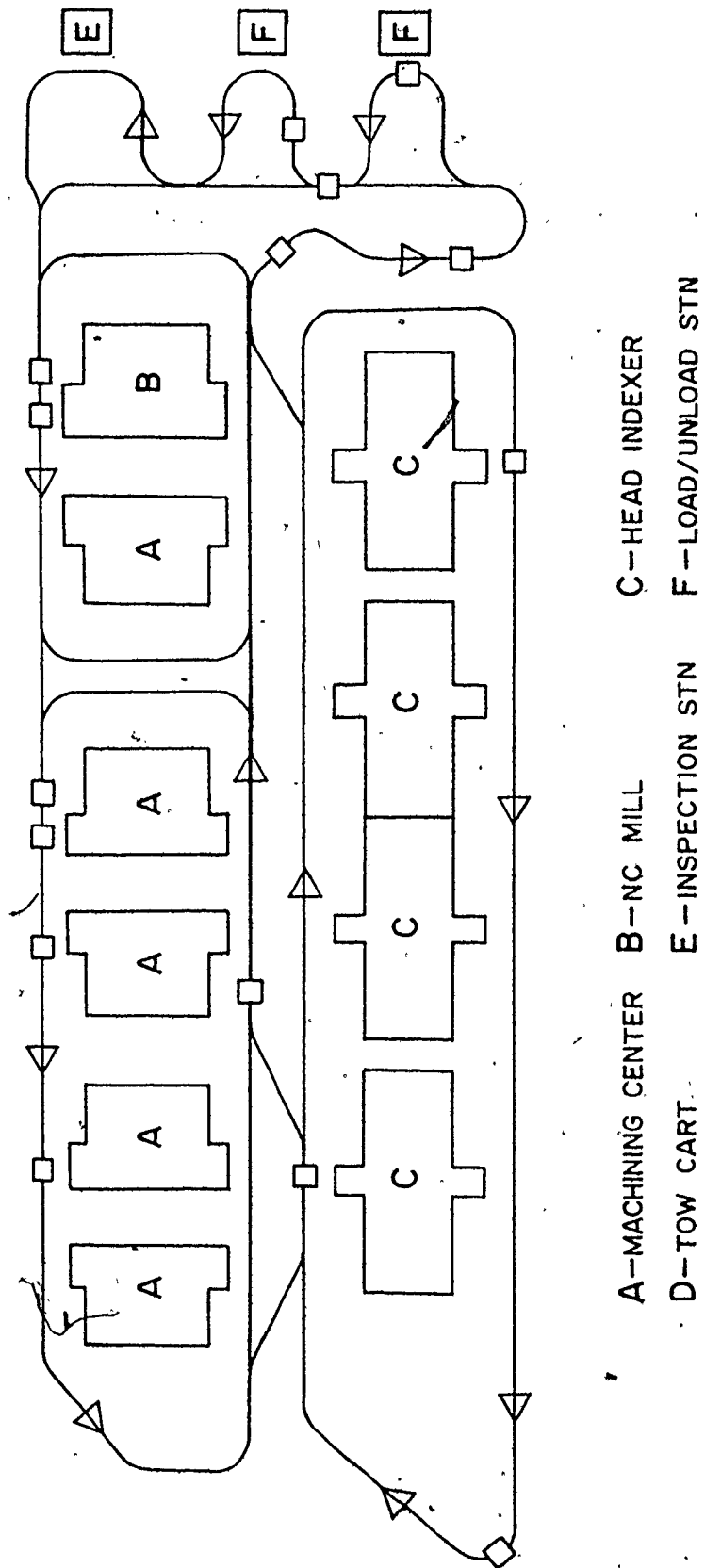


Fig. 1.3 Kearney and Trecker's System at Allis Chalmers [7].

The system handles 7 part types that make up the tractor gear box and transmission case. The part mix per order varies substantially. The average daily output is 25 tractors.

The labour requirements for each normal shift are 4 load/unload personnel, 2 general machine monitoring personnel, an inspector, a tool maintenance man and a system manager.

The investment breakdown are 50% for machine tools, 6% for material handling system, 6% for central coolant and chip disposal, 5% for DNC and FMS computers, 25% for fixtures and tooling, 8% for part programming installation and supervision.

#### 1.5.2 White Sundstrand system at Caterpillar Tractor Company [7];

This system [Fig. 1.4] consists of 4 five-axis machining centers, 3 four-axis drilling machines, 2 vertical turret lathes and a DEA inspection station. There are all together 16 loading and unloading stations. Six of the load/unload stations are dedicated to introduce parts into the system and pallet changing operations. The rest are non-dedicated and serve as in-process storage for parts. The machines are arranged on the opposite sides of a center rail on which 2 shuttle carts travel. Each cart is driven by a pinion that engages with a rack attached to one of the rails. A feedback loop ensures high cart positioning accuracy.

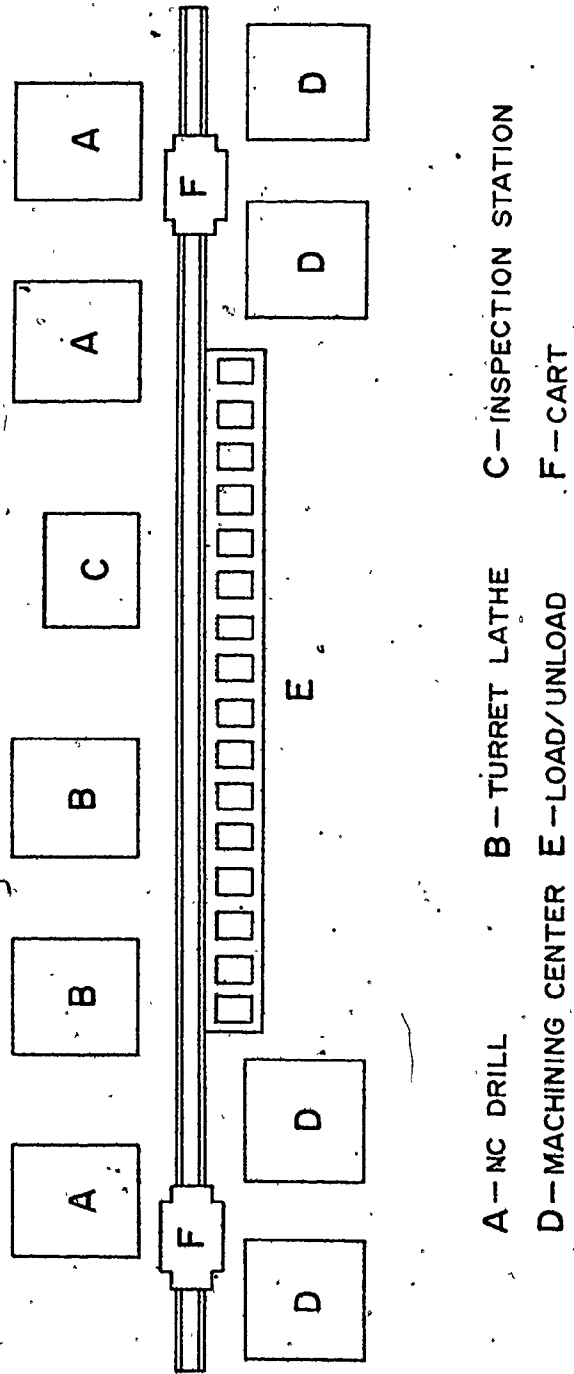


Fig. 1-4 White Sunstrand's System at Caterpillar [7].

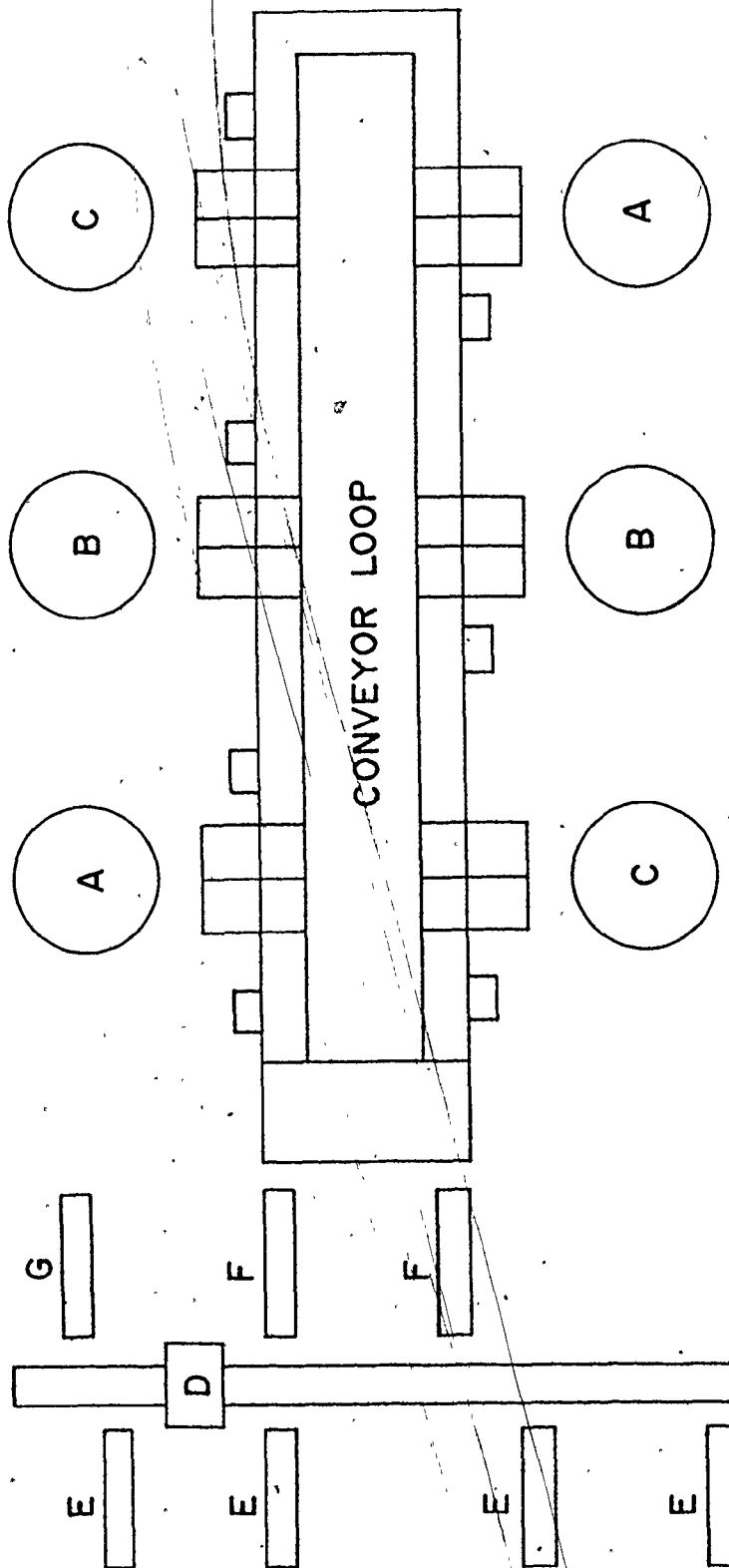
0 The system can easily be extended through addition of new working stations and track modules.

This system machines 10 different parts such as gear cases, main frame and clutch housing for two tractor modules. The part mix varies considerably from one order to another. Average daily output is about 12 tractor assemblies.

#### 1.5.3 White Sundstrand system [7] at Ingersoll Rand

This system [Fig. 1.5] consists of 6 machining centers on both sides of a powered roller conveyor loop. Parts are introduced via 4 load/unload stations. They are placed on coded pallets which are automatically transferred by a shuttle car to a buffer conveyor. The buffer conveyor feeds the parts onto the roller conveyor loop. Thus the material handling system combines both the random access cart system and a conveyor loop.

The system can accommodate 16 pallets at the same time. It is capable of machining 180 part types in batch sizes from one up. Yearly production is from 12 to 20,000 parts depending on part type.



A-NC DRILL  
 B-MACHINING CENTER 5-AXIS C-MACHINING CENTER 4-AXIS  
 D-SHUTTLE CAR E-LOAD/UNLOAD F-BUFFER CONVEYOR  
 G-REFIXTURING STATION

Fig. 1.5 White Sunstrand's System at Ingersoll Rand [7].

CHAPTER 2  
LITERATURE SURVEY OF EXISTING  
FMS MODELLING TECHNIQUES

Flexible Manufacturing Systems have great potential of increasing the productivity in batch production. Although several of these systems have been built and put into operation, relatively little is known about optimal operating conditions of such systems. Even less is known about how future systems should be designed. The lack of knowledge of this revolutionary concept of manufacturing has prompted extensive research efforts. The fact that the system components are so tightly integrated, means that interaction among the various system components is very important. The complexity of these systems makes it difficult to predict their performance using the existing operation research techniques. Existing flexible manufacturing systems have often been used for experimentation. This is an expensive and time-consuming process. System control procedures of existing systems are not easily altered. Therefore modelling techniques are needed to gain insight into the operation of such systems before building them. Several modelling techniques have been developed in recent years. They can be broadly classified into 3 categories: -

- (1) Analytical Models
- (2) Physical Models and
- (3) Discrete Simulation Models.

## 2.1 Analytical Models

An analytical model is simply a mathematical representation of a real life system or process. It represents the physical quantities and behaviour of the system by mathematical variables and expressions which are then manipulated to yield some desired information about the system. Assumptions and approximations are often required to reduce the complexity of the system to a much simpler version which can be handled by mathematical expressions. The results obtained from these models are not precisely accurate but should be good enough to guide the designer in making decisions.

Most of the analytical models developed for the analysis of flexible manufacturing systems are based on scheduling theory, reliability theory, queueing theory and other operation research techniques.

CAN-Q is one of these models which has been proven in several validation studies [8, 9]. It was developed by J. J. Solberg based on the computational algorithms for closed queueing networks with exponential servers. The schematic diagram of the model is shown in Fig. 2.1. The basic theory can be found in literature by Gordon and Newell [10] and Buzen [11].

CAN-Q treats a flexible manufacturing system as a closed queueing network having a fixed number of pallets circulating in the system. Each work station is considered as an exponential server. The material handling system is seen as a central station which every part must pass through

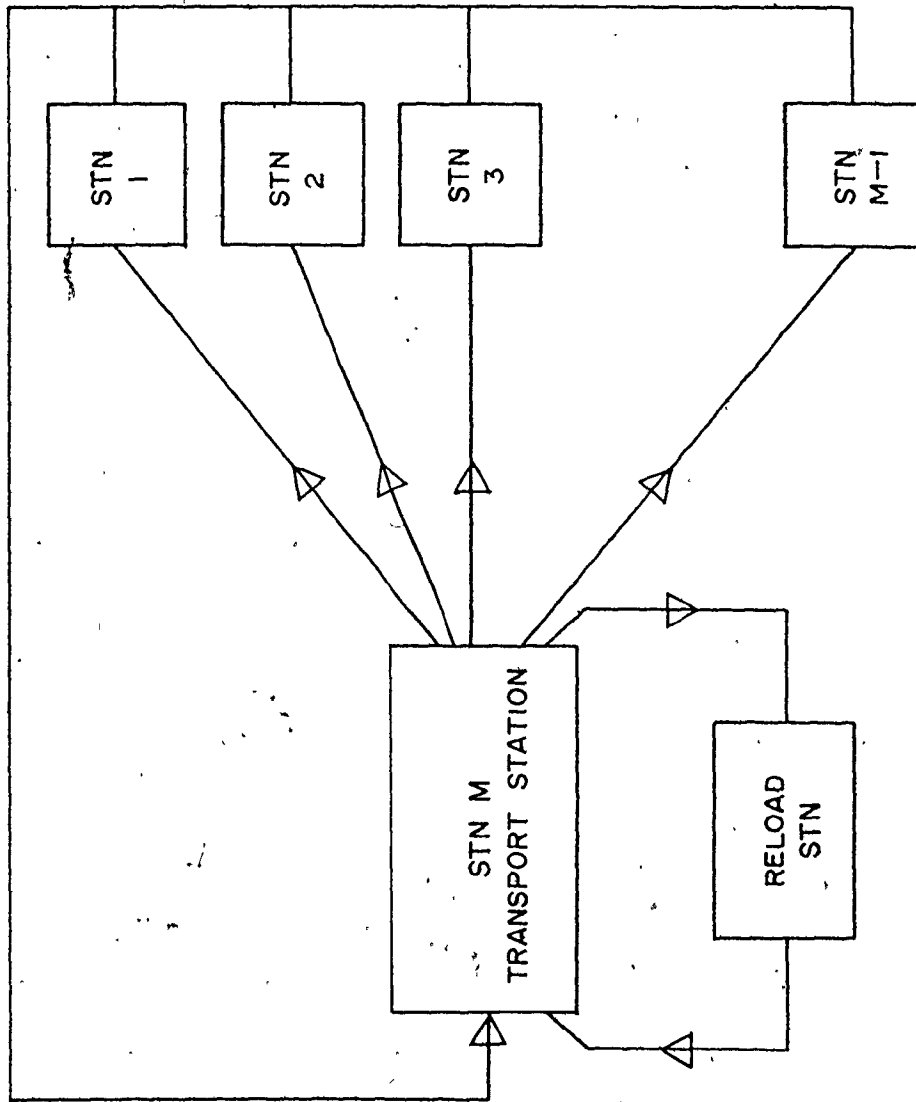


Fig. 2.1 Schematic Diagram for CAN-Q Mathematical Model [9].

before and after every operation. Each station including the material handling system possesses a queue to temporarily store the parts before the station becomes available. For the material handling system, a queue means every work station has an off-shuttle onto which the parts can be unloaded. The mathematical analysis requires that the queue should be of infinite size.

The CAN-Q model is a simple and easy-to-use model. It requires only a small set of input data. The inputs needed are number of stations, number of pallets, visit frequencies to each station, average processing time, average transport time. The outputs that can be derived from this model are production rate, utilisation of station and transporter, average flow time, average queue lengths, and other steady state performance measures.

Another mathematical model known to the author is the MVAQ model developed at Draper [12]. It employs the mean value analysis technique. The inputs to the model are number of pallets for part, number of machines and service time of part on machines. The outputs derived from the model are throughput of parts, mean waiting time for part at machine, mean queue size of part at machine and utilisation of machine. Both models can evaluate large systems without much difficulty. They are considered quick tools for scanning all the possible system configurations and reducing them to a few more promising candidates for further analysis.

This technique is useful during the early stage of system design, when little detailed information is available and many options are still open. On the other hand, these models also suffer from a number of inherent limitations due to their many simplifying approximations. They cannot be used to test the effects of various scheduling strategies and priority rules. They are also unable to find out the effects of limited queue size, component breakdown, availability of load/unload man and many other transient phenomena. The results of these models are valid only if the system has sufficient time to reach its steady state. The transient behaviour of the system is obscure to the analytical models.

## 2.2 Physical Models [13]

Physical models make use of hardware components having similar characteristics as those used in the actual system but much smaller in scale and therefore much cheaper to build.

Both Purdue University and Wayne State University have developed working physical models of FMS to study the characteristics of such systems. At Purdue University, the model was built to emulate the Caterpillar system using Fischer-Technik plastic construction kits [13]. The model's operation is controlled by a hierarchical control program implemented on a mini-computer. The computer is interfaced directly with the machines, carts and stations. The higher level program controls the overall operations and scheduling of parts movement

while the lower level program controls the actual motion of machines and carts.

This modelling technique has the advantage of duplicating the actual physical operation of the system. It therefore allows the interactions of important design parameters to be visualised and tested. However, the building of such a model is still a very time consuming and costly process. Modifications of physical parameters such as network topology and type of material handling system involve a considerable amount of work. Nevertheless, it is a useful tool for gaining practical experimentation with system elements, computer interface and control programming in the final stage of system design when little modification of the physical set-up is required.

### 2.3 Discrete Simulation Models

Discrete simulation models are computer programs which describe the activities or events that take place in the system. The system is conceptualised as a group of entities. Each entity is given a set of attribute values to describe its characteristics. The model keeps track of the discrete events occurring in the system and updates the status of each entity. It also maintains statistical information on the system performance. By repeating the simulation on different sets of input data, the system analyst will then be able to draw inferences on the effects of the various parameters.

The step-by-step nature of the simulation technique

means that the amount of computation increases very rapidly with the amount of detail in modelling the system. Since the simulation itself does not include any optimisation algorithm, the search for the best solution for a system requires many trial runs to explore the whole range of conditions. This results in lengthy computations.

The discrete simulator can provide much more information than the analytical model which is preferable only when the solution being sought is some indication of the optimal physical quantities such as number of carts, machines, pallets, etc. However, except in the case of very simple models, the formulation of an analytical model often requires much simplification and approximation to accommodate the limitations of the available mathematical techniques.

In comparison with the physical model which has an even higher degree of realism but less flexibility, discrete simulator offers the convenience of easy manipulation of parameters until the desired results are achieved.

The logical approach is therefore to use an analytical model to scan the preliminary design parameters and to determine the number of machines, pallets and carts required then proceed on with a discrete simulator to confirm the results obtained and to study the different topologies and scheduling rules. The physical model will be the final test bed for the control logic.

The discrete simulators can be written in any computer

language. There are many simulation languages specially developed for this purpose. Examples of these languages are GPSS [14], SIMSCRIPT [15], QGERT [16], GASP [17], ECSL [18] etc. They have proved their worth in saving time on model development, modification and debugging.

A number of discrete simulators have been developed in recent years for the simulation of flexible manufacturing systems. Although they resemble one another in the type of input and output specifications and system diagnostics, the method used in the actual simulation differs considerably. This depends on the degree of flexibility and complexity of the model. The simulation approach is naturally influenced by the selected simulation language.

Some of the existing discrete simulation models are discussed below.

#### 2.3.1 Kearney and Trecker model

This model was developed by Kearney and Trecker [19, 20] and was used during the design stage of the Allis Chalmers' Flexible Manufacturing System. The model was intended to be an experimental tool to test the different system configurations and their control strategies. The simulator was designed as a general purpose model so that each new alternative requires only alteration to the input parameters without changes to the program itself. This model was written in SIMSCRIPT and contains about 8000 statements. The model has since been used in the proposal and design of several other flexible

manufacturing systems.

The model was found to be very useful in the selection of material handling systems, testing the algorithms used for cart assignment and part loading and studying the effects of part mix changes.

A wide variety of output is available from this simulator. System status reports can be obtained to provide the user with an intermediate report on traffic density, queueing and the status of each component in the system. It also reveals the transient behaviour of the system. The final report contains the utilisation of all the system components, the production rate and flow time of each part type.

A typical input data set to the model has 600 cards, half of which are SIMSCRIPT initialisation data. The remainder are used to describe a particular system.

The major drawback of this model is that the users must have considerable knowledge of the SIMSCRIPT language in order to be able to set up and modify the input data required for the initialisation of the SIMSCRIPT package. The portability of this model is also limited by the availability of the SIMSCRIPT language.

### 2.3.2 Catline model

The Catline model [21, 22] was developed by Mayer and Talaváge. It is written in FORTRAN and employs the GASP IV simulation package for event monitoring, file management and statistics collection. It was developed specifically for the

Caterpillar System. This model maintains some degree of versatility for experimentation with part movement and part loading, and location of storage facilities. It simulates the loading of parts onto pallets, the transfer of these parts to the machine for the required operation, refixturing and finally removal and inspection of the finished parts. Since the model was built for a specific system, most of the system parameters have been fixed. Its main objective is to study the system performance under different control strategy for different part mix. The simulation is repeated with every combination of control options for each set of input data.

The input to the simulation program consists of two sections. The first section contains the GASP related data which specify the number of attributes for each entity, number of variables on which statistical data are to be collected, basic structure of the files used and the initialisation of other GASP variables. The second section of the data describe the system configuration such as part type description, type of operations required for each part type and description of other components in the system. Output occurs in three stages, the first stage includes input data verification, the second stage provides the intermediate results, and the third stage produces the desired statistical analysis.

The model does not allow major changes to the system configuration such as the type of material handling system, alternate routing for cart movement, etc. However, being a

special purpose model it is not complicated since no flexibility provisions are allowed. Therefore, the number of independent variables are not too many and the analysis can be conducted easily on every combination of alternatives to search for the best solution within a limited set of options.

### 2.3.3 GCMS model

This is a generalised simulation model developed by Lenz and Talavage [22,23]. It is written in FORTRAN and employs the GASP IV simulation package for event monitoring. The simulation is conducted by scheduling a series of events for the various entities in the system. It is capable of modelling conveyor and cart type of material handling systems with any topology.

Data input to the GCMS model includes GASP IV initialisation data and system description data such as number of part types, pallet types, cart types, stations and their attributes. System reliability data are also needed to simulate the effects of breakdown on the performance of the system. Output from the model includes part production rates, flow time and utilisation of various system components.

GCMS like Catline is relatively difficult to use. Data input is a very cumbersome procedure requiring knowledge of GASP IV simulation language. The GASP IV package requires a considerable amount of initialisation data. Users who are not familiar with the GASP IV language are particularly prone

to making mistakes in setting up the input data. Since the program does not provide input data check, such errors will not be detected until an error occurs in the actual simulation. The method used for checking cart interference is not reliable. The program also assumes that there is an infinite stock of raw materials ready for processing all the time. The effect of raw material arrival rate cannot be simulated. Debugging is extremely difficult even with the tracing facility provided by the programme which only traces the events that a part undergoes in the simulation. The interaction of events and the status of the system is not clear. This model has been reported to be plagued with obscure errors [23].

#### 2.3.4 CAMSAM model

This model was developed by Runner and Leimkuhler using the Q-GERT simulation language [24]. The language employs an activity-on - branch network philosophy. Nodes are used to denote a decision point where the next activity is to be scheduled. The nodes can also specify the queue size waiting for transaction. The branches represent activities which involve processing time. Transactions are directed through the network according to the branching characteristics of the nodes. Transactions are generated at the source node and assigned with attribute values which describe the pallet type, next station, time to be spent at the next station and counters for keeping track of parts passing through certain stations and nodes..

In this model every different system configuration requires a separate activity diagram. Although the CAMSAM model has demonstrated how different systems can be modelled using Q-GERT it was not the intention of its designer to develop it into a turnkey type of simulation package for the analysis of flexible manufacturing systems. It still requires a large degree of skill and a lot of time for its use. Unless the model is developed with the actual simulation program being transparent to the users, leaving the users with only the input data to worry about, it will remain a technique suitable only for experienced programmers with considerable knowledge of the simulation language.

#### 2.3.5 Cook's model

This modelling technique was developed by N. H. Cook [25]. The program was written in FORTRAN and implemented on a mini-computer. It incorporates the visual display into the simulation model so that the parts can be seen moving through the schematic picture of the system. It also provides the usual performance output quantities.

The system is defined by three types of entities - machine, queue and line. The simulation operates on pre-specified time increment. The status of each element in the display file is updated at each time increment. As the system operates, various records are maintained in order to evaluate the system's performance at the termination of the simulation.

System performance includes utilisation of the various components, jamming of the queue, availability of pallet and downtime statistics of the machines.

This model has the potential of being developed into a general purpose model which permits a variety of specific parts to be routed to specific machining sequences, one or more routes per part, various queue sizes, various machining times and various loading strategies. The data required for the simulation are simple since no initialisation data are required by high level simulation language as is the case in other models. This model has not yet been developed into a turnkey design package. It only demonstrates the technique which can be used for modelling different system configurations. The use of fixed time increments for simulation is a very slow process compared to an event-to-event simulation.

#### 2.4 Direction of Current Research

After reviewing the various models developed so far, it was felt that an easy to use user-oriented design package with comprehensive graphical outputs is still lacking. It was decided that the model to be developed should be a discrete simulation model capable of studying the dynamic behaviour as well as steady state performance of an FMS. It should be able to produce system performance reports as well as graphical output. The criteria used in developing this model will be discussed in Chapter 3.

## CHAPTER 3

### CRITERIA USED TO DEVELOP THE GENERAL PURPOSE SIMULATOR

#### 3.1 Design Procedure for a Flexible Manufacturing System

The major advantage of a flexible manufacturing system lies in its capability of producing a wide variety of parts. However, it is unrealistic to design an FMS capable of performing all production operations. Optimum results can only be obtained for a defined spectrum of workpieces. A common procedure followed by most flexible manufacturing system designers is presented in Fig. 3.1.

If a large number of parts are to be machined, they are first grouped into families using the group technology technique. Parts in the same family should share similar geometric features or manufacturing processes. The work contents required to process each part type in the family are then determined. This can be done manually or with the aid of automatic process planning. Knowing the work contents involved, machine tools and system configurations can then be selected. The designer may come up with a number of feasible system configurations differing in the number of stations, type of material handling system, part assignment, tool allocation and queue sizes of different stations. Mathematical models can be used to determine parameters such as number of stations, carts and pallets. The system can be further analysed using discrete

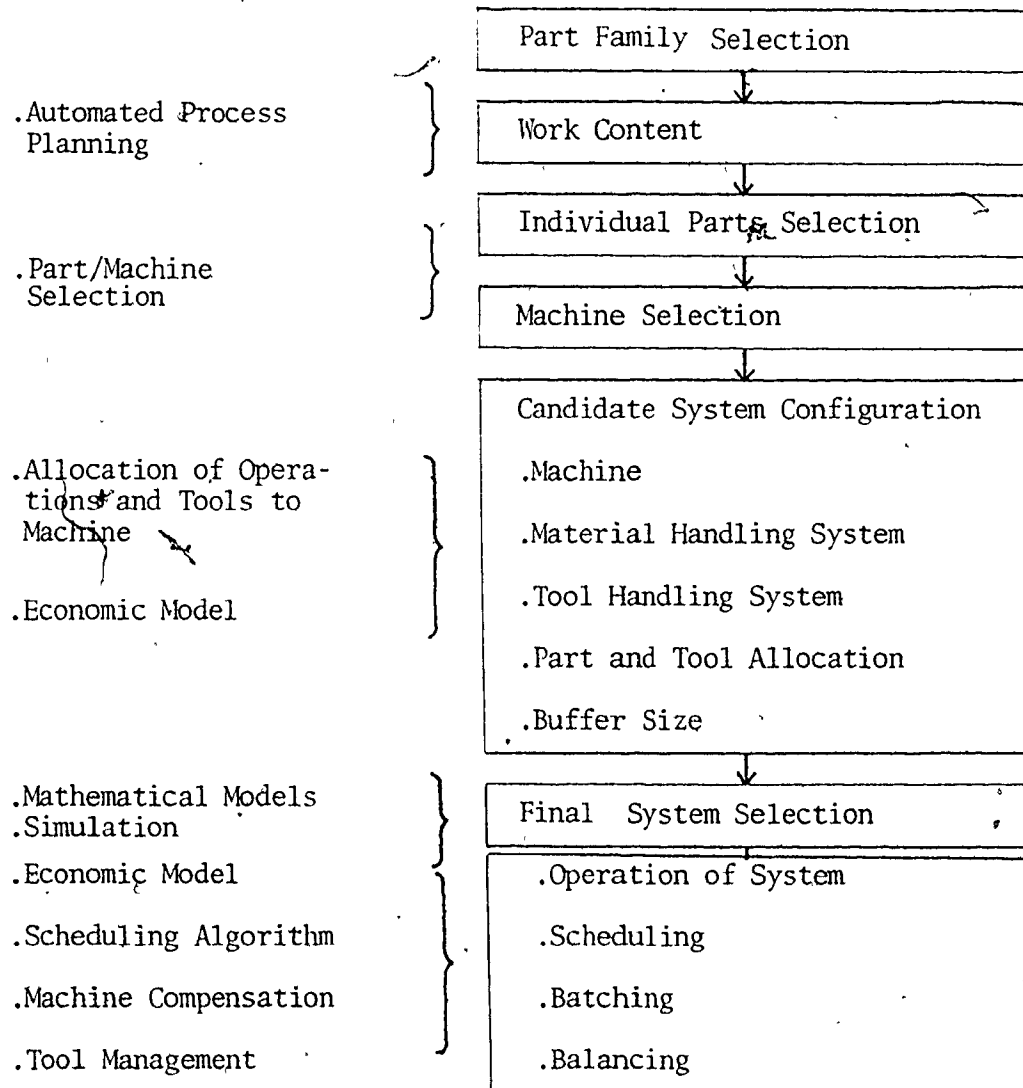


Fig. 3.1 FMS System Design Procedure [26].

simulation to study the more subtle effects of different machine tool arrangements, different priority rules for scheduling and breakdown of various system components. Although many discrete simulation programs have been developed [19, 23; 24, 25] and contributed towards a better understanding of flexible manufacturing systems, there are still many improvements to be made. The main defects of the existing models are: -

- (a) Data input and modification are very inconvenient. In addition to the system description data, many models require initialisation data for the simulation language used (e.g., Kearney and Tecker model, Catline, GCMS).
- (b) Users are unable to visualise the operation of the system. Cook's model is the only model known to the author that has incorporated some graphical display into the simulation package.
- (c) Many of these models (e.g., Catline model) were developed for a specified system. Adoption of these models for different systems requires extensive modification. Others (Q-GERT, Cook's model) merely demonstrated a technique for simulating different configurations. They are not self-contained, user-oriented, general purpose models.

### 3.2 Overall Objective

The main objective here is to develop a user-oriented,

general purpose computer simulation model incorporating graphical animation for studying any configuration of flexible manufacturing system. It is hoped that the model developed can ultimately be used as a design tool to configure an optimal or near optimal system under a set of prescribed conditions and to study the effects of various scheduling rules. It is also hoped that with the graphical animation, it will serve as an essential training module for people involved in the management and operation of such systems.

Keeping the overall objective in mind, a general purpose simulator is therefore proposed. The main features of this simulator are: -

- (a) Versatility: - The model must have the capability of simulating most system configurations and different priority rules for scheduling and dispatching.
- (b) Simplified data input: - Only system description data would be required. They must be organised systematically in a data file which can be edited easily using any text editor available with the operating system of the computer.
- (c) Graphical output: - use of computer graphics is highly desirable. It can facilitate visual inspection, verification of the input data describing network topology and provide instantaneous feedback on the system status at any moment.
- (d) Results analysis: - Results collected from a simulation run must be self explanatory and provide an

easily readable summary on the various performance measures.

- (e) Modular program structure: - In order to overcome the constraint due to the computer storage limitations, the program needs to have a modular structure to facilitate the use of an overlaying technique. A modular structure also allows easier design, testing and modifications. User defined functions can be easily linked with the simulation package, hence further enhancing the flexibility of the model.
- (f) Database organisation: - A common database should be designed to provide a central control of all data and reduce the redundancy and inconsistency of the stored data.

### 3.3 Design Criteria for the Simulation Model

The following design criteria are established to define the scope of the simulation model. They are based mainly on the configurations of existing flexible manufacturing systems.

- (a) The model should be able to represent different types of stations such as machine tools, load/unload station or any auxiliary equipment such as washing station, inspection station, etc.
- (b) The model should be able to simulate the two most common types of material handling systems, viz., conveyor and cart systems.

- (c) The model should be capable of simulating dedicated in-and-out shuttles as well as non-dedicated rotary shuttles.
- (d) The models should allow easy descriptions of the system topology using a network of track points. It should be feasible to define locations where parts are transferred from track to shuttle and vice versa. It should also be capable of modelling route branching of the material handling system as well as bi-directional tracks. A check of blocking caused by busy carts or conveyor breakdown would be a desirable feature.
- (e) The model should be able to simulate the sequence of operations specified by the user. The processing of parts will follow that fixed sequence but the stations and routes will be selected according to some priority rules specified by the user.
- (f) The model should be able to generate randomly distributed variables such as arrival time, time leading to breakdown, time taken to repair, random sampling of parts for inspection and any randomly distributed processing time.
- (g) The model should be able to simulate breakdown of various system components.
- (h) The model should allow the implementation of various decision rules for: 1) selecting the part type to be loaded into the system; 2) selecting the part to be

processed from the incoming queue at a station;  
 3) selecting a cart to transport a part from one station to another; 4) selecting a station for a part to go to if more than one station is available; and 5) deciding the alternative action when a cart cannot unload at a station due to a congested queue.

### 3.4 Selection of Simulation Language

A simulation language provides the basic structure which facilitates the building of simulation models or helps save time spent in preparation, debugging and modification of simulation programs. The basic functions of a simulation language are: -

- (1) Event control and sequencing
- (2) System state initialisation
- (3) Time advance control, either by fixed increment or event occurrence
- (4) Statistical computations and report generation
- (5) Information storage and retrieval
- (6) Program monitoring
- (7) Random deviates generation.

#### 3.4.1 Comparison of some common simulation languages

A brief description and comparison of some commonly used simulation languages are given below [27,,28].

##### 3.4.1.1 GPSS (General Purpose Simulation System)

This simulation language was developed by Gordon [14]. It can best be described as a computerised version of the work study engineer's flow chart. A GPSS model is constructed

by combining a set of standard blocks into a block diagram which defines the logical structure of the system. Each block represents a different type of interaction of the system with a transaction. The system is conceptualised as a group of facilities, storage and queues. Transactions are generated and introduced into the system with some user defined parameters or attributes describing the type of transactions. The GPSS simulation language provides the facility to control the flow of transactions and keep track of the number of completed transactions. Simulation can be terminated after a prescribed duration of time or after a specified number of transactions have been completed. There are no formal statements as in a normal language, but these are implied by the data supplied about the blocks and their implied behaviour.

The main appeal of GPSS is its modelling simplicity. It has the flexibility required for studying general systems, but it is limited in computing power and lacks the capability for using real arithmetic. As a result it is difficult to incorporate user defined functions involving real arithmetic. GPSS does not have a minicomputer version.

#### 3.4.1.2 SIMSCRIPT

SIMSCRIPT was developed by Kiviat Villanueva, and Markowitz [15]. It is a general purpose language divided into five levels. At its lower levels, it functions as a general purpose language comparable in power to FORTRAN, ALGOL and PL/I. Higher level SIMSCRIPT contains simulation facilities

such as modelling using entity, attribute and set concepts. At its highest level, it provides statement types for time advance, event processing, generation of samples and accumulation and analysis of simulation generated data. In constructing a simulation model, one must correctly describe the activities involved and the execution sequence of subprograms representing the activities in order to reproduce the time-dependent behaviour of the actual system. Events can either be generated in the simulation model or fed to the model from the outside world.

The main appeal of SIMSCRIPT is that it is both a programming and simulation language. As a result it allows the user to define special purpose subroutines. However, the setting up and changing of the initial conditions for a simulation model are usually rather complicated and require substantial knowledge and experience with the language itself. It is not known to the author that there is a minicomputer version for SIMSCRIPT.

#### 3.4.1.3 GASP (General all-purpose simulation package)

GASP is not so much a simulation language but rather a set of subroutines in FORTRAN that perform functions useful in simulation. It was developed by Pritsker [16] for modelling discrete, continuous and combined discrete-continuous simulations. The user constructs a model in FORTRAN and links it with the GASP package. Its principal advantage is that it can be used on any computer with a FORTRAN compiler. No special

processor is required. Since the base language, FORTRAN, is widely used, it allows the user to write subroutines in this high level language to describe very complex decision processes such as implementation of user defined priority rules. It can also interface easily with FORTRAN based graphics subroutines. It also has a modular structure which allows the use of an overlay technique on a minicomputer. A minicomputer version of GASP is available and operates on a PDP 11/48.

#### 3.4.1.4 ECSL (Extended Control and Simulation Language)

ECSL [18] was developed at the University of Birmingham, England. The ECSL approach is built around the use of an activity cycle representing the actual system. Entities being modelled pass through an alternating series of queues (passive state) and activities (active states). Entities are neither created nor destroyed. They circulate indefinitely in their closed activity cycles. An interactive program called CAPS (Computer Aided Programming System) accepts a description of entities and activity cycles. The output from CAPS is a file containing ECSL simulation program statements. Both ECSL and CAPS will run on any computer which has an ANSI standard FORTRAN IV compiler.

#### 3.4.2 Criteria for selection

The criteria used in selecting the simulation language for our general purpose simulator are: -

- (a) Ability to simulate complicated decision making such as checking of cart interference, generating feasible routes between two stations, etc.
- (b) Ability to interface with user defined functions in order to allow the user to implement self-defined decision rules which are not provided by the simulation language.
- (c) The possibility of using the simulation language on a mini-computer is an important factor. Most users are now opting for distributed processors and minicomputers are gaining wider popularity.
- (d) The ability to use it on a wide range of computers without the need of a special compiler makes a FORTRAN based simulation language more desirable.

GASP is selected mainly because it is easily understood and can be easily modified to meet all the above mentioned requirements. Since its subroutines are written in FORTRAN, it does not need a special processor or compiler and can easily interface with existing subroutines for graphical animation. It is also decided that only the basic simulation functions such as event control; time advance mechanism, random deviates generation, collection of performance statistics and file management would be adapted from GASP. Other more complicated routines such as event description, scheduling strategy, part tracing and graphical animation routines would be developed separately to suit our objectives.

## CHAPTER 4

### DESCRIPTION OF THE GENERAL PURPOSE FMS SIMULATOR (FMSSIM)

#### 4.1 Introduction

Following the guidelines set out in Chapter 3, a general purpose simulator FMSSIM (Flexible Manufacturing System SIMulator) was developed. An event-oriented philosophy is used in the simulation. The system is modelled by defining the changes that occur at event times. The operation of the system is conceptualised as a succession of discrete events centering on the parts to be processed. The time axis is decomposed into points at which events could occur. The simulation progresses by executing the logic associated with each event and the system time is advanced from one event to the next. The GASP simulation package was adapted and used in this simulator. Only the mathematical and logical relations that transpire at the occurrence of each event need to be specified. The timing mechanism and monitoring of the event files are managed by the GASP package.

#### 4.2 Program Concepts

The three basic building blocks used to model the flexible manufacturing system are station, track and shuttle. A station is a facility where an operation is performed. A track is a path along which the parts will travel from station

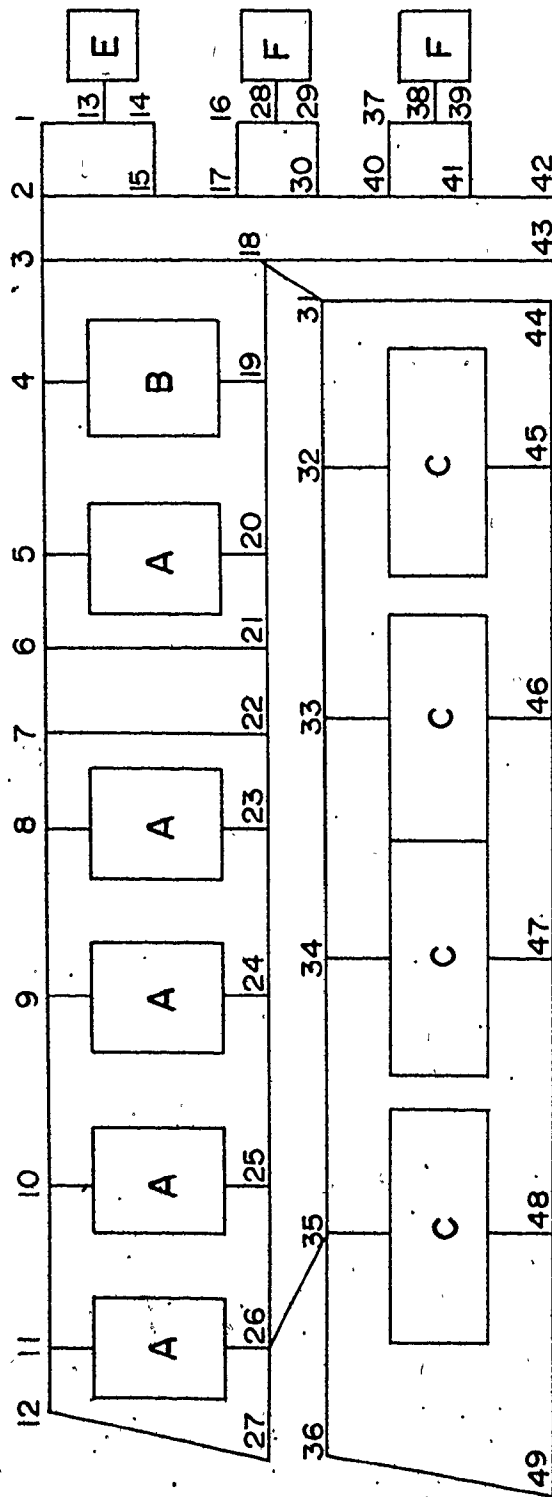
to station. A shuttle is a queue connecting the track to the station and vice versa.

#### 4.2.1 System topology

The topology of the system is defined by a network of track points. Each track point represents a location where transfer of parts from track to shuttle or shuttle to track takes place. It can also represent a node in the material handling system where a branching occurs. The graphical representation of the system also requires track points to be included at places where the track route changes direction. A straight track is always assumed between two track points. Figures 4.1-4.3 illustrate how actual systems will be represented in the simulation model.

Each track point can have a number of successors so that multiple routes between track points can be generated. A single direction track (such as tow cart or conveyor) is represented by a chain of successive points. A bi-directional track between two points is simulated by defining the two points as successor of one another. When a part has to travel from one station to another, a route is generated in a sequence of track points. There may be more than one feasible route between two stations. The route can be checked for blocking caused by busy cart or conveyor breakdown. Some decision rules are then used to select the best possible route.

The type of material handling system (cart or conveyor) can also be specified in the description of track points as



C-HEAD INDEXER

A-MACHINING CENTER B-NC MILL

E-INSPECTION STN F-LOAD/UNLOAD

Fig. 4.1 Schematic Diagram for Modelling Kearney and Trecker's System at Allis Chalmers.

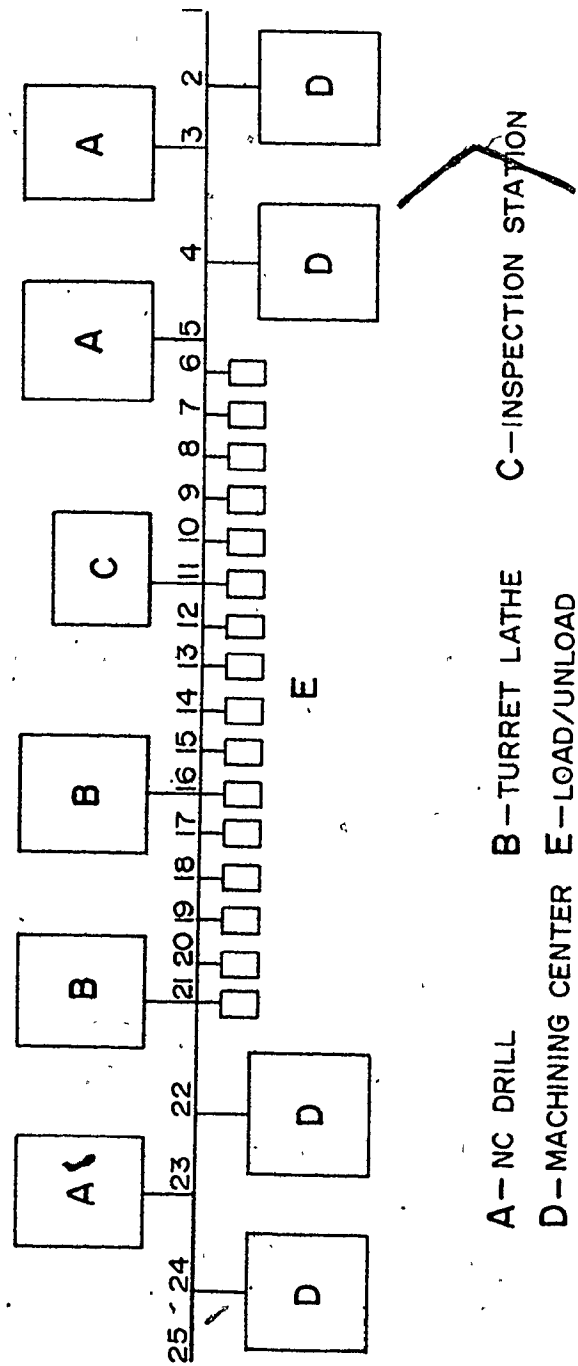


Fig. 4.2 Schematic Diagram for Modelling White Sunstrand's System at Caterpillar.

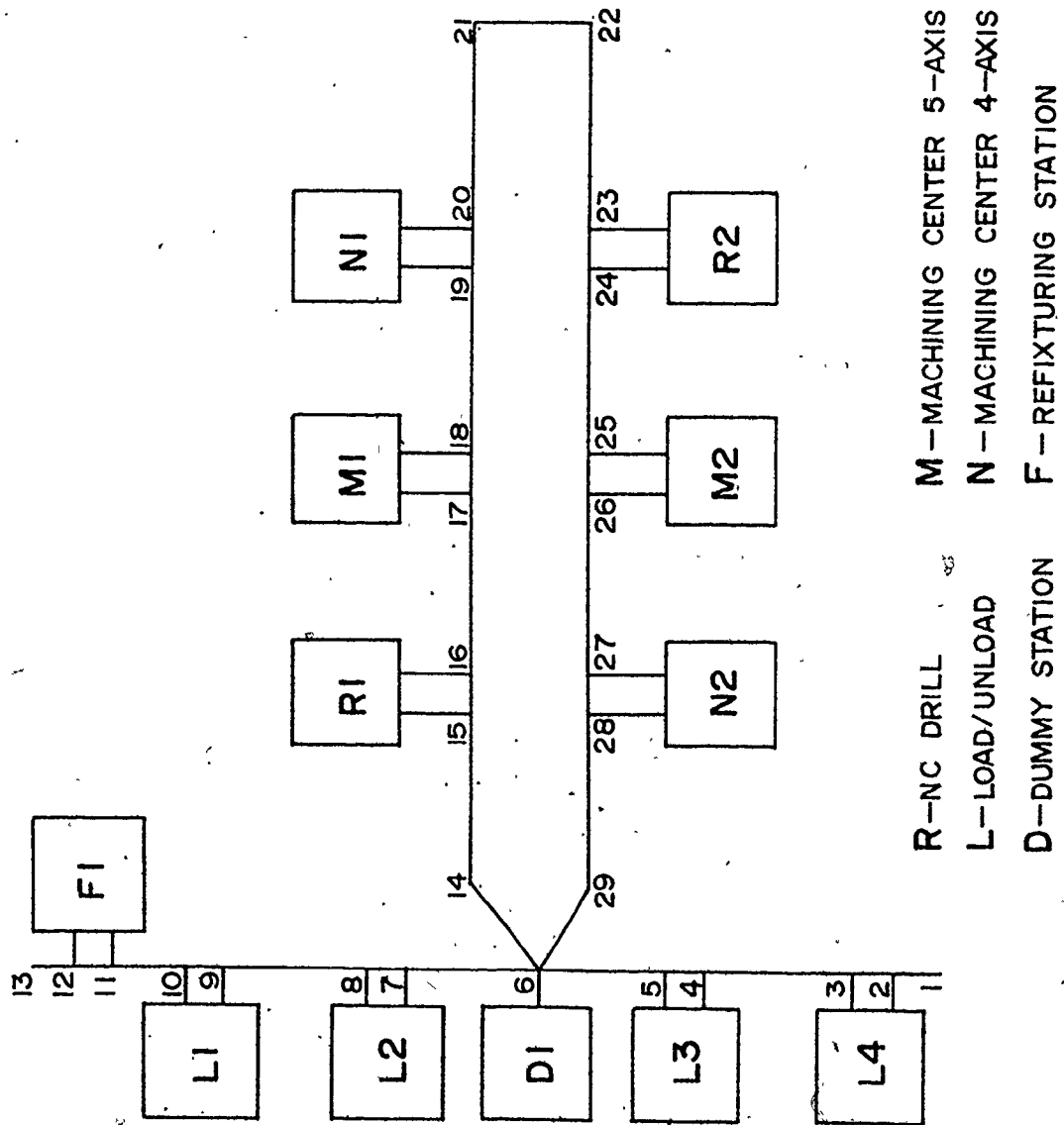


Fig. 4.3 Schematic Diagram for Modelling White Sunstrand's System at Ingersoll Rand.

part of the input data. If the track between two points is a conveyor, its speed has to be specified. Zero speed indicates that the track joining the two points is a cart track (or any non-moving track) since all points are specified individually, a combined conveyor and cart system can be modelled by describing the track points accordingly. Tables 4.1 and 4.2 illustrate how the two different systems shown in Figs. 4.2 and 4.3 are being encoded for simulation using the developed FMSSIM package.

#### 4.2.2 Material handling system

In a cart system, when a part has to be moved to its next station, a cart is selected and summoned to pick up the part. In some existing systems (such as Ingersoll Rand's System, Fig. 1.5), the movement of carts is confined to a specified track. This is simulated by specifying the feasible track points over which the cart can travel as part of the cart description data.

When a conveyor is used, parts are loaded immediately onto it as soon as they leave the machine. Routes are found to carry the parts to their next destination. If several routes are available, the shortest route will be chosen.

In a combined cart and conveyor system (Fig. 4.3), a dummy station is required at the junction between the conveyor and the cart track to represent the transfer mechanism used for transferring the parts from the cart to the conveyor and vice versa.

TRACK POINTS	SUCCESSOR POINTS				CONVEYOR SPEED BETWEEN TRACK POINT AND SUCCESSOR			
	(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)
1	2	0	0	0	0	0	0	0
2	1	3	0	0	0	0	0	0
3	2	4	0	0	0	0	0	0
4	3	5	0	0	0	0	0	0
5	4	6	0	0	0	0	0	0
6	5	7	0	0	0	0	0	0
7	6	8	0	0	0	0	0	0
8	7	9	0	0	0	0	0	0
9	8	10	0	0	0	0	0	0
10	9	11	0	0	0	0	0	0
11	10	12	0	0	0	0	0	0
12	11	13	0	0	0	0	0	0
13	12	14	0	0	0	0	0	0
14	13	15	0	0	0	0	0	0
15	14	16	0	0	0	0	0	0
16	15	17	0	0	0	0	0	0
17	16	18	0	0	0	0	0	0
18	17	19	0	0	0	0	0	0
19	18	20	0	0	0	0	0	0
20	19	21	0	0	0	0	0	0
21	20	22	0	0	0	0	0	0
22	21	23	0	0	0	0	0	0
23	22	24	0	0	0	0	0	0
24	23	0	0	0	0	0	0	0

TABLE 4.1 Track Point Description for Bidirectional  
Cart Track (Caterpillar System) (Fig. 4.2).

TRACK POINTS	SUCCESSOR POINTS				CONVEYOR SPEED BETWEEN TRACK POINT AND SUCCESSOR			
	(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)
1	2	0	0	0	0	0	0	0
2	1	3	0	0	0	0	0	0
3	2	4	0	0	0	0	0	0
4	3	5	0	0	0	0	0	0
5	4	6	0	0	0	0	0	0
6	5	7	14	0	0	0	50	0
7	6	8	0	0	0	0	0	0
8	7	9	0	0	0	0	0	0
9	8	10	0	0	0	0	0	0
10	9	11	0	0	0	0	0	0
11	10	12	0	0	0	0	0	0
12	11	13	0	0	0	0	0	0
13	12	0	0	0	0	0	0	0
14	15	0	0	0	50	0	0	0
15	16	0	0	0	50	0	0	0
16	17	0	0	0	50	0	0	0
17	18	0	0	0	50	0	0	0
18	19	0	0	0	50	0	0	0
19	20	0	0	0	50	0	0	0
20	21	0	0	0	50	0	0	0
21	22	0	0	0	50	0	0	0
22	23	0	0	0	50	0	0	0
23	24	0	0	0	50	0	0	0
24	25	0	0	0	50	0	0	0
25	26	0	0	0	50	0	0	0
26	27	0	0	0	50	0	0	0
27	28	0	0	0	50	0	0	0
28	29	0	0	0	50	0	0	0
29	6	0	0	0	50	0	0	0

TABLE 4.2 Track Point Description for a Combined Cart and Conveyor (Ingersoll Rand) System (Fig. 4.3).

#### 4.2.3 Part types

Parts are the only transactions which enter and leave the system. All events are defined based on the different stages which the parts go through. Each part requires a fixed sequence of operations. To simplify the simulation, all processes conducted consecutively on the same station are considered to be a single operation and the operation time will then be the total of all the processing times plus the time for two changes. There may be several stations capable of performing the same operation with different processing times. Each operation is therefore defined by the stations where the operations can be carried out and the corresponding processing time. The first operation is always a loading operation by which a part enters the system. The last operation is always an unloading operation by which a part leaves the system. The load/unload station can also be used for refixturing.

#### 4.2.3 Shuttle

The type of shuttle associated with each station is included in the station description. The shuttles are classified into (i) in-shuttle, (ii) out-shuttle, (iii) common shuttle. As the names imply in- and out-shuttles are strictly for incoming and outgoing parts respectively. Common shuttles are non-dedicated shuttles which can accommodate both incoming or outgoing parts such as a rotational shuttle.

#### 4.2.5 Pallet

In a flexible manufacturing system, parts are always transported in pallets which have the proper fixture to hold the parts. The type of fixture on a pallet may be able to accommodate several different part types. Each pallet type is identified by the part type which can go into it and the actual number of pallets available for use. Before a part can be loaded into the system, it must be checked whether the proper pallet is available. When a part is completed, the pallet will be released so that a new part can be introduced into the system.

#### 4.2.6 System failure

The breakdown of the various system components (station, cart or conveyor) can be simulated if their reliability characteristics are known. The type of probabilistic distribution describing the time leading to breakdown and the time required for repair must be specified by the user. If simulation of breakdown is not desired, the time leading to breakdown is made longer than the duration of the simulation. This way, we can study the effect of breakdown of any specific part of the system.

#### 4.2.7 Decision rules

There are several options available for each of the five decision rules which can be selected by specifying the

corresponding codes in the input data. The various options for each rule are summarised as follows: -

- (a) Rule 1: - Selection of part types to be loaded into the system.
- Option 1: Part type with highest priority.
  - Option 2: Part type which is most arear in its production.
  - Option 3: User's defined rule.

- (b) Rule 2: - Selection of part to be processed at a station from its incoming shuttle.
- Option 1: First-in first-out at shuttle.
  - Option 2: Part with highest priority.
  - Option 3: Part with shortest processing time.
  - Option 4: Part with longest processing time.
  - Option 5: Part with least number of operations remaining.
  - Option 6: Part with most number of operations remaining.
  - Option 7: Part with shortest remaining processing time.
  - Option 8: Part with longest remaining processing time.
  - Option 9: Part with smallest ratio of processing time to the total processing.
  - Option 10: User's defined rule.

Option 3 and Option 9 are commonly used in job shop scheduling and proved to be very successful in flexible manufacturing systems [29].

(c) Rule 3: - Selection of cart to transport a part from one station to another.

Option 1: Idle cart has highest priority.

Option 2: Cart with nearest destination.

Option 3: User's defined rule.

If several carts are available, they are checked for interference on all possible routes. Those which are blocked by other carts on the way will be eliminated. If all carts are blocked, the cart which has the shortest waiting time for the route to be cleared will be selected.

(d) Rule 4: - Selection of a station that a part will go to for its next operation.

Option 1: Station which has the shortest operation time.

Option 2: Station which has the shortest queue.

Option 3: User's defined rule.

(e) Rule 5: - Selection of alternative action for a cart if it cannot unload a part at a station due to a full incoming shuttle.

Option 1: Wait at the incoming shuttle until a space is available.

Option 2: Go to the next station which can perform the operation.

#### 4.2.8 Arrival pattern

The effect of the availability of raw materials for processing can be simulated by defining the arrival pattern (the probability distribution of the inter-arrival time) of various part types. If no arrival pattern is specified, the raw materials are assumed to be always available and new parts will be loaded as long as pallets are available.

#### 4.3 Event Scheduling

The key to the event-oriented simulation is the ability to organize events so that they can be executed in a chronological order as in the real system. Since the state of the system remains constant between event times, a complete dynamic portrayal of the system can be obtained by advancing simulation time from one event to the next. The filing and monitoring of events as well as the timing mechanism are managed by the GASP package. The description of each event and the consequences of its occurrence (such as a change in the system status or triggering off of the subsequent events) were specifically written for the developed Flexible Manufacturing System SIMulator (FMSSIM). The operation of a flexible manufacturing system can be fully described by eleven event types. Each of them is described by a separate subroutine. The overall sequence is shown in the form of a flowchart in Fig. 4.4. The description of each event with names of subroutine denoted in brackets are given as follows:

- (1) Part Arrival Event (denoted by ARIVE)

This event signifies the arrival of a certain part type.

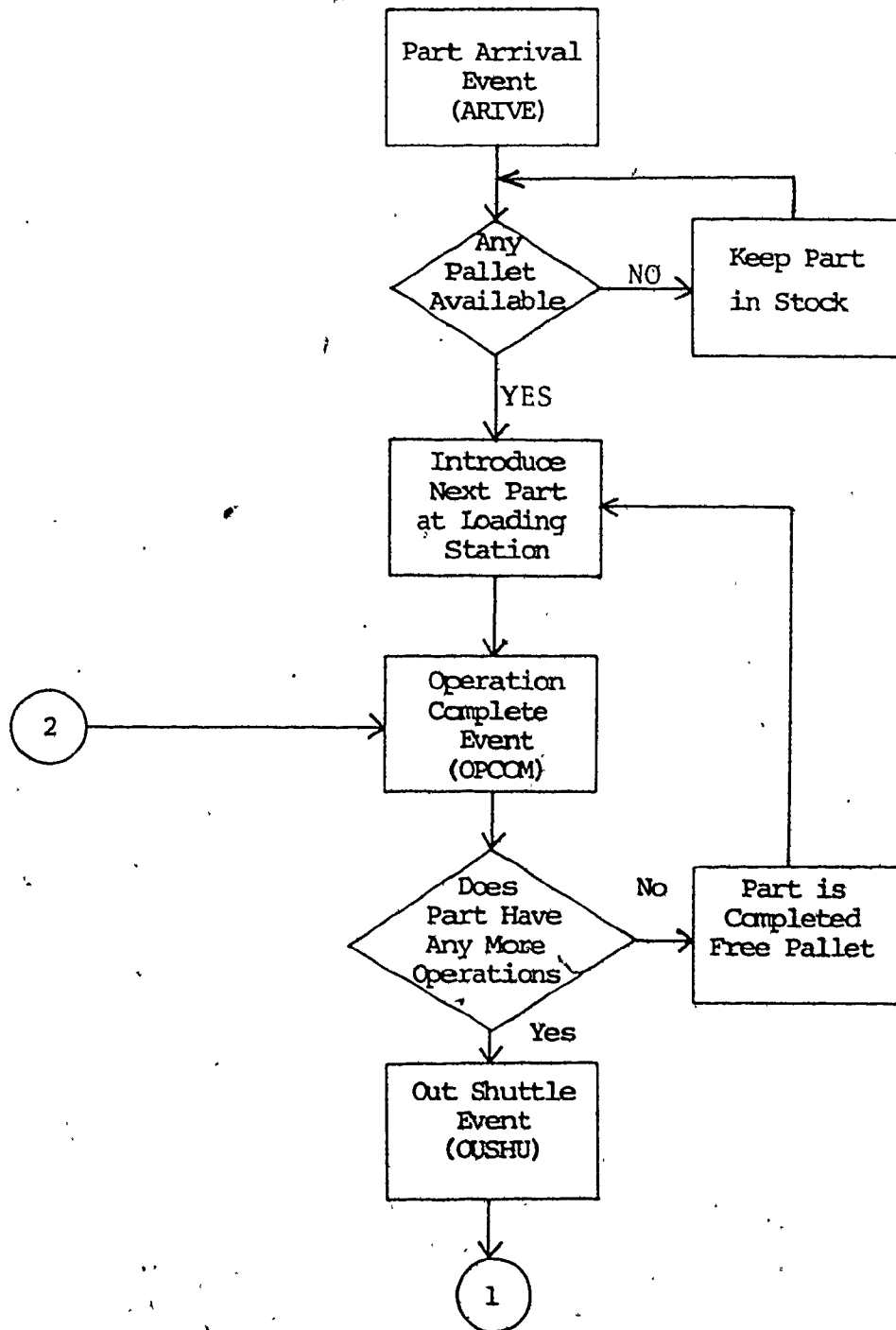


Fig. 4.4

Flow Chart of the Event Sequences for a Given Part.

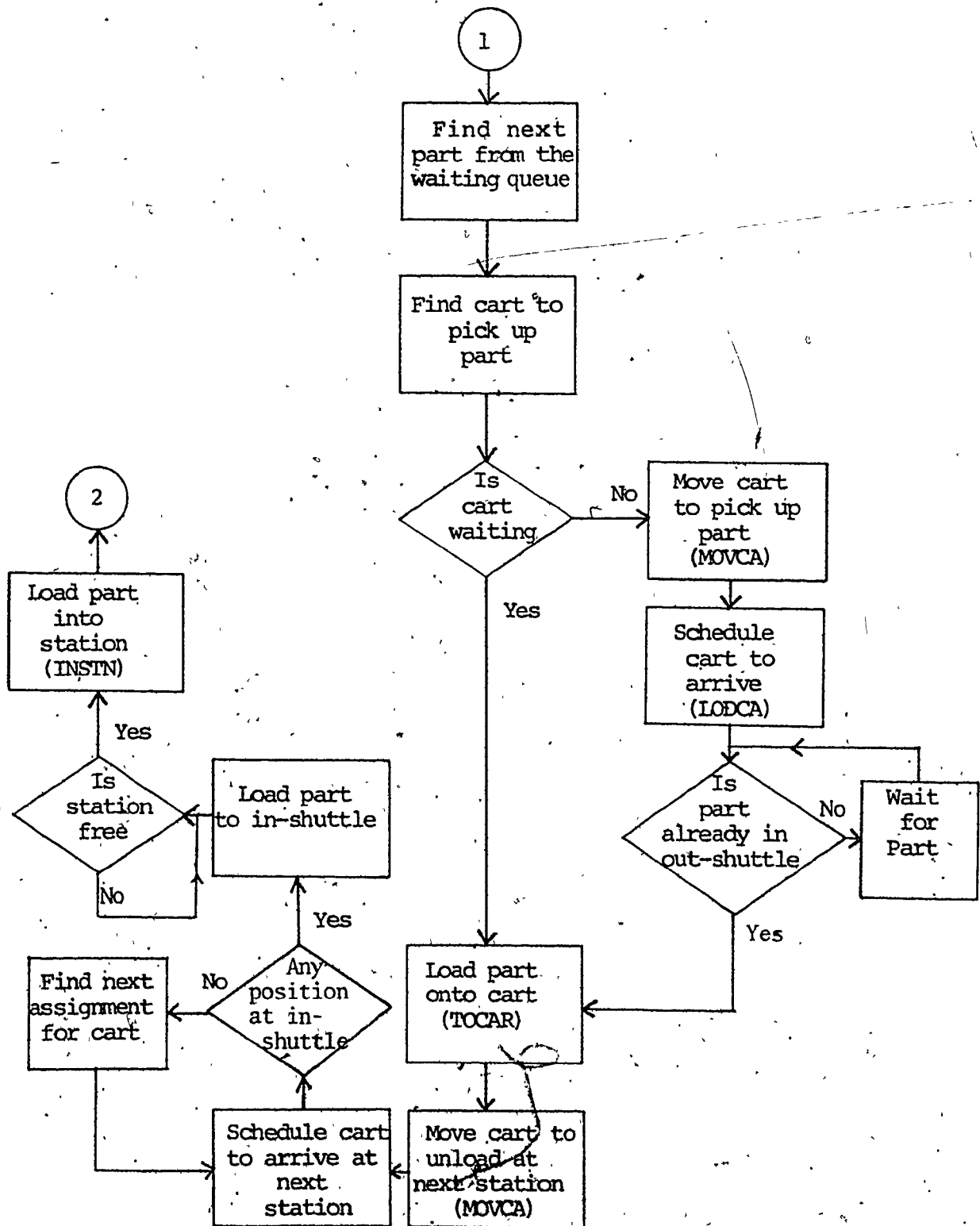


Fig. 4.4 (Cont'd)

It changes the stock level of the part type and schedule the next arrival event. If any of the loading stations is free, it will schedule an Operation Complete (OPCOM) event at the loading station.

(2) Operation Complete Event (denoted by OPCOM)

This event signifies the completion of an operation. It sets the station flag to indicate that the station is busy and updates the performance statistics of the station. It chooses the next operation and station to go to. If carts are used, a cart is then selected to pick the part up and Move Cart (MOVCA) event is scheduled to transport the part to its next station. If an empty space is available in the outgoing shuttle, an Out Shuttle (OUSHU) event is scheduled.

(3) Out-shuttle Event (denoted by OUSHU)

This event signifies that a part has entered the outgoing shuttle of a station. It updates the part status and utilisation statistics of the shuttle. It resets the machine status flag and schedules the next part to be processed if there are parts waiting in the incoming shuttle. It will also schedule a To Cart (TOCAR) event if the right cart is waiting at the outgoing shuttle. In the case of a conveyor the part will be loaded directly to the conveyor which is again simulated by a To Cart (TOCAR) event.

(4) Load Cart Event (denoted by LODCA)

This event is used only for cart systems and it.

signifies that a cart has arrived to pick up a part at a station. The cart status and performance statistics are updated. It checks if the part it is fetching has entered the outgoing shuttle. If so, it will schedule a To Cart (TOCAR) event.

(5) To Cart Event (denoted by TOCAR)

This event signifies that a part has moved onto the cart or conveyor and is ready to be transported to its next station. In a conveyor system, the part is immediately scheduled to move to its next destination. In a cart system, the cart status and performance statistics are updated. A Move Cart (MOVCA) event is then scheduled immediately.

(6) Unload Cart Event (denoted by UNLCA)

This event signifies that a cart has arrived at a station to drop off a part or a part has arrived at a station to be unloaded in a conveyor system. If the incoming shuttle is full and the part cannot be unloaded, the part can be carried away to the next available station or wait at the incoming shuttle. If a part can be unloaded, an In Shuttle (INSHU) event is then scheduled.

(7) In-Shuttle Event (denoted by INSHU)

This event signifies that a part has entered the incoming shuttle of a station. If a cart is used, the cart which has unloaded the part is scheduled to perform its next assignment by a Move Cart (MOVCA) event. If the station is idle, an In Station (INSTN) event is then scheduled. Otherwise

the part will wait in the shuttle.

(8) In-Station Event (denoted by INSTN)

This event signifies that a part has entered the station and is ready to begin its operation. Again the OPCOM event is scheduled. The status of the station and shuttle are updated.

(9) Move Cart Event (denoted by MOVCA)

This event is used only for cart systems. It signifies that a cart has completed its assignment and is ready for the next. This event is scheduled 1) after a cart has unloaded a part or, 2) if a part cannot be unloaded it will transport the part to its next available station, or 3) summoned by a part to pick it up, or 4) the movement of a cart has to be delayed due to a blocked route. When a MOVCA event occurs, it searches through all the parts which have been assigned to it (either on the cart waiting to be unloaded or in the shuttle waiting to be picked up) and finds the shortest route for its next assignment. If the part is on the cart, an UNLCA event is scheduled. Otherwise, a LODCA event is scheduled.

(10) Breakdown Event (denoted by BREAK)

This event signifies that a component in the system has failed. The component can be a station, a cart or a track point on a conveyor. The time taken to repair is calculated from its reliability statistics supplied in the input data. A (Repair) event is then scheduled. The status and downtime

statistics of that component is updated. If an event has been scheduled on the component, it is rescheduled with a delay equal to the repair time.

(11) Repaired Event (denoted by REPAR)

This event signifies that a component has been repaired and is ready to be put back into service. The status and performance statistics are updated and the next BREAK event is scheduled.

Each event has three attributes associated with it. These attributes are:

ATTRIB (1): Time of occurrence of an event.

ATTRIB (2): Code for event type.

ATTRIB (3): Code for entity involved (part number).

When an event is scheduled, these three attributes must be determined and entered into an event file. The GASP filing system is used to enter and remove events. The monitoring routine always checks the most imminent event to occur, removes the event along with its three attributes from the file and branches to the corresponding subroutine describing the changes caused by the event. The system status is then updated accordingly. After the status has been changed, the next event will be scheduled according to the circumstances prevailing during the occurrence of the event. When an event occurs, it can change the system status in several ways:

- 1) it alters the attributes of the entities (such as position

of the cart, number of parts on the cart, number of parts in the shuttle, etc.), 2) it changes the number of entities present (e.g., the arrival of parts increases the stock level of a certain part type), and 3) it alters the performance statistics of the system (such as the utilisation of the station, carts, shuttle, etc.). Each event is described by a subprogram to be linked to the GASP package. The basic modes of control are shown in Fig. 4.5.

The simulation process is initialised by introducing the starting events (Arrival event (ARIVE) for each part type, Operation Complete event (OPCOM) at the loading station and the first Breakdown event (BREAK) for each component in the system). These events will in turn produce a chain of events until the simulation is completed. Event types 2 to 9 are repeated as the part moves from station to station for processing until it is completely done. The completed part is then replaced by a new part and the cycle repeated. Breakdown event (BREAK) and Repair event (REPAR) form another event loop. A Breakdown event schedules a Repair event and a Repair event schedules the next Breakdown event. An Arrival event is independent and each Arrival event schedules the next Arrival event after a duration equal to the interarrival time.

#### 4.4 Entities and Attributes

The model consists of five types of entities. They

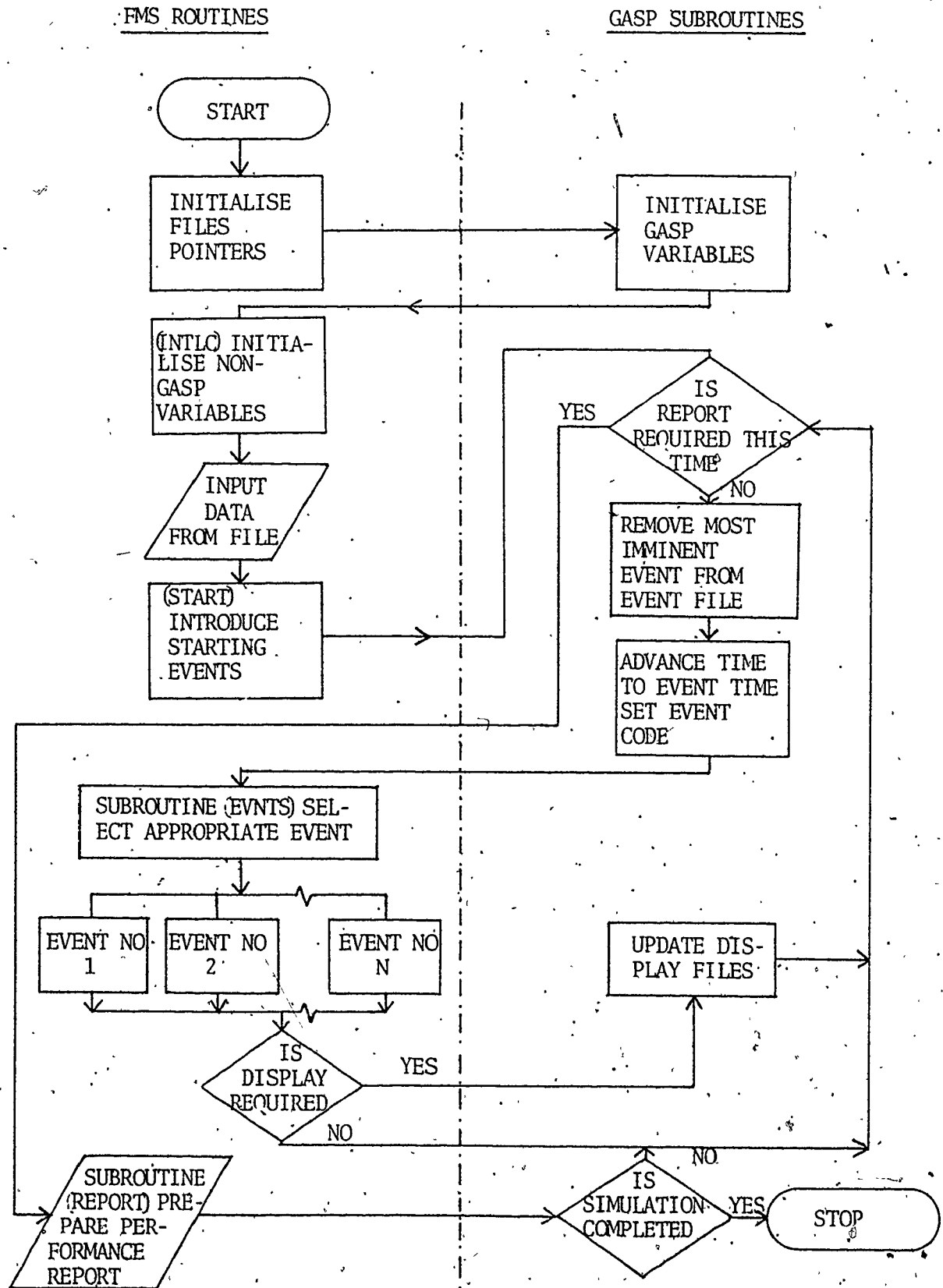
EXECUTIVE PROGRAM

Fig. 4.5 Basic Mode of Operation.

are: parts, stations, carts, pallets and track points.

Each type of entity has several characteristics or attributes.

Basically, these attributes can be classified into two types: description data and status vectors.

#### 4.4.1 Description data

They are input data used to describe the system and are fixed throughout the simulation. The attributes associated with each type of entity are:

##### (a) Part Description

Parameters used to describe parts include the maximum number allowed in the system, priority, number of parts to be produced, number of operations required to produce the part, arrival pattern and parameters for random function describing the arrival pattern. The operation number, stations where operations can be performed and the process time are associated with each operation.

##### (b) Station Description

Station description includes the number of positions in each type of shuttle, track points for each type of shuttle, time to move parts from shuttle to station (or the reverse operation), time to move parts from track to shuttle (or the reverse operation) and parameters defining the reliability of the station.

##### (c) Cart Description

Cart description includes the number of carts, number of pallets it can hold, feasible track points defining the path

that the cart can travel, cart speed and parameters defining the reliability of the cart type.

(d) Pallet Description

Pallet description includes the number of pallets available for each pallet type and the part types that can go on to the pallet.

(e) Track Description

Track description includes the station with which the track point is joined to, subsequent track points, conveyor speed if it lies on a conveyor, location of the track point and parameters defining the reliability of the track point.

4.4.2 Status vectors

Status vectors are variables which change according to event occurrence.

(a) Part Status

Part status vector includes the part type, priority, pallet number, cart number, current station, current operation, next station, next operation, number of operations left, type of shuttle it is in, operations completed, and the time when the part enters the system.

(b) Station Status

Station status vector includes the time when the station begins its most recent operation, status flag of the station (idle , down, occupied), time when the station

will be available if down, and parts number in each type of shuttle.

(c) Cart Status

Cart status vector includes the last point passed, time of passing the last point, current speed, part numbers on the cart, status flag of the cart (up or down), cart type, time when it will be available if down, activity (unloading, loading, waiting or idle), destination, and successive track points.

(d) Pallet Status

Pallet status vector includes the part number in pallet, station number, pallet type, last point passed, time of passing, cart number, and successive track points on the conveyor.

(e) Track Status

Track status is indicated by a flag denoting the operational (up) or non-operational (down) states

The detail organisation of the data structure is given in Appendix H.

#### 4.5 Performance Measures and System Outputs

The costly investment involved in building an FMS has made it not only desirable but necessary to achieve a maximum machine utilisation. This requires considerable effort to be made in planning the system configurations, loading of

parts into the system and assigning the parts to the most suitable machines. The scheduling problem is much more complicated than one can possibly anticipate. Static optimisation procedures, using an algorithm to determine at the beginning of the scheduling period, a complete schedule for that period, are commonly used in conventional job shops. This method frequently requires reoptimisation when contingencies arise or results in frequent manual overrides to handle unexpected situations. In FMS, this situation is further complicated by the many options provided by the flexibility of the system for doing the same job. No fixed schedule can be considered optimal for any considerable length of planning horizon. Dynamic scheduling procedures utilising the most current information about the system status are often more practical for such systems. Heuristic loading and scheduling methods are therefore widely used in the operation of flexible manufacturing systems.

The developed general purpose simulator (FMSSIM) has been designed to incorporate most of the commonly used dispatching rules into the model. The designer needs only to specify the rules he wishes to use. Most of these rules have been successfully used in conventional job shops. In order to achieve the desired goals, some performance measures must be used to analyse a given FMS.

#### 4.5.1 Selection of performance measures

There are many possible criteria used for judging

the performance of an FMS. Some definitions associated with these performance measures are [29, 30].

$C_j$  = Completion time of job  $j$ , the time at which processing of the last operation of the job is completed.

$r_j$  = time at which job  $j$  is ready to begin processing.

$F_j$  = Flowtime of job  $j$ . It is the amount of time job  $j$  spends in the system.  $F_j = C_j - r_j$ .

$d_j$  = due date of job  $j$ .

$L_j$  = Lateness of job  $j$ .  $L_j = C_j - d_j$ . It measures the amount by which a job is early or late.

$T_j$  = Tardiness of job  $j$ .  $T_j = \max(0, L_j)$ . It measures only the positive lateness.

The performance criteria commonly used in job shop scheduling are:

$$(a) \text{ mean flowtime} = \bar{F} = \frac{1}{n} \sum_{j=1}^n F_j$$

It has been generally accepted that by minimising the mean flowtime, the overall performance of the system will be improved. Shorter jobs are given preference to reduce the waiting time of other jobs.

$$(b) \text{ mean tardiness} = \bar{T} = \frac{1}{n} \sum_{j=1}^n T_j$$

Most of the due date oriented dispatching rules are aimed at minimising mean tardiness.

$$(c) \text{ maximum flowtime} = F_{\max} = \max_{1 \leq j \leq n} \{F_j\}$$

Since maximum flowtime is related to the maximum number of jobs

in the shop [31]. Therefore minimising the maximum flowtime will tend to reduce the maximum number of jobs in the system.

$$(d) \text{ Maximum tardiness} = T_{\max} = \max_{1 \leq j \leq n} \{T_j\}$$

A problem commonly encountered in minimising the mean flowtime or mean tardiness is that some low priority jobs will never be processed. Minimising the maximum flowtime or maximum tardiness overcomes this problem.

(e) Mean work-in-process inventory can be based on the average number of jobs in the shop during the interval from  $t_1$  to  $t_2$ .

$$\bar{N}(t_1, t_2) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} N(t) dt$$

or the sum of the processing times of all operations on all jobs in the shop at time  $t$ :

$$\bar{P}(t_1, t_2) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} P(t) dt.$$

(f) Facility utilisation: It is the fraction of the total time during which the facility is engaged in a productive activity or a required process.

For most steady state processes, these measures have been proven to exhibit the following interrelationships [31].

(a) the mean flowtime is directly proportional to the mean work-in-process inventory.

- (b) the mean flowtime differs from the mean lateness and the mean waiting time by a constant amount.
- (c) a scheduling procedure which is relatively good with respect to any one of these mean values is comparably good with respect to each of the others, and
- (d) a scheduling procedure which minimises mean flowtime also minimises mean lateness, mean waiting time, and the mean number of jobs in the system.

Since it is impractical to include every possible criteria in the performance output, only those performance measures which are most relevant in the design stage of FMS are incorporated into the model. They are the production statistics (including flowtime) and the utilisation of the various facilities (stations, shuttle and carts).

#### 4.5.2 Evaluation of performance measures

The performance output collected by the model is divided into five categories:

- (1) Production summary
- (2) station performance
- (3) shuttle performance
- (4) cart performance
- (5) pallet performance

4.5.2.1 Part production summary: It reports for each part type the number of parts completed, percentage of number of parts completed to the total number of parts scheduled, the

minimum, maximum and mean flowtime. Performance can be judged by comparing the average flowtime to its total processing time. With allowances provided for transportation of parts, congestion will become apparent. Maximum flowtime allows us to predict the due date for a part and draw conclusions on due date oriented performance measures. Arrays are used in the program to keep track of the stock level of raw materials and the number of completed parts. The duration of time during which a part is in the system is then calculated and collected in array SSOBV by the GASP subroutine COLCT. Subroutine COLCT gathers sample data for variables based on an observation of the variable when used in the collection mode. In the computation and reporting mode it calculates the mean, standard deviation, minimum, maximum and number of observations. At the end of the simulation, these values stored in SSOBV are printed out.

4.5.2.2 Station performance summary: It includes the time while the station is busy, idle and down. It also calculates their percentage with respect to the total simulation time. The busy time takes into consideration the time when the station is used in processing a part excluding the loading and unloading to and from the shuttle. It also excludes the time when a part continues to occupy the station when the outgoing shuttle is full. This set of statistics provides a measure of station utilisation and identifies the station which constitutes a bottleneck in the system. Array TATSS is used

to collect the station performance statistics. Within the array, a time status vector is used to keep track of the time when the status of a station changes. When an operation is completed at a station, the duration from the previous status change is recorded as busy time. When a station begins an operation the status of the station is checked, depending on whether the station was idle or down, the duration will be recorded as idle time or down time respectively. When a station fails, the duration from a previous status change is recorded as idle or busy time depending on whether the station is idle or busy at the time of breakdown.

4.5.2.3 Shuttle performance summary: It includes the utilisation of incoming, outgoing and common shuttles. The maximum queue size observed during the entire simulation is also recorded to provide a measure of the congestion in each shuttle. If a station has a long idle time and a high utilisation of outgoing shuttles, the congestion is most likely the result of a congested shuttle. GASP subroutine TIMST is used to collect and compute the shuttle performance which are basically time persistent variables.

4.5.2.4 Cart performance summary: It includes the time when the cart is busy, idle, waiting and down. Waiting time refers to the time when the cart is waiting at the station for loading or unloading because of a congested shuttle. These pieces of information are collected in array CSTAT and updated every

information is collected for stations. The utilisation of carts provides a measure of whether sufficient carts are available.

4.5.2.5 Pallet performance summary: It includes the maximum number of pallets used and the utilisation of pallets. The information is gathered by the GASP subroutine TIMST and stored in array SSTPV. Since SSTPV is also used for storing shuttle statistics, it is divided into four segments. The first segment occupying the first 10 sets of data (for a maximum of 10 pallet types) is reserved for pallet statistics. The shuttle statistics on incoming, outgoing and common shuttle share the remaining 45 sets of data (for a maximum of 15 stations).

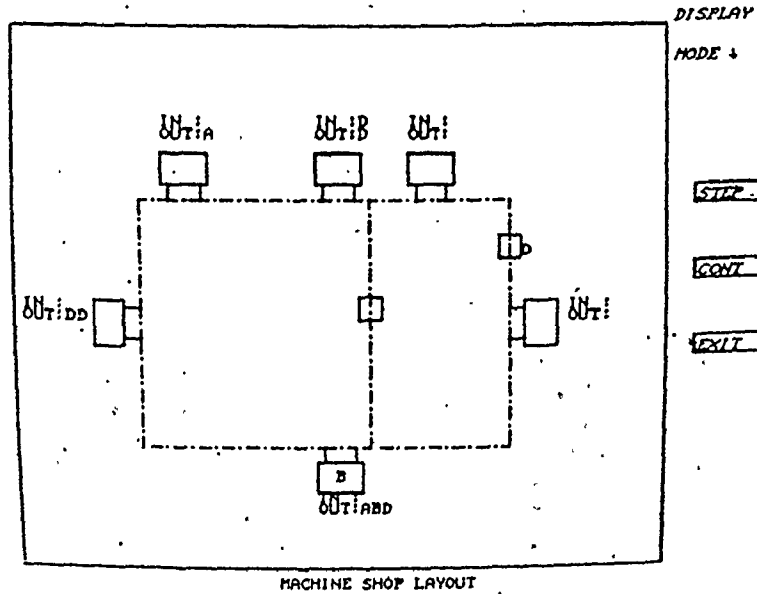
A typical printout of the system performance summary is shown in Appendix G.

#### 4.6 Graphical Output

A typical graphical display is shown in Fig. 4.6. It consists of a schematic layout of the system which remains practically unchanged throughout the simulation and the movement of parts and carts which are updated after each event. It also displays a clock which indicates the time at which the status of the system is represented. The production of each part type is also shown. A congested shuttle, breakdown of stations or carts are represented by flashing that part on the display screen.

CURRENT TIME: 48.50

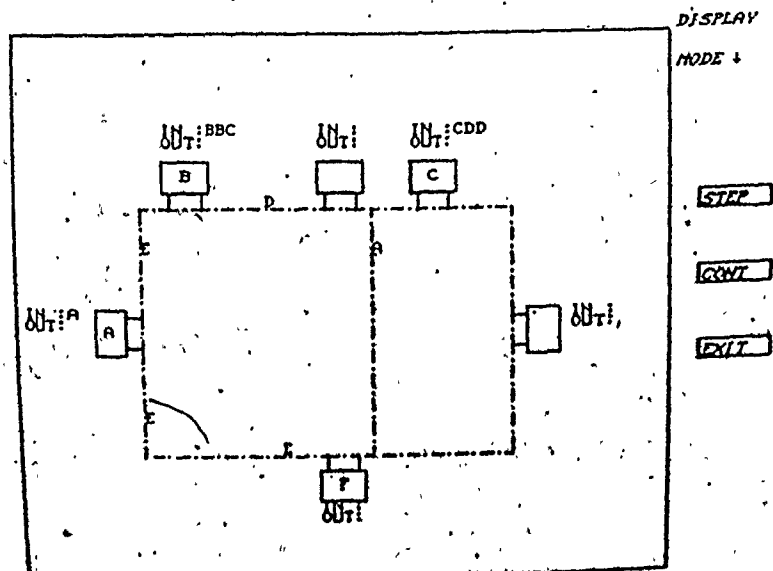
PART TYPE	A	B	C	D	E	F
PART COMP	0	0	0	0	0	0



### Graphical Display for Cart System.

CURRENT TIME: 17.90

PART TYPE	A	B	C	D	E	F
PART COMP	0	0	0	0	0	0



The simulation and graphics are two separate programs. Information on the status of the system, required for the graphical output, is collected during the simulation and recorded in a display status file (Fig. 4.7).

The period during which the display is required can be specified at the beginning of the simulation. The program also allows the user to establish the display file under a name specified by him. The graphical output can therefore be examined without repeating the simulation program. The separation of the simulation and graphical animation also helps to reduce the computer storage requirement and hence allows the simulation of a bigger system requiring a larger working memory.

There are basically two modes of display viz. single step and continuous display. In single step display, the display proceeds in single steps, at the command of the user. It allows the user to examine the system status carefully. Continuous display provides an uninterrupted graphical animation of the simulated system.

#### 4.7 Verification and Validation

"Verification is the process of establishing that the computer program executes as intended. Validation is the process of establishing that a desired accuracy or correspondence exists between the simulation model and the real system " [32].

It was therefore very important to verify and validate the computer simulation package prior to its use in actual design work.

1	2	3	4	5	6	7	8	9	10
Part Type In Station	Part Types at In-shuttle			Part Types at Out-Shuttle			Station Breakdown Flag	In-Shuttle Full Flag	Out-Shuttle Full Flag

4.7(a) Display Status Files for Station  
(one record for each station)

1	2	3	4	5	6
x-coor. of Cart	y-coor. of Cart	Part Types in Cart			Cart Breakdown Flag

4.7(b) Display Status Files for Cart  
(one record for each cart)

1	2	3
Part No. on Pallet	x-coor. of pallet	y-coor. of pallet

4.7(c) Display Status Files for Pallets Travelling on  
Conveyor (only pallets on conveyor are recorded,  
one record for each pallet)

Fig. 4.7 Structure of Display Status Files

Two different methods have been used to verify the FMSSIM model. The first method was to conduct a manual emulation of the system and record the sequence of events that would have occurred. This is then compared with the sequence of events from the intermediate output of the model. This procedure is thorough but time consuming. It was therefore conducted on a few selected cases for a relatively short duration (about 200 to 300 events).

The second method was to check the graphical output provided by the model. This method provided a quick way of checking the more obvious errors and any anomalies in the operation of the system such as interference of carts, sequences in which parts go through the system, etc.

Common procedures used in model validation involve a comparison of the model results and the actual system performance. Since data on most existing FMS are proprietary, we could only compare the general trend in which the system performance varies with the change of parameters. The findings were then checked with some published results from secondary sources. Also models of simpler systems have been constructed using a different language (GPSS) and run on the CDC 6400. The results were compared with those obtained from the FMSSIM simulator.

Case studies have been designed not only to demonstrate how the model can be used to analyse different system configurations and scheduling rules but also to subject the model to different sets of parameters for verification and validation.

A detailed description of these case studies is the subject of Chapter 5.

## CHAPTER 5

### CASE STUDIES

#### 5.1 Description of the Case

A hypothetical case has been selected to demonstrate how the FMSSIM simulator can be used by a system designer to assess a proposed flexible manufacturing system. The hypothetical system is designed to manufacture a family of six different types of wear plates for centrifugal pumps. The process plans of each part type are given in Appendix J. To reduce the input data required by the simulator, all consecutive operations to be performed in the same station are grouped into a single operation whose processing time is equal to the aggregate process time of all operations including tool change as shown in the process plans (Appendix J). These parts are mainly rotary parts with turning being the major operation, and drilling and milling as minor operations. It is assumed that the raw castings for each part type are in plentiful supply. The part type which is most near in its production will have highest priority at the loading station, provided a suitable pallet is available. Otherwise the part type which is next near in production will be introduced until all available pallets have been loaded into the system. When a part is completed, it is returned to the loading station to be removed from its pallet. Another part

will then be introduced. The parts which require a change of pallet to carry them through the drilling and milling operations will be returned to the loading station for refixturing.

## 5.2 Simulation Procedure

In actual systems the machine selection is based on the machining requirements for all parts to be processed in the system. For the purpose of this case study, the system was first configured intuitively, as shown in Fig. 5.1. It consists of 6 stations: 1 loading station, 1 NC drill, 1 NC mill and 3 NC lathes. Each station has a dedicated in-shuttle and out-shuttle. The process times for each part type were taken from the process plans in Appendix J. A datafile was generated following the format explained in the user's manual (Appendix B). An echo of the input data can be obtained to check if they have been properly entered. The arrangement of data as they appear in the original data file and its echo printout obtained from the simulation program are shown in Appendix G.

Computer simulation experiments were conducted to analyse the effects of various system parameters by varying one parameter at a time. Intermediate system performance reports were collected and analysed to find out if the system has reached its steady state. In most cases, the system reaches a steady state after a duration of 600 units of system time (Min.) which is equivalent to a 10-hour work shift. If steady

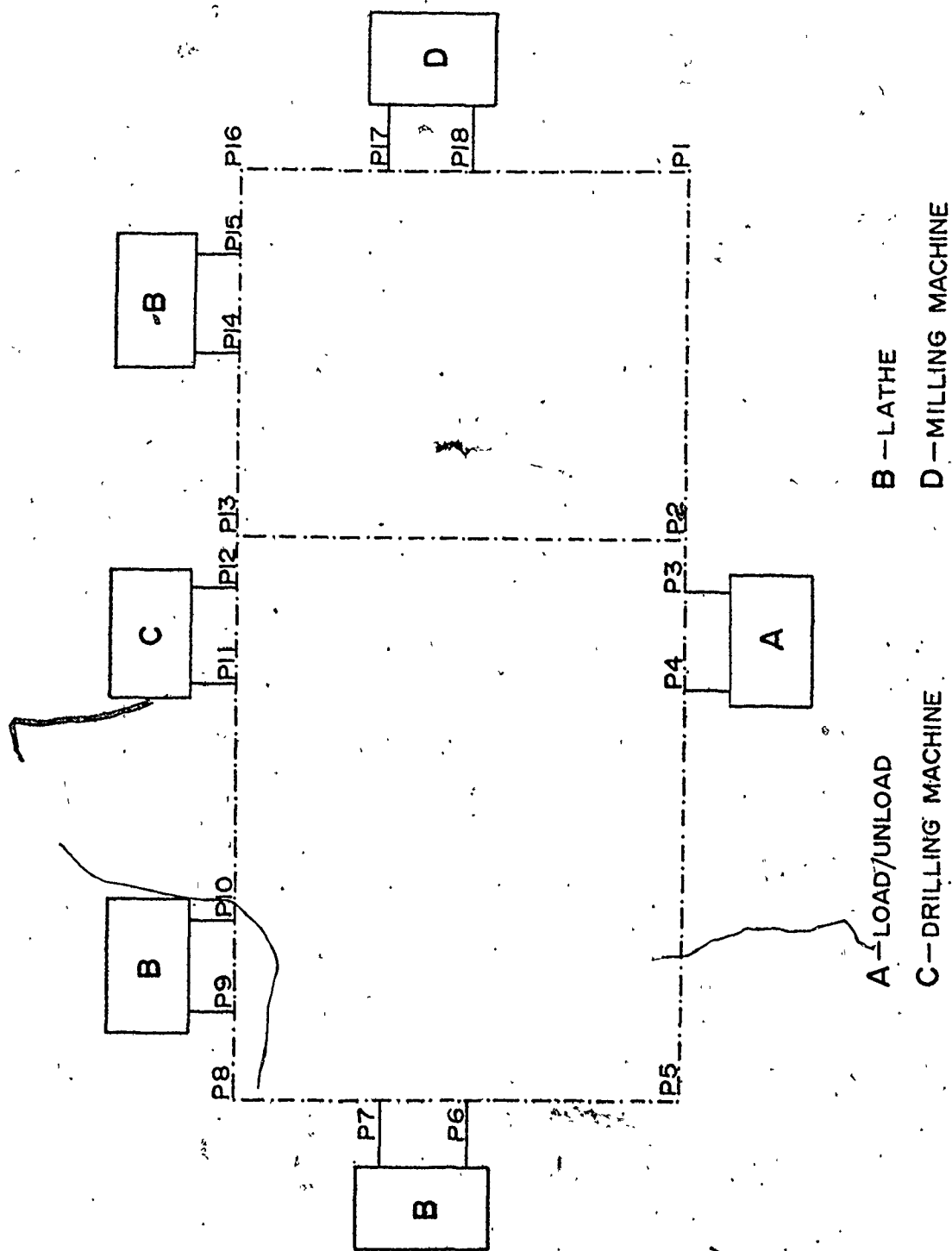


Fig. 5.1 Layout of Proposed System Used in Case Studies.

state has not been reached after this time period, the simulation was continued for another 200 time units and the process would be repeated until a steady state was obtained. Steady state analyses were based on production rate, total amount of work performed, station utilisation, shuttle utilisation and cart utilisation (if carts were used).

The following is a list of experiments conducted on the chosen hypothetical system.

- (a) Experiment 1: A conveyor was used for material handling. The sensitivity of the system in response to variation in conveyor speed was studied. The results are summarised in Table 5.1.
- (b) Experiment 2: A tow cart system utilizing a unidirectional track was used for material handling. The sensitivity of the system in response to variation in cart number and speeds was studied. The results are summarised in Tables 5.2 and 5.3.
- (c) Experiment 3: The effects of in-shuttle capacity on both the conveyor and tow-cart system were studied. The results are summarised in Table 5.4.
- (d) Experiment 4: The effects of out-shuttle capacity on both the conveyor and tow-cart systems were studied. The results are summarised in Table 5.5.

- (e) Experiment 5: The effects of number of pallets was examined for the conveyor system. The effects of introducing an additional lathe machine was also examined: The results are summarised in Table 5.6.
- (f) Experiment 6: Effects of different scheduling rules were examined. The results are summarised in Table 5.7.
- (g) Experiment 7: The effects of changing the topology of the system by removing the bypass was examined for a conveyor system. The results are summarised in Table 5.8.

### 5.3 Results and Discussion

The major findings obtained from the outcomes of these simulation experiments are summarised as follows:

#### 5.3.1 Comparison of different material handling systems

The results of Experiments 1 and 2 show that the conveyor is a better material handling system in comparison with tow-carts neglecting the factors of economy, reliability and physical limitations associated with the two systems. Its use results in a higher total work done (Fig. 5.2), especially at lower transportation speed, and higher station utilisation (Fig. 5.3). It reduces congestion by providing additional in-process storage space on the conveyor itself. Since

CONVEYOR SPEED (FT/MIN)	SIMULATION TIME (MIN) (to steady state)	TOTAL NUMBER OF PARTS PRODUCED	TOTAL PROCESSING TIME OF ALL STATIONS (MIN)	AVERAGE % UTILIZATION OF LATHES	AVERAGE QUEUE SIZE AT IN-SHUTTLE	AVERAGE QUEUE SIZE AT OUT-SHUTTLE (NO. OF PARTS)
100	600	84	2232	94.9	0.92	0.01
200	600	87	2405	97.1	1.66	0.01
300	600	86	2400	97.4	1.69	0.01
400	600	88	2405	97.5	1.84	0.01
500	600	86	2416	97.5	1.83	0.01

TABLE 5.1 SUMMARY OF RESULTS FOR EXPERIMENT 1.

NUMBER OF CARTS	SIMULATION TIME (MIN) (to steady state)	A = TOTAL NUMBER OF PARTS PRODUCED, B = TOTAL PROCESSING TIMES OF ALL STATIONS C = AVERAGE % UTILIZATION OF LATHES																	
		CART SPEEDS																	
		100 FT/MIN			200 FT/MIN			300 FT/MIN			400 FT/MIN			500 FT/MIN					
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
1	600	19	680	28.0	44	1385	51.8	65	1903	79.0	76	2182	89.8	82	2348	96.6			
2	600	33	1083	43.7	72	2034	75.0	81	2298	94.9	83	2365	97.1	85	2390	97.4			
3	600	48	1457	58.9	80	2300	92.7	81	2300	95.3	82	2297	94.3	85	2408	97.4			
4	600	60	1721	70.7	83	2363	96.3	83	2316	95.7	84	2409	97.2	85	2418	97.5			
5	600	66	1898	79.1	81	2343	96.0	84	2395	97.2	87	2398	97.4	86	2405	97.5			
6	600	76	2182	87.7	84	2364	96.5	84	2373	97.2	85	2410	97.3	85	2394	97.5			

TABLE 5.2 SUMMARY OF RESULTS FOR EXPERIMENT 2.

NUMBER OF CARTS	SIMULATION TIME (MIN) (to steady state)	CART SPEEDS														
		100 FT/MIN			200 FT/MIN			300 FT/MIN			400 FT/MIN			500 FT/MIN		
		C	D	E	C	D	E	C	D	E	C	D	E	C	D	E
1	600	0.06	1.06	94.3	0.20	1.47	89.1	0.52	1.24	84.6	0.71	0.63	82.2	1.16	0.32	80.4
2	600	0.12	0.99	92.9	0.42	0.40	87.9	1.06	0.29	79.8	1.40	0.16	67.7	1.56	0.11	65.8
3	600	0.33	0.81	91.3	1.01	0.32	80.6	1.17	0.12	55.0	1.34	0.08	44.7	1.54	0.05	41.5
4	600	0.46	0.60	88.5	1.23	0.16	66.3	1.23	0.09	38.0	1.53	0.06	35.2	1.54	0.05	31.0
5	600	0.46	0.37	80.1	1.21	0.14	46.6	1.51	0.08	33.8	1.57	0.06	26.6	1.54	0.05	22.0
6	600	0.82	0.30	72.1	1.35	0.12	40.9	1.51	0.08	26.2	1.50	0.06	20.8	1.53	0.05	18.4

TABLE 5.3 SUMMARY OF RESULTS FOR EXPERIMENT 2 (CONT.).

TYPE OF TRANSPORTER AND SPEED	SIMULATION TIME (MIN) (to steady state)	A = TOTAL NUMBER OF PARTS PRODUCED B = TOTAL PROCESSING TIME FOR ALL STATIONS (MIN) C = AVERAGE UTILIZATION OF LATHES (%) D = AVERAGE QUEUE SIZE AT IN-SHUTTLES FOR LATHES (NO. OF PARTS) E = AVERAGE IN-SHUTTLE UTILIZATION (%)														
		IN-SHUTTLE CAPACITY (NUMBER OF POSITIONS FOR PARTS)														
		0					1					2				
		A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
2 CARTS (100 FT/MIN)	600	26	856	35.2	0.00	0.0	37	1105	45.3	0.13	13.0	39	1091	43.7	0.14	7.0
2 CARTS (200 FT/MIN)	600	50	1500	58.5	0.00	0.0	69	1971	81.0	0.32	32.0	68	2004	82.6	0.51	25.5
2 CARTS (300 FT/MIN)	600	68	1898	77.1	0.00	0.0	77	2195	89.5	0.54	54.0	81	2300	94.7	1.06	53.0
CONVEYOR (100 FT/MIN)	600	71	2023	82.1	0.00	0.0	83	2356	96.0	0.69	69.0	84	2353	95.1	0.93	46.5

TABLE 5.4 SUMMARY OF RESULTS FOR EXPERIMENT 3.

TRANSPORTER AND SPEED	SIMULATION TIME (MIN)  (to steady state)	OUT-SHUTTLE CAPACITY (NUMBER OF POSITIONS FOR PARTS)																					
		0					1					2					3						
		A	B	C	D	E		B	C	D	E		A	B	C	D	E		A	B	C	D	E
2 CARTS (300 FT/MIN)	600	68	1952	79.7	0.00	0.0	82	2321	94.8	0.29	29.0	81	2298	94.7	0.30	15.0	83	2342	95.0	0.30	10.0		
2 CARTS (200 FT/MIN)	600	56	1608	65.4	0.00	0.0	62	1823	74.8	0.52	52.0	68	2034	75.0	0.57	28.5	72	2061	76.2	0.58	19.3		
2 CARTS (100 FT/MIN)	600	32	1018	42.1	0.00	0.0	35	1086	45.1	0.70	70.0	33	1088	44.7	0.84	42.0	36	1092	44.6	1.03	34.3		
CONVEYOR (100 FT/MIN)	600	83	2336	94.4	0.00	0.0	84	2383	95.1	0.01	1.0	84	2353	95.1	0.01	0.5	84	2353	95.1	0.01	0.3		

TABLE 5.5 SUMMARY OF RESULTS FOR EXPERIMENT 4.

NUMBER OF LATHES	SIMULATION TIME (MIN) (to steady state)	NUMBER OF PALLETS															
		8				12				16				20			
		A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
3	600	73	1980	79.5	0.43	84	2232	94.9	1.25	81	2347	96.9	1.69	77	2346	96.8	1.79
4	600	76	2046	61.8	0.23	99	2805	86.1	0.44	100	2917	89.6	0.92	103	3021	94.4	1.01

TABLE 5.6 SUMMARY OF RESULTS FOR EXPERIMENT 5.

SCHEDULING RULES	SIMULATION TIME (MIN)	TOTAL NUMBER OF PARTS PRODUCED	TOTAL PROCESSING TIME (MIN)	AVERAGE NUMBER OF PARTS IN IN-SHUTTLE	STATION UTILISATION				NUMBER OF PARTS PRODUCED FOR EACH PART TYPE						AVERAGE THROUGHPUT TIME FOR EACH PART TYPE (MIN)					
					LATHES	LOADING	DRILLING	MILLING	PART TYPE 1	PART TYPE 2	PART TYPE 3	PART TYPE 4	PART TYPE 5	PART TYPE 6	PART TYPE 1	PART TYPE 2	PART TYPE 3	PART TYPE 4	PART TYPE 5	PART TYPE 6
SPT	600	101	2468	2.48	96.3	72.9	28.6	21.7	8	2	28	21	23	19	181	70	62	78	73	83
FOPNR	600	85	2270	2.65	96.6	61.9	24.6	2.5	19	19	22	3	20	2	89	88	75	155	80	267
FIFO	600	87	2362	2.65	96.5	64.0	25.9	16.4	13	15	15	14	15	15	107	117	102	110	109	109
RANDOM	600	88	2368	2.62	96.6	64.1	25.4	15.5	15	13	17	15	15	13	102	126	86	114	108	118

Table 5.7 Summary of Experiment 6.

TOPOLOGY	SIMULATION TIME (MIN)	TOTAL NUMBER OF PARTS PRODUCED	TOTAL PROCESSING TIME FOR ALL STATIONS (MIN)	AVERAGE NUMBER OF PARTS IN IN-SHUTTLE	AVERAGE STATION UTILISATION (%)				AVERAGE THROUGHPUT TIME (MIN)					
					LATHES	LOADING	DRILLING	MILLING	PART TYPE 1	PART TYPE 2	PART TYPE 3	PART TYPE 4	PART TYPE 5	PART TYPE 6
WITH BYPASS	600	87	2372	2.65	96.6	64.0	25.9	16.4	107	116	102	110	109	109
WITHOUT BYPASS	600	86	2358	2.61	96.5	63.5	25.4	15.0	114	118	103	115	105	116

Table 5.8 Summary of Experiment 7.

# EFFECTS OF TRANSPORTER SPEED

Data File FMSDT1.DAT

System Layout : FIG. 5.1

MHS : AS INDICATED

Number of Carts : AS INDICATED

Cart Speed : AS INDICATED

Out Shuttle Capacity: 2 POSITIONS

In Shuttle Capacity : 2 POSITIONS

Number of Pallets : 12 PALLETS

Simulation Time 600 MIN.

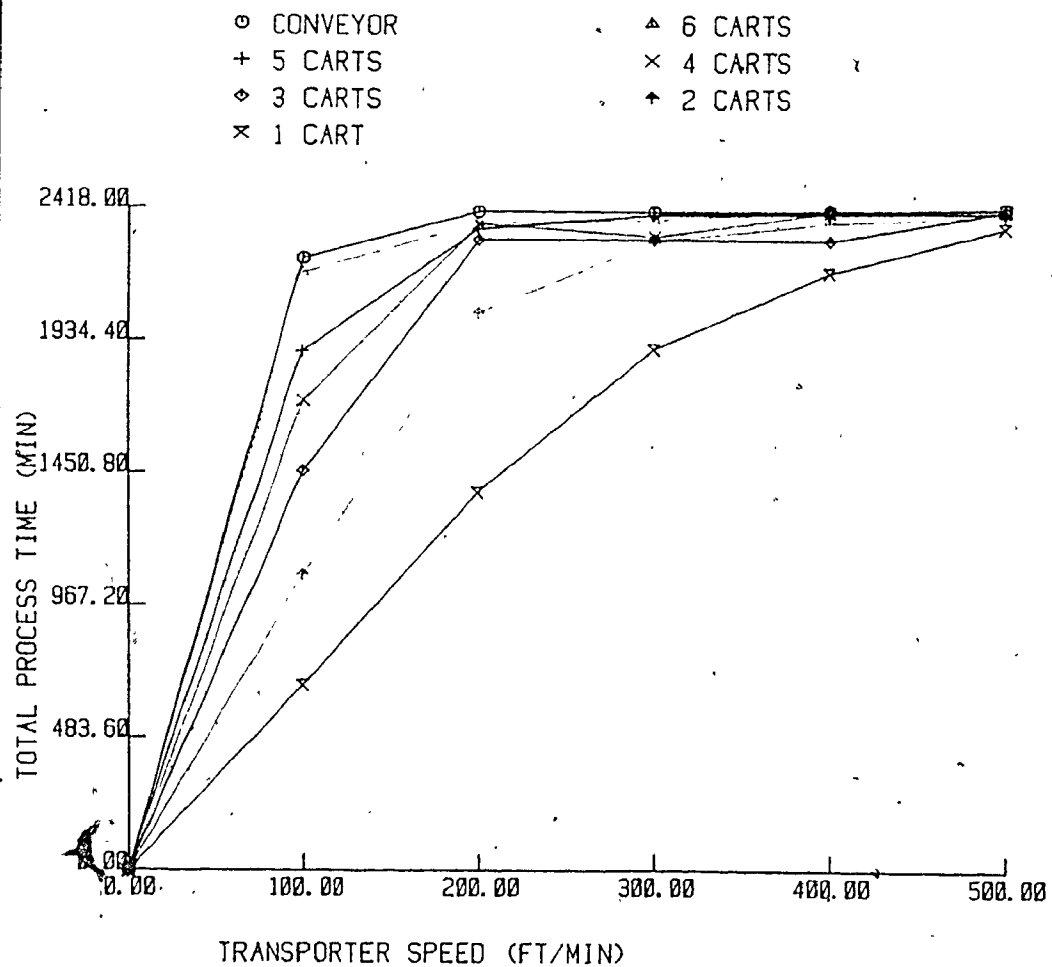


Fig. 5.2 Effects of Transporter Speed on Production.

## EFFECTS OF TRANSPORTER SPEED

Data File FMSDT1.DAT

System Layout : FIG. 5.1  
 MHS : AS INDICATED  
 Number of Carts : AS INDICATED  
 Cart Speed : AS INDICATED  
 Out Shuttle Capacity: 2 POSITIONS  
 In Shuttle Capacity : 2 POSITIONS  
 Number of Pallets : 12 PALLETS

Simulation Time 600 MIN.

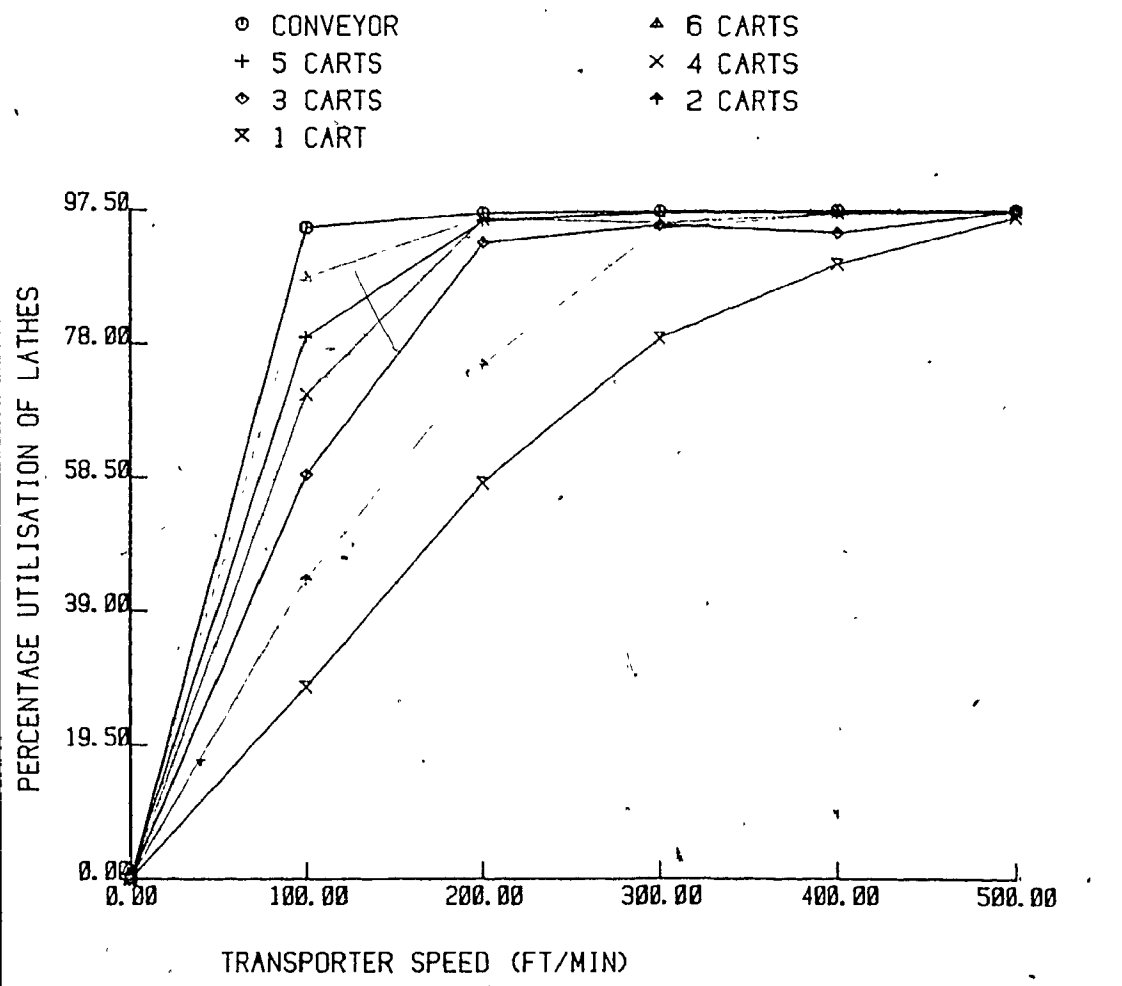


Fig. 5.3 Effects of Transporter Speed on Station Utilisation.

different part types have different work content, the total number of parts completed do not provide an accurate representation of the production rate of the system. The total busy time for all stations is used for comparison instead. In most cases, it still agrees quite well with the total number of parts completed. As for the station utilisation, only the utilisation of the lathes are shown since they are the most heavily utilised and hence most critical in their effects on the system performance.

For both material handling systems, the total processing time (Fig. 5.2) and station utilisation (Fig. 5.3) exhibit the same general trend. They increase with the transporter speed and the number of carts in the case of a cart system. When the system approaches its saturation state, neither the transporter speed nor the number of carts have any significant effects on the system performance.

In the case of a cart system, the cart utilisation tends to decrease as the number of carts and their speeds increase (Fig. 5.4). Increasing the number of carts reduces an individual cart's share of the total workload. Higher cart speed results in shorter transportation time, hence a lower cart utilisation.

The in-shuttle queue size also increases as the number of carts and cart speed increase (Fig. 5.5). Opposite trends are exhibited by the out-shuttle (Fig. 5.6). This is predictable since both an increase in the number of carts and their speeds will facilitate the removal of parts from the

## EFFECTS OF TRANSPORTER SPEED

Data File FMSDT1.DAT

System Layout : FIG. 5.1  
 MHS : AS INDICATED  
 Number of Carts : AS INDICATED  
 Cart Speed : AS INDICATED  
 Out Shuttle Capacity: 2 POSITIONS  
 In Shuttle Capacity : 2 POSITIONS  
 Number of Pallets : 12 PALLETS

Simulation Time 600 MIN.

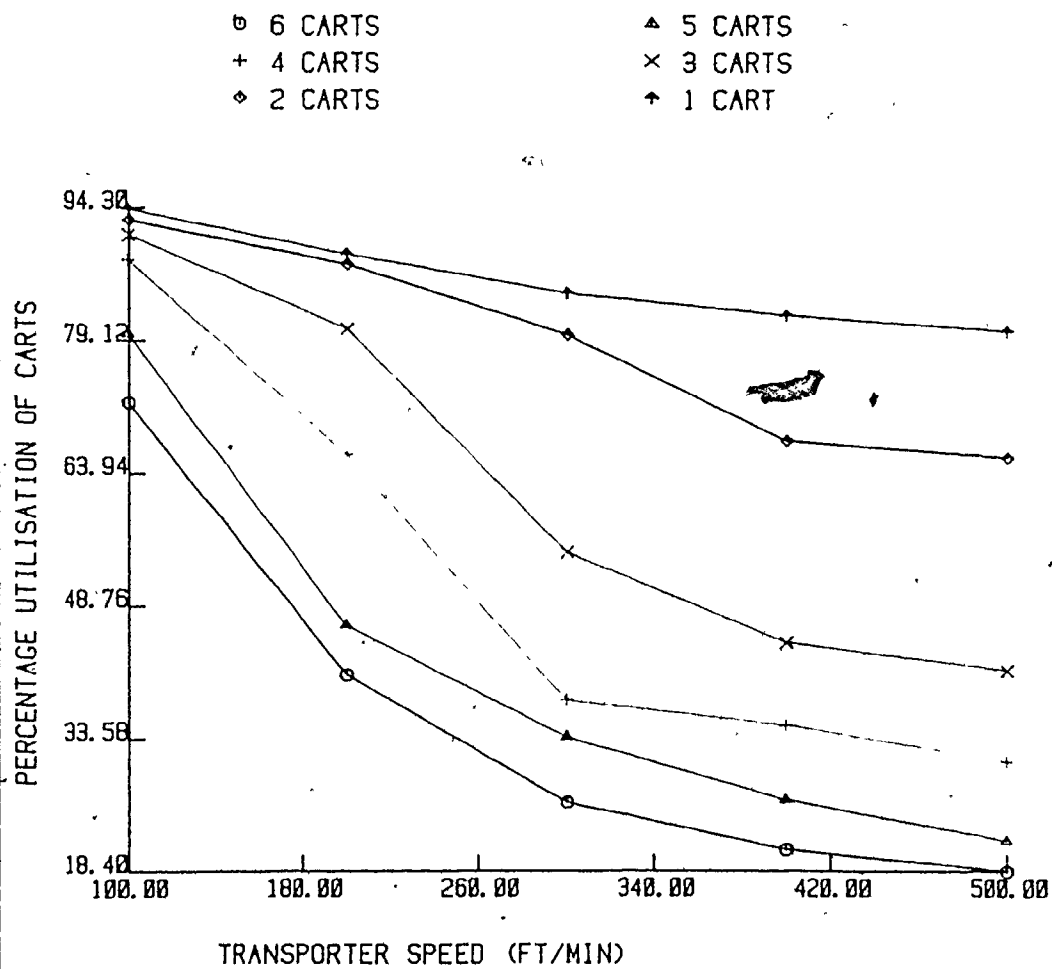


Fig. 5.4 Effects of Transporter Speed on Cart Utilisation.

# EFFECTS OF TRANSPORTER SPEED

Data File FMSDT1.DAT

System Layout : FIG. 5.1  
 MHS : AS INDICATED  
 Number of Carts : AS INDICATED  
 Cart Speed : AS INDICATED  
 Out Shuttle Capacity: 2 POSITIONS  
 In Shuttle Capacity : 2 POSITIONS  
 Number of Pallets : 12 PALLETS

Simulation Time 600 MIN.

○ CONVEYOR  
 + 5 CARTS  
 ◇ 3 CARTS  
 × 1 CART  
 ▲ 6 CARTS  
 × 4 CARTS  
 + 2 CARTS

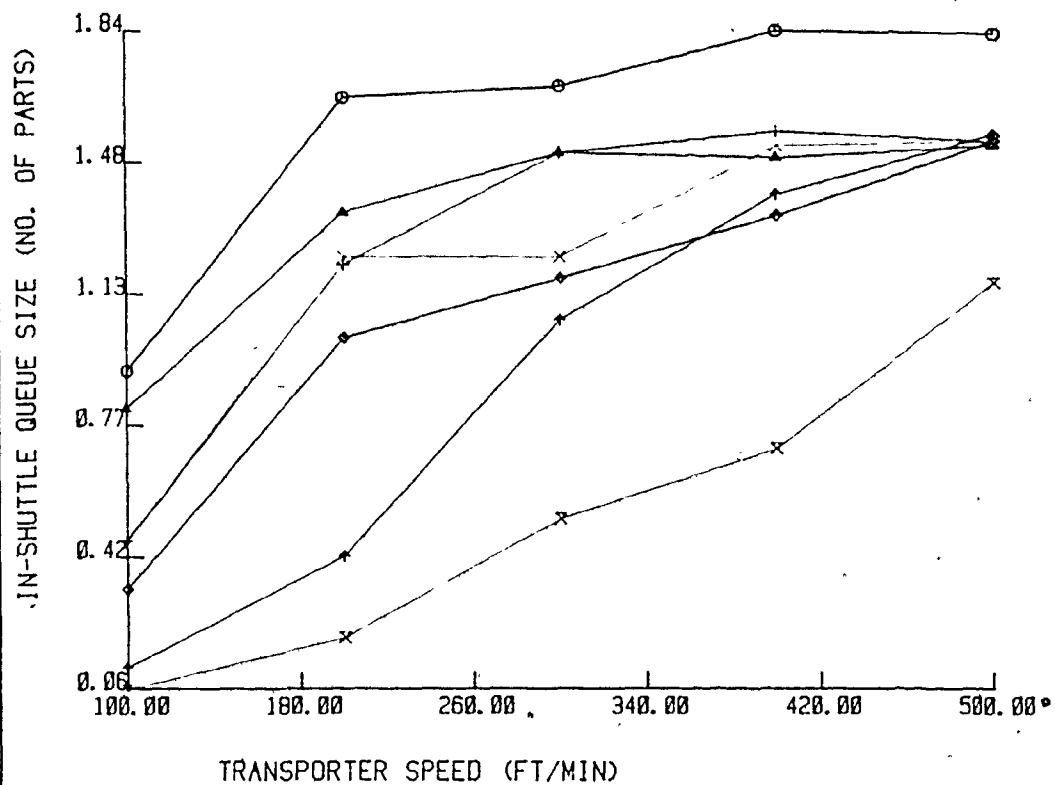


Fig. 5.5 Effects of Transporter Speed on In-shuttle Queue Size.

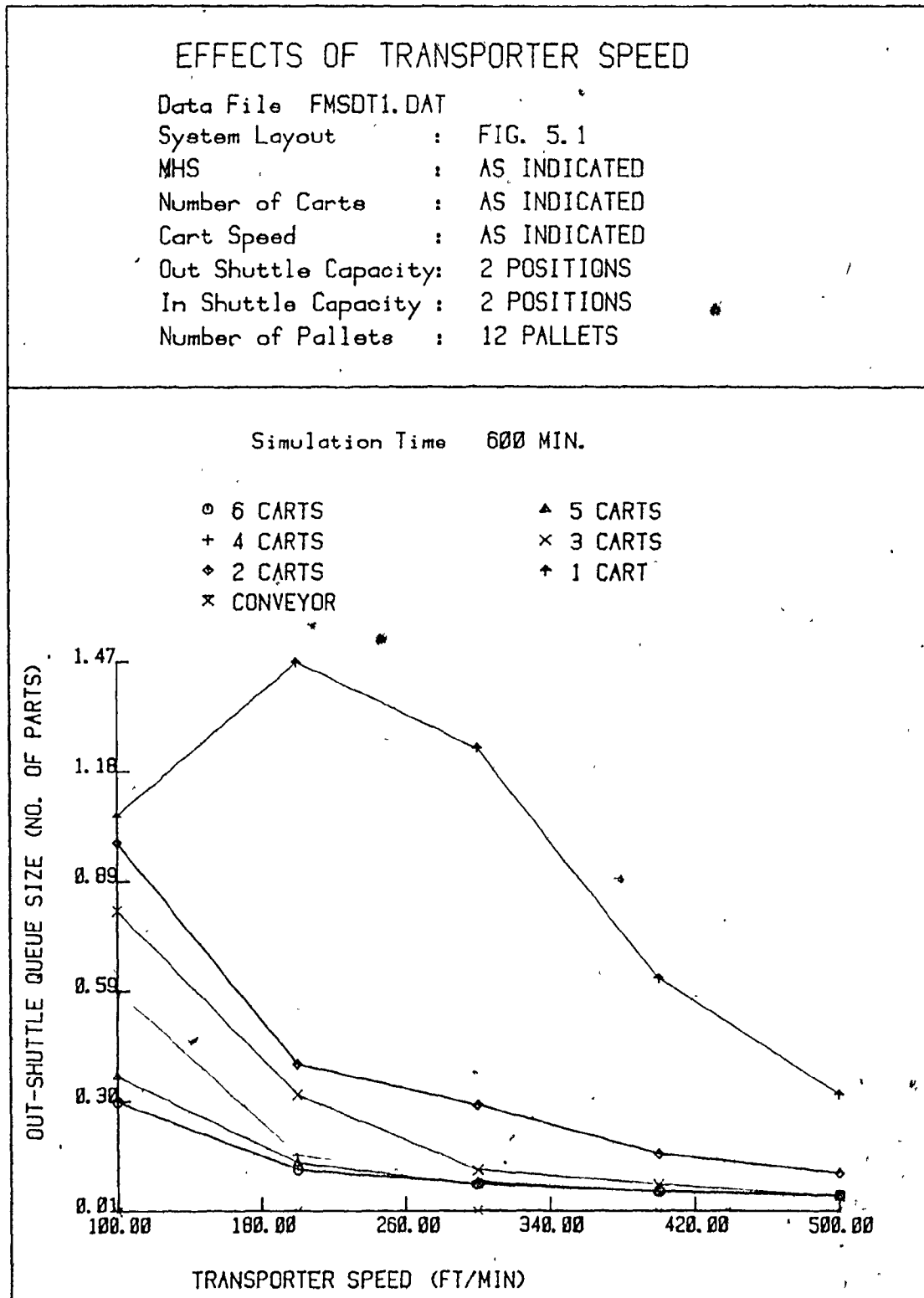


Fig. 5.6 Effects of Transporter Speed on Out-shuttle Queue Size.

out-shuttle and bring in parts to the in-shuttle at a faster rate. This has an effect of shifting the load from the out-shuttles to the in-shuttles.

The conveyor can be considered as an infinite number of carts since it is always available when needed. As a result, if conveyor is used, the out-shuttle queue size is practically nil (Fig. 5.6). The in-shuttle is the bottleneck of such a system. Higher station utilisation can be ensured by the provision of sufficient queueing space at the in-shuttles.

Examining Fig. 5.3 when a tow-cart system is used; the ideal case appears to be 3 carts at 200 ft/min. Therefore, when 1 cart breaks down, the remaining 2 carts can still maintain a relatively high production rate. In fact if the speed of the remaining 2 carts can be increased to 300 ft/min., the system will have as high a production and station utilisation as that having 3 carts running at 200 ft/min.

### 5.3.2 Effects of in-shuttle capacity

The main function of an in-shuttle is to provide in-process storage space for the incoming parts. This helps to ensure a steady supply of parts to the station. Since it is very costly to keep an expensive machine idle, it is always desirable to have as much storage space as possible before the machine. However, limited floor space often does not allow for excessive queuing. Some trade-offs must therefore be made based on the results of simulation as well as all

other factors.

The sensitivity of the system performance in response to the change in the in-shuttle capacity was studied for various cart speeds. The effects that in-shuttle capacity has on the station utilisation (only the average utilisation of the lathes was considered) and the average number of parts queuing at the in-shuttle of the lathes are shown in Figs. 5.7 and 5.8 respectively. In conducting these experiments, only the in-shuttle capacity of the lathes (the most heavily loaded machines) are altered. The queue sizes at other stations were held constant. The experiments were conducted for carts at various cart speeds (100, 200 and 300 ft/min.) as well as a conveyor transporter at 100 ft/min.

The results constitute strong evidence that, for the system under consideration, in-shuttle capacity of 1 part is sufficient to ensure very high station utilisation. There is however a significant improvement in the production rate as well as facility utilisation when the in-shuttle capacity increased from zero to 1 part.

From Fig. 5.9 it is also noted that the in-shuttle utilisation is very low for all cart speeds which indicates that in this particular case, the in-shuttle capacity is not critical. Since the number of pallets used in this case are small, the maximum number of parts floating in the system is expected to be small in all cases. The in-shuttle utilisation is higher at faster cart speeds simply because the cart is bringing in the parts at a faster rate, however,

# EFFECTS OF IN-SHUTTLE CAPACITY

Data File FMSDT2.DAT

System Layout : FIG. 5.1

MHS : AS INDICATED

Number of Carts : 2 CARTS

Cart Speed : AS INDICATED

Out Shuttle Capacity: 2 POSITIONS

In Shuttle Capacity : AS INDICATED

Number of Pallets : 12 PALLETS

Simulation Time 600 MIN.

○ CONVEYOR (100 FT/MIN)    ▲ CARTS (300 FT/MIN)  
+ CARTS (200 FT/MIN)    × CARTS (100 FT/MIN)

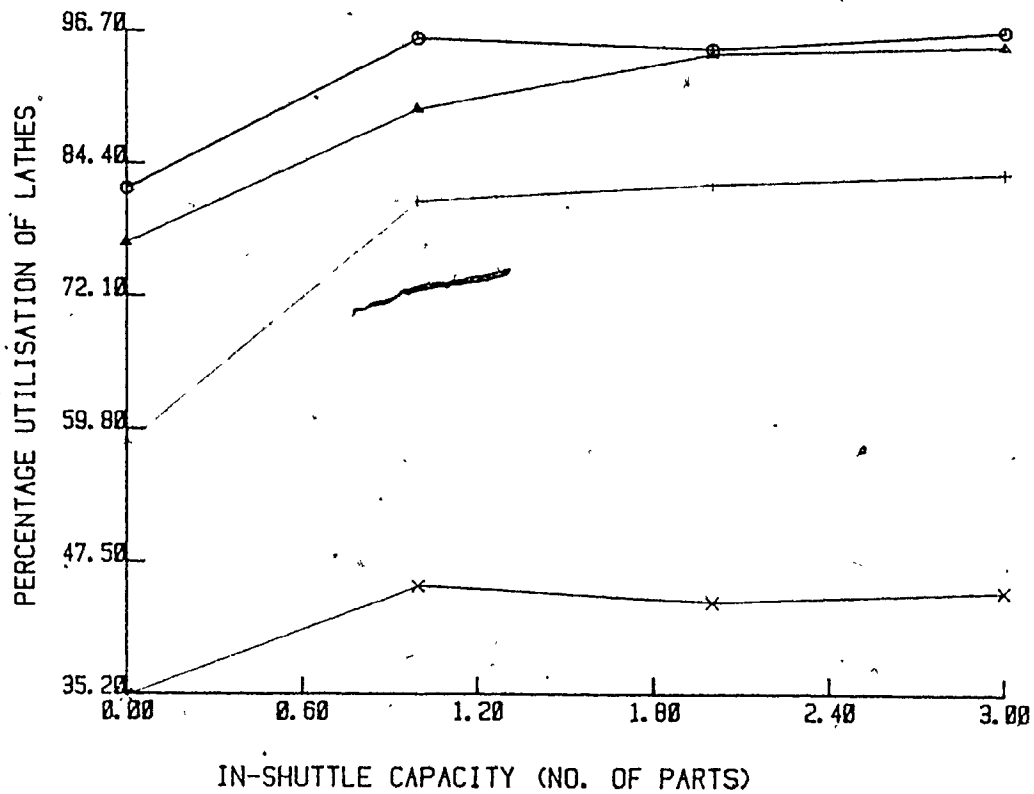


Fig. 5.7 Effects of In-shuttle Capacity on Station Utilisation.

# EFFECTS OF IN-SHUTTLE CAPACITY

Data File FMSDT2.DAT

System Layout : FIG. 5.1  
 MHS : AS INDICATED  
 Number of Carts : 2 CARTS  
 Cart Speed : AS INDICATED  
 Out Shuttle Capacity: 2 POSITIONS  
 In Shuttle Capacity : AS INDICATED  
 Number of Pallets : 12 PALLETS

Simulation Time 600 MIN.

○ CONVEYOR (100 FT/MIN)    ▲ CARTS (300 FT/MIN)  
 + CARTS (200 FT/MIN)    × CARTS (100 FT/MIN)

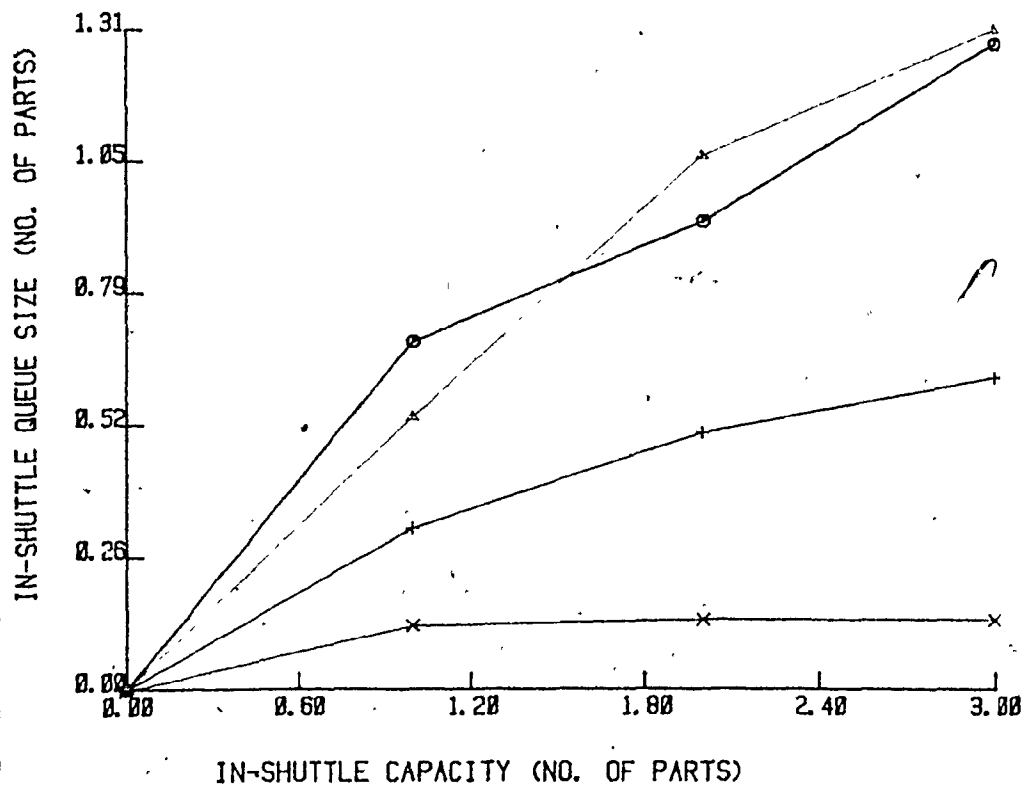


Fig. 5.8 Effects of In-shuttle Capacity on In-shuttle Queue Size.

# EFFECTS OF IN-SHUTTLE CAPACITY

Data File FMSDT2.DAT

System Layout : FIG. 5.1  
 MHS : AS INDICATED  
 Number of Carts : 2 CARTS  
 Cart Speed : AS INDICATED  
 Out Shuttle Capacity: 2 POSITIONS  
 In Shuttle Capacity : AS INDICATED  
 Number of Pallets : 12 PALLETS

Simulation Time 600 MIN.

○ CONVEYOR (100 FT/MIN)    ▲ CARTS (300 FT/MIN)  
 + CARTS (200 FT/MIN)    × CARTS (100 FT/MIN)

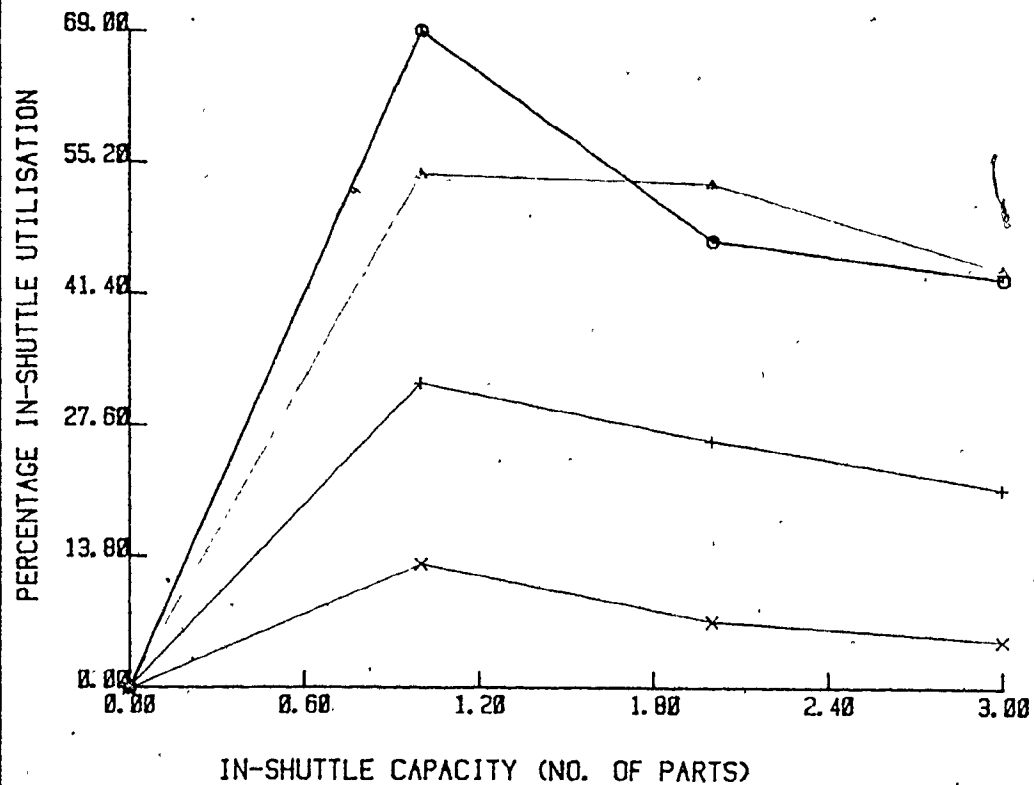


Fig. 5.9 Effects of In-shuttle Capacity on In-shuttle Utilisation.

they are far from saturation. If more pallets are used, this may no longer be true. This point will be studied later in this chapter.

### 5.3.3 Effects of out-shuttle capacity

Out-shuttles provide a temporary storage for parts leaving the station and waiting for the transporter to carry them to their next destination. A congested out-shuttle will cause a part to remain on the station after its operation is completed and thus keeping an expensive piece of equipment idle. It is therefore desirable to have as big a storage buffer in the out-shuttle as possible. However, the maximum size of an out-shuttle is again constrained by the floor space allocated to each station.

The effects of out-shuttle capacity on the station utilisation and queue size building up in the out-shuttle were studied for various cart speeds. As in the case of in-shuttle, only the out-shuttle capacity of the lathes were changed with in-shuttle capacity of other stations held constant.

The results show that in the case of the conveyor the average queue size at out-shuttle is always very low (Fig. 5.11). Since the conveyor is always available for the transportation of parts out of the stations, the parts never have to wait in the out-shuttle unless the conveyor breaks down. The out-shuttle capacity therefore has very little effect on the station utilisation in the case of a conveyor (Fig. 5.10).

# EFFECTS OF OUT-SHUTTLE CAPACITY

Data File FMSDT3.DAT

System Layout : FIG. 5.1  
 MHS : AS INDICATED  
 Number of Carts : 2 CARTS  
 Cart Speed : AS INDICATED  
 Out Shuttle Capacity: AS INDICATED  
 In Shuttle Capacity : 2 POSITIONS  
 Number of Pallets : 12 PALLETS

Simulation Time 600 MIN.

○ CONVEYOR (100 FT/MIN)    ▲ CARTS (300 FT/MIN)  
 + CARTS (200 FT/MIN)    × CARTS (100 FT/MIN)

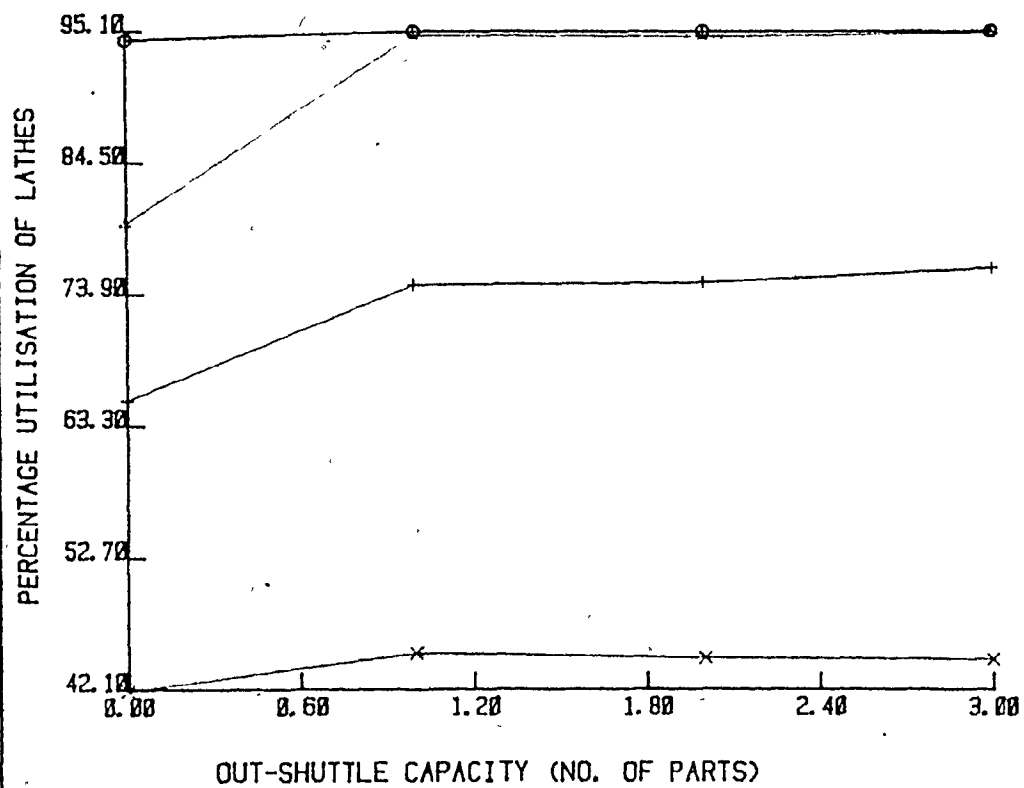


Fig. 5.10 Effects of Out-Shuttle Capacity on Station Utilisation.

# EFFECTS OF OUT-SHUTTLE CAPACITY

Data File FMSDT3.DAT  
 System Layout : FIG. 5.1  
 MHS : AS INDICATED  
 Number of Carts : 2 CARTS  
 Cart Speed : AS INDICATED  
 Out Shuttle Capacity: AS INDICATED  
 In Shuttle Capacity : 2 POSITIONS  
 Number of Pallets : 12 PALLETS

Simulation Time 600 MIN.

○ CONVEYOR (100 FT/MIN)    ▲ CARTS (300 FT/MIN)  
 + CARTS (200 FT/MIN)    × CARTS (100 FT/MIN)

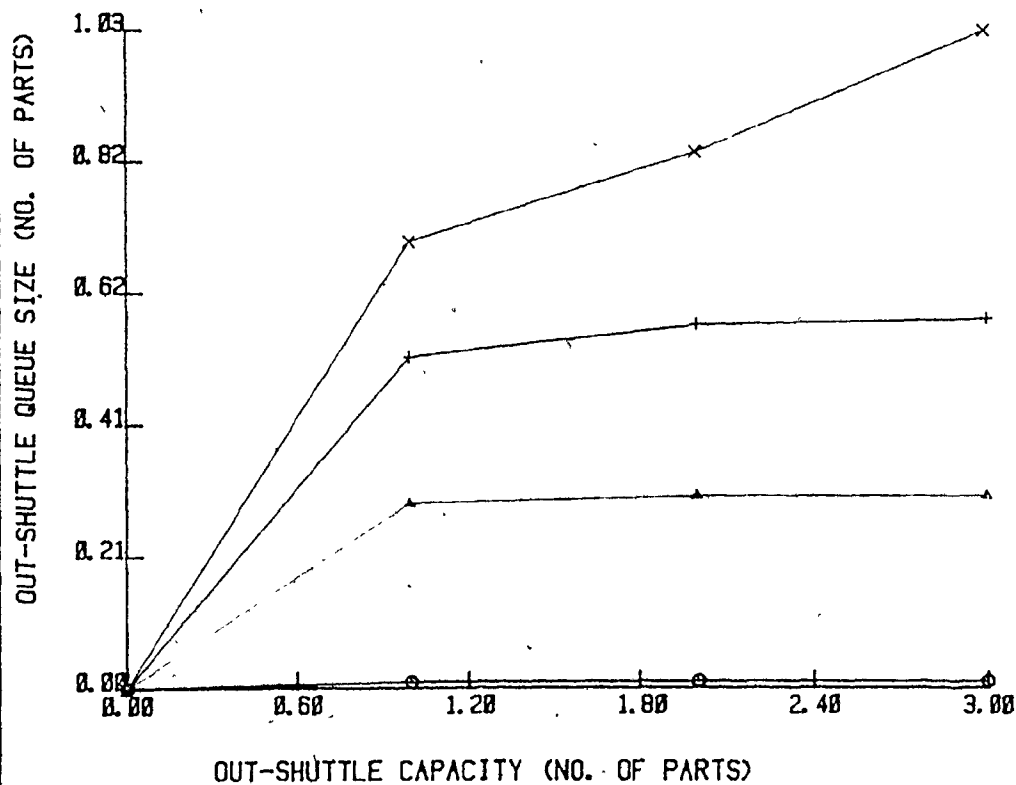


Fig. 5.11 Effects of Out-shuttle Capacity on Out-shuttle Queue Size.

For a cart system, an increase in out-shuttle capacity is accompanied by an increase in station utilisation (only the utilisation of the lathes were considered). Again, the effect is only significant when the out-shuttle capacity changes from zero part to 1 part. Any increase beyond 1 part does not significantly increase the station utilisation. This is partly due to the fact that the number of pallets used (12 pallets) is relatively low.

The results also show that the out-shuttle utilisation declines with an increase in transporter speed (Fig. 5.12). Since the faster the transporter travels, the higher will be the rate of part removal from the out-shuttle and the less time the parts will have to wait in the out-shuttle. This indicates that with a faster cart speed, we can afford to have a smaller out-shuttle capacity, or in other words, a slower cart speed can be compensated for by providing a larger out-shuttle buffer.

Both the in-shuttle and out-shuttle serve as useful buffers when there is a station breakdown or a transporter breakdown. The optimum shuttle's capacity depends on the type of transporter, the speed of the transporter and the maximum number of pallets allowed to enter the system.

#### 5.3.4 Effect of number of pallets

Four different pallet types are used in the system under consideration. Each of them has a fixture for different part types. Increasing one pallet type will increase the

# EFFECTS OF OUT-SHUTTLE CAPACITY

Data File FMSDT3.DAT

System Layout : FIG. 5.1  
MHS : AS INDICATED  
Number of Carts : 2 CARTS  
Cart Speed : AS INDICATED  
Out Shuttle Capacity: AS INDICATED  
In Shuttle Capacity : 2 POSITIONS  
Number of Pallets : 12 PALLETS

Simulation Time 600 MIN.

○ CONVEYOR (100 FT/MIN)    ▲ CARTS (300 FT/MIN)  
+ CARTS (200 FT/MIN)    × CARTS (100 FT/MIN)

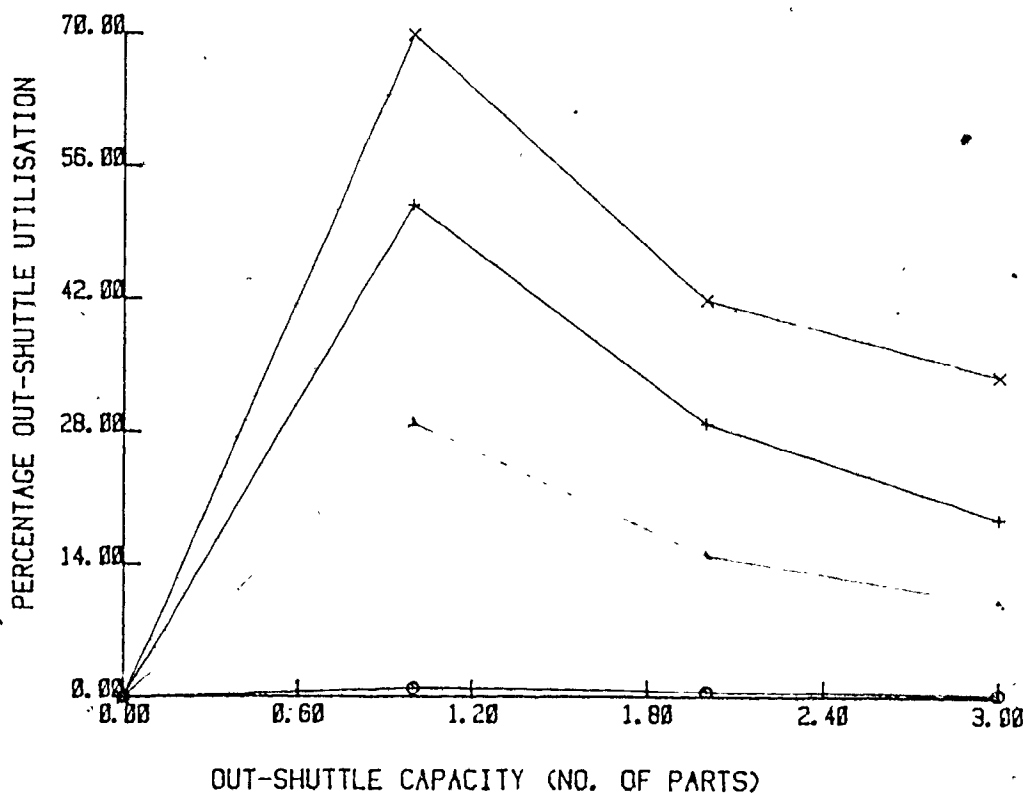


Fig. 5.12 Effects of Out-shuttle Capacity on Out-shuttle Utilisation.

probability of introducing the corresponding part type. Hence, the number of all pallet types was changed by the same amount and the results were collected for 8, 12, 16 and 20 pallets.

The results show that the station utilisation and total processing time of all stations increases with the number of pallets (Fig. 5.13 and 5.14). This trend continues until the system reaches its saturation state when the station utilisation is so high that any further increase in pallets does not affect the production rate any more. Instead, the extra pallets will wait at the shuttles for a longer time. This can be seen in the rapid increase in the in-shuttle queue size (Fig. 5.15).

The number of pallets determines the maximum number of parts allowed in the system. We would expect the production rate to increase with the number of pallets as long as the flowtime remains unchanged. However as the stations become saturated, the flowtime will increase since the parts have to wait in the queue for a longer time. This nullifies the effect of increased number of pallets.

### 5.3.5 Effects of introducing an additional lathe

In this particular system, the lathes are most heavily utilised among all stations. The effect of introducing an additional lathe into the system is examined for different pallet numbers. The new system layout is shown in Fig. 5.16.

# EFFECTS OF PALLET QUANTITY

Data File : FMSDT4.DAT

System Layout : FIG. 5.1 AND FIG. 5.16

MHS : CONVEYOR

Number of Carts : NIL

Cart Speed : NOT APPLICABLE

Out Shuttle Capacity: 2 POSITIONS

In Shuttle Capacity: 2 POSITIONS

Number of Pallets : AS INDICATED

Simulation Time 600 MIN.

○ 3 LATHES

▲ 4 LATHES

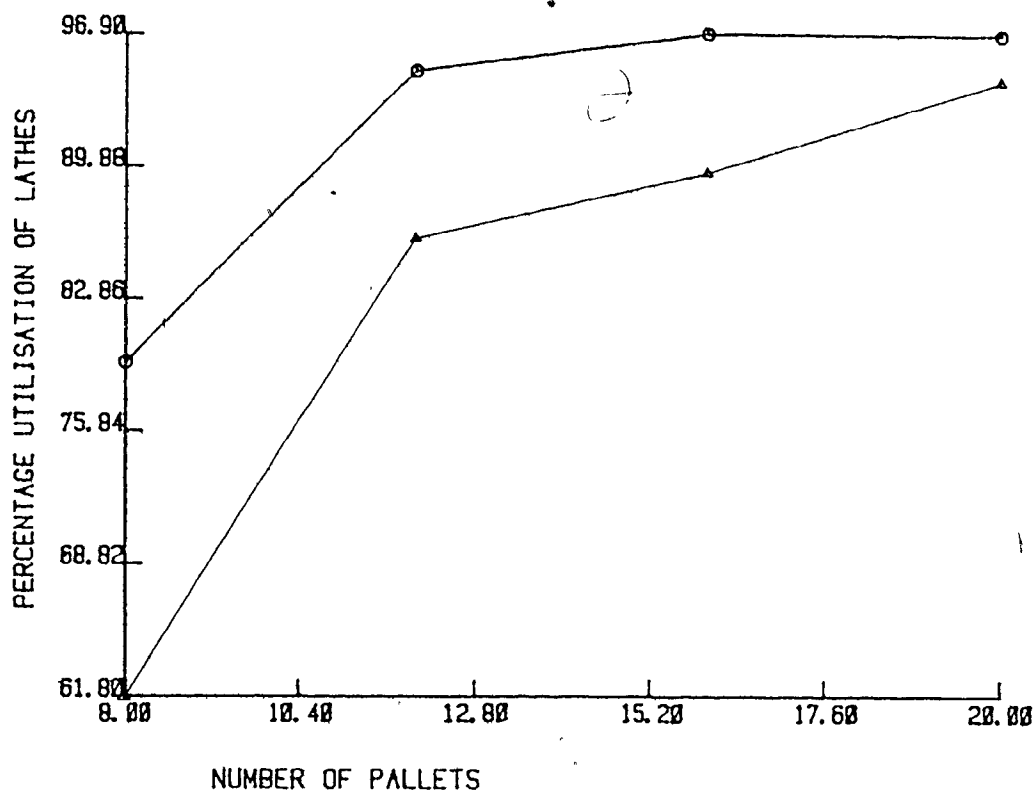


Fig. 5.13 Effects of Pallet Quantities on Station Utilisation.

# EFFECTS OF PALLET QUANTITY

Data File FMSDT4.DAT

System Layout : FIG. 5.1 AND FIG. 5.16

MHS : CONVEYOR

Number of Carts : NIL

Cart Speed : NOT APPLICABLE

Out Shuttle Capacity: 2 POSITIONS

In Shuttle Capacity : 2 POSITIONS

Number of Pallets : AS INDICATED

Simulation Time 600 MIN.

○ 3 LATHES

▲ 4 LATHES

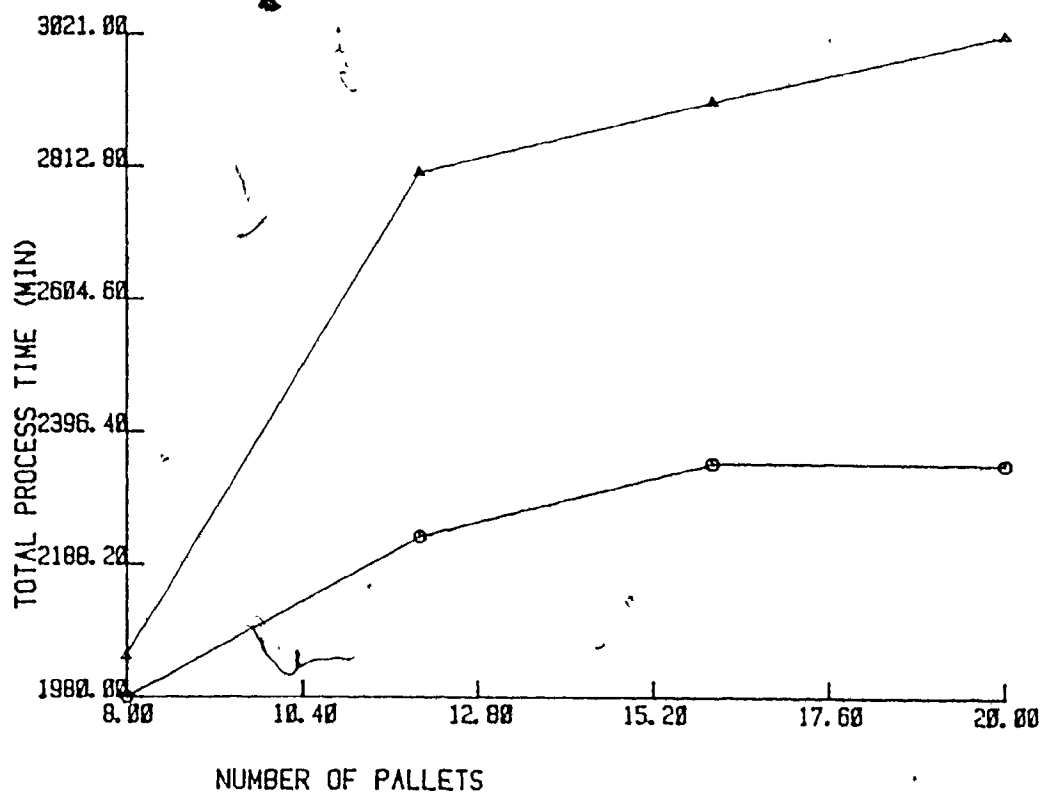


Fig. 5.14 Effects of Pallet Quantities on Production.

## EFFECTS OF PALLET QUANTITY

Data File FMSDT4.DAT

System Layout : FIG. 5.1 AND FIG. 5.16

MHS : CONVEYOR

Number of Carts : NIL

Cart Speed : NOT APPLICABLE

Out Shuttle Capacity: 2 POSITIONS

In Shuttle Capacity : 2 POSITIONS

Number of Pallets : AS INDICATED

Simulation Time 600 MIN.

○ 3 LATHES

▲ 4 LATHES

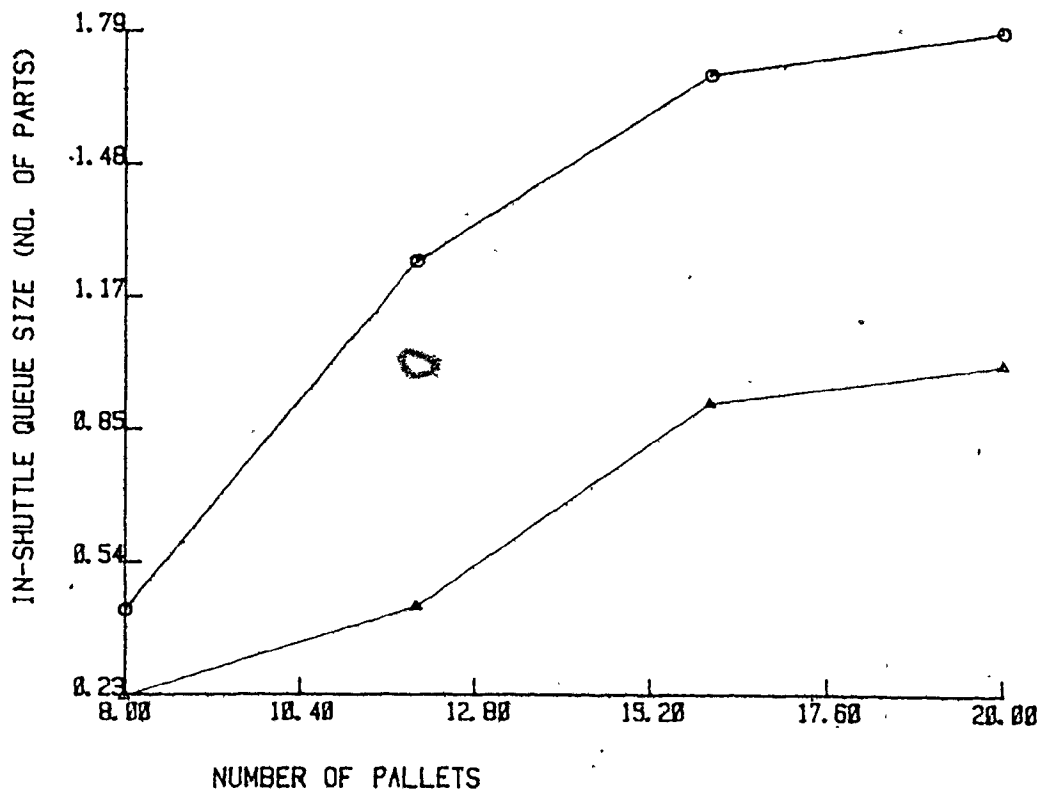


Fig. 5.15 Effects of Pallet Quantities on In-shuttle Queue Size.

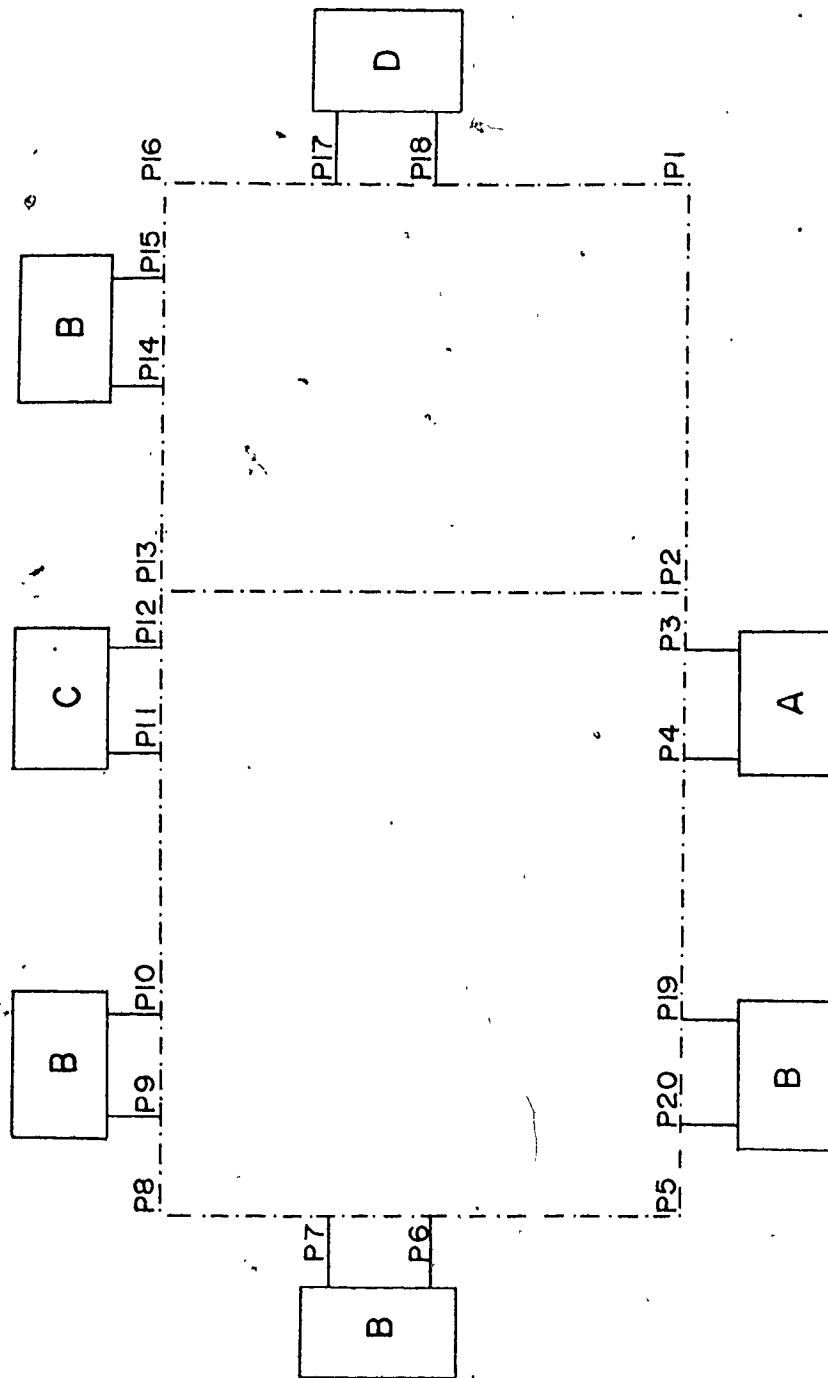


Fig. 5.16 Layout of Modified System with Additional Lathe.

Comparing the two sets of results (with and without the additional lathe) we found that the production rate (in terms of the total processing time) increases significantly with the introduction of the additional lathe (Fig. 5.14). However, this can only be realized if there are sufficient pallets to ensure that all lathes have an adequate supply of parts to maintain their high utilisation rate.

Since the work load is shared by more machines, the average machine utilisation (for the lathes) is found to be lower than it was previously. Nevertheless, it is expected that with a further increase in the number of pallets, the machine utilisation will eventually approach the previous level when the system reaches its saturation state. The plot in Fig. 5.13 clearly indicates this trend.

Another effect of introducing an additional lathe is the reduction of in-shuttle queue size (Fig. 5.15). Since the parts are distributed among more available facilities, this effect was expected.

From these results, we conclude that the introduction of an additional lathe in this system must be accompanied by a corresponding increase in the number of pallets in order to achieve the desired increase in production. The economic justification of an additional machine, however, is beyond the scope of this research.

#### 5.3.6 Effects of different scheduling rules

Scheduling rules play a very important role in selecting

the part type to be machined and consequently have their effects manifested in the overall production ratios of each part type produced and the utilisation of various stations.

In order to provide equal chances for each part type to be introduced into the system we have allocated the same number of pallets to each part type, i.e., three pallets for each of the six part types. The experiments were conducted for four different sets of scheduling rules. These rules are: -

- (a) SPT: - shortest processing time
- (b) FOPNR: - fewest number of operations remaining
- (c) FIFO: - first in first out
- (d) Random

The results are summarised in Table 5.7.

- (a) SPT Rule: Using this rule, when more than one part is waiting in the in-shuttle, the part which has the shortest processing time at the current station is selected. The objective is to clear the shorter jobs first so that the average waiting time of all parts will be reduced. The results show that the SPT rule leads to the highest production rate in terms of the total number of parts produced as well as the total processing time of all stations. However, it naturally favours the part types with short processing

time while the more lengthy jobs (e.g., part type 1) have very low priority and are produced in very small quantity.- The SPT rule also tends to improve the utilisation of the less critical stations such as the drilling machine and the milling machine, while maintaining equally high utilisation of the lathes. The total quantity of parts completed increases significantly when the SPT rule is used but the total processing time of the system does not increase proportionally since the parts produced have shorter processing time. The average throughput time is also reduced substantially in comparison with those obtained using other scheduling rules.

(b) FOPNR  
Rule: -

This rule selects the part which has the least number of remaining operations. The results show that the production rate is the lowest in comparison with other scheduling rules. It also tends to produce only the jobs with less number of operations. Part types which require more operations (e.g., type 4 and type 6) are given very low priority and are produced in very small quantities.

- (c) FIFO  
Rule: - This rule selects the parts on a first come first serve basis. Production rate and utilisation of stations are average. It produces all part types in almost equal quantities.
- (d) Random  
Rule: - The rule selects the part randomly. The results are similar to the FIFO rule. All part types are produced in more or less equal quantities without any preference for certain part types.

Within the context of this particular system under study, the SPT rule seems to be the best scheduling rule as it gives higher production, higher utilisation of the less critical stations, shorter throughput time and less congestion at the in-shuttles.

### 5.3.7 Effects of removal of the bypass

The bypass, as discussed previously, is meant to provide a shorter route for those parts which do not require a milling operation. After drilling, parts can be returned to the loading station for refixturing via the shorter route between track point 13 and track point 2 (Fig. 5.1) The bypass is, therefore, expected to reduce the transportation time of those parts which do not require a milling operation. The bypass is removed to test whether it has served its intended function. This experiment also demonstrates the ability of

the program to allow the user to change the system topology quite easily. The new topology is shown in Fig. 5.17. The changes involved are simply the removal of the two track points that define the bypass. Table 5.9 shows the change in input data for the new topology. The effect of removing the bypass was studied for the case of a system using a conveyor with transportation speed of 100 ft/min.

The results (Table 5.8) show that the bypass did improve the throughput time of those part types requiring no milling operation (types 1, 2, 3 and 5) except for type 5. However, it does not result in a significant improvement in station utilisation and production rate since the transportation times are relatively short compared with process time and waiting time at the shuttles. Therefore any improvement on the transportation time will only have a very minor effect on the overall performance of the system.

#### 5.4 Recommendations

This case study provides examples of the kind of issues that can be easily explored using the FMSSIM simulation. It provides insight and useful information about the effect of various parameters on the operation of the system. This simulator however does not include any cost analysis or economic considerations. The user has to consider the simulation results together with other important aspects to arrive at a final conclusion. For instance, the choice between different types of material handling systems will depend very

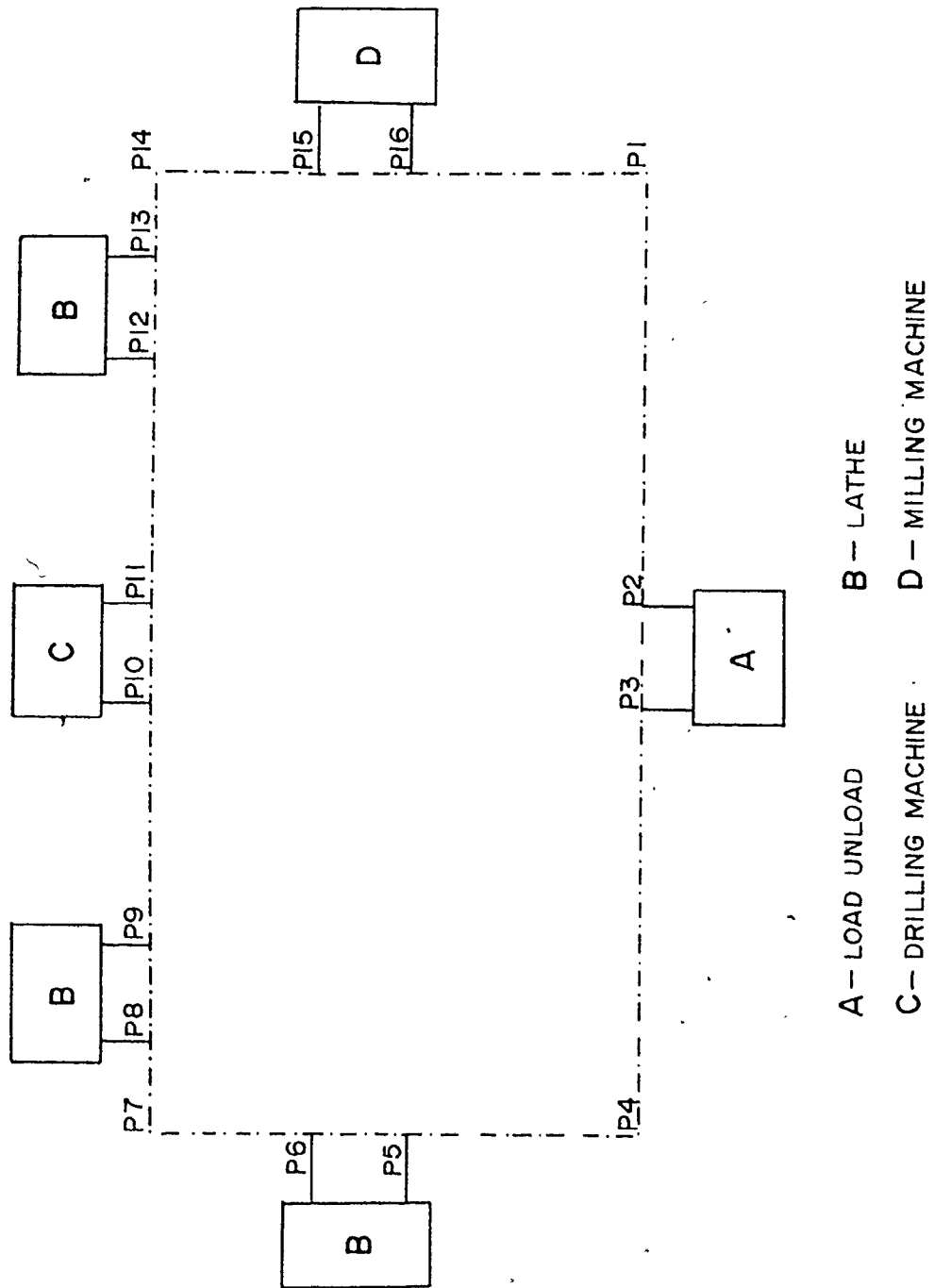


Fig. 5.17 Layout of Modified System Without Bypass.

18												
1	0	2	0	0	0	320	100	100	0	0	0	
2	0	3	0	0	0	230	100	100	0	0	0	
3	1	4	0	0	0	220	100	100	0	0	0	
4	1	5	0	0	0	200	100	100	0	0	0	
5	0	6	0	0	0	80	100	100	0	0	0	
6	2	7	0	0	0	80	170	100	0	0	0	
7	2	8	0	0	0	80	190	100	0	0	0	
8	0	9	0	0	0	80	260	100	0	0	0	
9	3	10	0	0	0	100	260	100	0	0	0	
10	3	11	0	0	0	120	260	100	0	0	0	
11	4	12	0	0	0	200	260	100	0	0	0	
12	4	13	0	0	0	220	260	100	0	0	0	
13	0	2	14	0	0	230	260	100	100	0	0	
14	5	15	0	0	0	260	260	100	0	0	0	
15	5	16	0	0	0	280	260	100	0	0	0	
16	0	17	0	0	0	320	260	100	0	0	0	
17	6	18	0	0	0	320	190	100	0	0	0	
18	6	1	0	0	0	320	170	100	0	0	0	

(a)

16												
1	0	2	0	0	0	320	100	100	0	0	0	
2	1	3	0	0	0	220	100	100	0	0	0	
3	1	4	0	0	0	200	100	100	0	0	0	
4	0	5	0	0	0	80	100	100	0	0	0	
5	2	6	0	0	0	80	170	100	0	0	0	
6	2	7	0	0	0	80	190	100	0	0	0	
7	0	8	0	0	0	80	260	100	0	0	0	
8	3	9	0	0	0	100	260	100	0	0	0	
9	3	10	0	0	0	120	260	100	0	0	0	
10	4	11	0	0	0	200	260	100	0	0	0	
11	4	12	0	0	0	220	260	100	0	0	0	
12	5	13	0	0	0	260	260	100	0	0	0	
13	5	14	0	0	0	280	260	100	0	0	0	
14	0	15	0	0	0	320	260	100	0	0	0	
15	6	16	0	0	0	320	190	100	0	0	0	
16	6	1	0	0	0	320	170	100	0	0	0	

(b)

TABLE 5.9 Track Description for System With (a) and Without (b) Bypass.

much on the cost of installation as well as the operating cost of each system. A cart system with 3 carts moving at 300 ft/min. may be comparable to a conveyor system moving at 100 ft/min. with respect to the various performance measures studied. Also the increase in production with the introduction of an additional lathe has to be viewed in the light of the extra capital cost incurred. Economic considerations are however beyond the scope of the present research.

From the results of the simulation, we have observed several consistent trends which may be applicable to other flexible manufacturing systems. The results obtained up to this stage are consistent with the findings reported by other simulation models. A summary of these common findings is given as follows:

- (1) The SPT scheduling rule has been found to be consistently the most effective for minimising flowtime and maximising station utilisation. Eden [33] tested 10 dispatching rules and found that SST (Shortest Service Time - similar to SPT) "is most likely to give highest utilisation for the system". This is further confirmed by Conway [34] who conducted studies on a variety of job shop conditions and Hutchinson [29] who has performed several simulation tests on flexible manufacturing systems.
- (2) Runner [24] has compared conveyor and cart speed using the CAMSAM Model and reported that "Conveyorised system is more productive than the cart system for a

broad range of speed". The criteria used for comparison in that model was based on machine utilisation.

- (3) Solberg [8] using his CAN-Q mathematical model, has predicted that increasing the number of pallets will result in an increase in production, station utilisation and average queue size. The same findings were reported by Runner [24] using the CAMSAM Model.
- (4) Runner [24] also found that at high speeds, the flexible manufacturing system is relatively insensitive to the speed of the cart. However when the cart speeds were lowered, the production rate and machine utilisation decrease rapidly.
- (5) Hutchinson [20] in summarising some of his simulation results commented that it is more effective to have parts waiting to be processed at in-shuttles than to have parts accumulating on the out-shuttle. The experimental results of the FMSSIM simulator show that high station utilisations are often associated with high in-shuttle utilisation.

All findings reported above are in agreement with the general trends observed in the results of this case study using the developed FMSSIM simulator.

Some recommendations derived from the outcomes of the case study are:

- (1) A conveyor is a better material handling system in

terms of increasing production, improving facility utilisation and reducing congestion since it acts as an infinite buffer for parts in the system. However, a cart transportation system may be more adaptable to complicated network topology.

- (2) In-shuttles and out-shuttles provide the essential buffer to maintain high facility utilisation. The optimal size of the buffer depends very much on the type of material handling system, the speed and number of transporters.
- (3) The flexible manufacturing system is very sensitive to the availability of fixtured pallets. Since the part types introduced into the system depend on the availability of the pallet type that can hold the parts, the distribution of pallet types has an important effect on the final pattern of the part mix produced. This can be used to tailor the production to the customer's orders.
- (4) Any additional facility must be accompanied by a corresponding increase in the number of pallets to reap the full advantage of the extra production capability.
- (5) The effectiveness of a flexible manufacturing system relies very much on the particular set of scheduling rules used in dispatching and scheduling. SPT is effective in improving the production rate and throughput time but jobs with longer processing time

tend to stay in the system for a long time. This effect will be equally pronounced irrespective of the magnitude by which the processing times differ from one another. Therefore if the original part mix has part types which differ very slightly in their processing time they will still have this lopsided production pattern without any significant improvement in the overall system performance when the SPT rule is used. The type of scheduling rule must therefore be selected carefully depending on the type of part mix, and the developed simulator can be used effectively for this purpose.

## CHAPTER 6

### CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

#### 6.1 Conclusions

The FMSSIM simulator has been proven to be a useful testbed for studying both the dynamic and steady state behaviour of a proposed flexible manufacturing system. It can model a wide variety of flexible manufacturing systems with different topology, different part mix and different decision rules. The two most commonly used material handling systems (i.e., carts and conveyor) can be simulated. It also has the capability of simulating random breakdown phenomena and different part arrival patterns.

Another distinct feature of the FMSSIM simulator is the graphical output produced on the monitor. The graphical output condenses the status of the system into an easily interpretable visual display. It shows the system clock, production figures of all part types and part movement through a schematic layout display. Breakdown of components and congested shuttles are indicated by flashing the corresponding component on the monitor.

Since, in most cases, the simulations have to be repeated many times in the search for an optimal solution, the amount of work incurred in changing the data can be enorm-

ous. The capability of the FMSSIM simulator is further enhanced by the simplified format for inputting data. The elimination of the initialisation data required by the simulation language and the ease of editing data on the monitor have substantially simplified data input compared with many other simulators developed so far. With all the data readily collected, it takes less than an hour to set up a data file similar in size to the one used in the case study and any subsequent changes of parameters will be trivial. Simplified data input is a great advantage. The input data diagnostics and printout of data in an easily readable format enables the user to check the input data before he proceeds with the simulation. This reduces the debugging time quite substantially.

The system output can be easily diagnosed.

User's defined decision rules can also be implemented after the user becomes familiar with the organisation of the data structure (Refer to user's manual for illustration Appendix B).

Unlike most of the other models developed so far, the FMSSIM simulator does not rely on the availability of any simulation language processor. It is a standalone package which can operate on any computer with a Fortran compiler. The GASP simulation package has been simplified and incorporated into the FMSSIM simulator. The size of FMS that can be simulated by FMSSIM simulator is constrained only by the memory

of the computer used (Refer to Appendix B for the limits imposed on the sizes of the various system components).

The FMSSIM simulator implemented on the PDP 11/34 requires 22 K of memory. The graphics package which operates separately from the simulator requires 16 K of memory.

The simulation time on a computer varies with the complexity of the system. It is proportional to the number of events required to simulate the system and not their duration. As the number of stations, parts, routes, pallets etc. increases, the computer simulation time will also increase. In the case studies, the average simulation time required to simulate each case for 600 time units varied from half an hour to 45 minutes.

The FMSSIM simulator can be a useful tool for the flexible manufacturing system designer in the following aspects: -

(a) Design of Flexible Manufacturing Systems

The FMSSIM simulator can be used to obtain qualitative and quantitative information about most flexible manufacturing systems. It allows the designer to experiment with various alternatives before building the actual costly system. It can be used to predict the actual production figures and indicate which elements in the system are most critical. In the design of an optimal system, one always wishes to minimise capital investment and maximise production and profit. However, this must be done with the full awareness of the impact each piece of equipment has on the overall performance of the system. The FMSSIM simulator can serve

as a very useful experimental tool to gain insight into the interactions of various system components.

(b) Operation of Flexible Manufacturing Systems

Graphical outputs obtained from the simulation permits the user to watch each individual part as they progress through the system to see where congestion may occur. This can be extremely useful in the actual operation of a system. Most simulators produce lengthy printed outputs which describe the status of the system at specified times. Examination and analysis of such reports may take a long time. The graphical output shows the operation of the system in an easy to understand visual form. The ability to produce a graphical output representing the actual system also points towards the potential of developing the simulator into a real time controller.

The simulator provides a set of scheduling rules for the user to experiment with. From the simulation report, the user can then compare the operation of the system under different scheduling rules and select one which will produce the optimum operating condition.

In conclusion, the FMSSIM simulator has achieved the following tasks: -

- (1) It predicts the utilisation of various components in the FMS such as stations, shuttles and carts.
- (2) It identifies the critical elements in the system.
- (3) It analyses different network topologies

- (4) It predicts the sensitivity of system performance to changes in transporter speed, pallet quantity and queue size.
- (5) It displays the movement of parts within the system.

## 6.2 Suggestions for Future Research

There are several areas which represent logical extensions of the current research.

### 6.2.1 Cost analysis

Cost minimisation is the primary aim for all production systems. Cost analysis is therefore an important aspect for future investigation. Attempts should be made to breakdown all costs associated with a Flexible Manufacturing System. The production cost in manufacturing each workpiece can be estimated based on the direct machine hours utilised and the estimated usage of other facilities such as transportation system and computers. The operating cost can then be compared with other alternative production systems.

Another cost related issue is to develop a cost based composite scheduling rule. The scheduling rules used so far are based on performance criteria such as throughput time, work-in-process inventory and lateness. In real life often decisions are made using cost as a performance measure. A more universal scheduling rule would be to use a cost based scheduling rule in order to optimise operating cost of processing a particular part mix.

### 6.2.2 Interactive control module

The ability to produce a graphical output updated from event to event is made possible by maintaining an array of status flags for each entity in the system and keeping track of their status as the simulation proceeds. The same facilities can be of great value for a real time scheduler\* by allowing the user to interrupt the simulation process to alter the various decision rules and to introduce changes to the system. This interactive man-machine decision system elements will be an important step towards a real time scheduler\*. Looming in the more distant horizon would be the interfacing of the scheduler with an actual physical system or model to provide a real time controller\* for such a system..

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\* The extensions discussed in Section 6.2.2 were provided by Dr. H. ElMaraghy [35].

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APPENDIX A

A SUMMARY OF EXISTING FMS'S  
[Reference 2]

<u>SYSTEM</u>	<u>APPROX. YEAR</u>	<u>VENDOR</u>	<u>MISSION</u>	<u>WORK STATIONS</u>	<u>APPROX. COST</u>	<u>MATERIAL HANDLING</u>
Japan Yanmar Diesel (Amagasaki Plant)	1972	Hitachi	Prismatic-Engine castings approx. 2 ft. cube-900 units per month	5 Machine Tools	$¥150 \times 10^6$	Palletized-Roller Conveyor-Loop
Toyota- Tipros	1973	Toyota	Batches of 100 Prototype Engin- es-800 parts per month	9 Machine Tools (1 machining cen- ter) 4 machine tools do preliminary work	Unknown	Palletized. Roller conveyor
German Democratic Republic Auerbach Prisma I	1971	Fritz Heckert	Prismatic mach- ine tool parts, 250 mm cube, in small batches	2 Machining centers	Unknown	Swivel shuttles in- terface with operator for loading machin- ing centers and rotating carousel at center of system. Palletized parts
German Democratic Republic Fritz Heckert- Prisma 2	1972	Fritz Heckert	Prismatic parts- 1.0m x 1.0m x 1.5 m envelope - high accuracy for machine tools, 8000 parts per year.	1 Rough mill 2 Vertical mills 3 Machining centers 2 Measuring stations 2 stations vac- ant, formerly grinders 2 Washing-cooling stations	Unknown	Sophisticated, air cushion for palletized parts; driven by linear induction motors; buffer position at each work station and 16 in pool. Repeatability of 3 $\mu$ m positioning at stations

Herbert Warnke- PC 3	1977	Svoda & Fritz Heckert & Warnke	Prismatic parts 4.0 m cube up to 24 tons - 7.0 m possible - High accuracy, large parts for metal forming machines (presses, brakes), 120 parts; 2.5 parts per day production	5 Vertical turrets with 250 mm and 160 mm spindles	Unknown	Single cart on straight rails of 57 m; serving 14 stations: Hydrostatic
Niles ROTA FI25	1971	Fritz Heckert	Batches of rota- tional parts up to 125 mm dia- meter. 400 parts, 135,000 per year. Minimize floor space	1 Rough lathe 3 Turret lathes 2 Turret mills/ drills 1 Grinder with in processing gauging	Unknown	Parts checked and manually entered. Auto- matically moved to over- head, multilevel carousel of 270 part capacity
7 October Kombinat ROTA FG200	1973	Fritz Heckert	60-200 mm gears for machine tools. 150,000 per year in batches of 10 to 500	16 Work sta- tions, each with robot to interface mat- erial handling system	Unknown	Blanks are placed on 3 tier pallet, up to 16 per tier. Pallets are moved by stacker crane to work station's local queue, where robot serves as interface to machines. Rack serves as pool buffer
Federal Republic of Germany Heidel- berger Druck- maschinen	1969		Printing press precision parts	13 Machining centers	Unknown	Integrated conveyor, palletized

Heller	1977	Heller	Machine tool parts approx. 1.5x2x3	1 Machining center, plans for 3 more	Unknown	Palletized, with stacker crane and conveyor
Univ. of Stuttgart	1976	Integration by Univ.	Investigations and batch contract work. Prismatic parts	4 Machining centers	Unknown	2 stacker cranes and rack for pool storage. Palletized
Univ. of Berlin	1976	Integration by Univ.	Investigators	2 Machine Tools	Unknown	Robot interface for machine tools. Overhead conveyor for remote storage and roller conveyor
United States Ingersol Rand- Omniline	1972	White-Sunds-trand	180 parts, generally in batches, but service parts as well. 3 foot cube. 70,000 per year, up to 16 parts simultaneously	2 4-axis mills 2 5-axis mills 2 4-axis drills	Unknown	Roller conveyor of palletized parts. Loop with buffer position at each machine
Caterpillar	1974	White-Sunds-trand	Cast iron case and cover for tractor transmission. 6 parts. 1200 per year. Approx. 3 foot cube	5 Omnimills 2 G&L turret lathes 3 Omnimills 1 DEA inspection	Unknown	Palletized parts, 2 carts move parts between machines and load area, which also serves as buffer. Carts perform shuttling operations, use straight line track.

United States Sundstrand Aviation	1967	White- Sunds- trand	Aluminum pump parts and magnesium castings for air- craft speed drive housings, approx. 16 inch cube. 2000 per month in batches of 25 to 300	8 OM-2 Omnimill machining centers 2 Multiple spindle drilling machines	Unknown	Palletized workpieces have code to direct to next station on roller conveyor (power and free)
Allis Chalmers	1971	Kearney- Trecker	Produces cast iron tractor parts for direct assembly 23,600 per year. Approx. 3 foot cube	5 Machining centers 1 Mill 4 Duplex multi spindle head indexers	\$5 mil.	Palletized workpieces moved under computer control to work station on towed carts. Local, multi position queue at work stations and carts serve as buffer pool. Complex network
North American Rockwell	1973	Kearney- Trecker	Cast iron differ- ential carriers for trucks in lots of 10 to 50. 33 parts. 1.5 foot cube. 8 parts simultaneously. 24,000 per year	8 Machining centers	Unknown	Same as Allis Chalmers except a simple loop with spur rather than a network.
Avco Lycoming	1976	Kearney- Trecker	Aluminum aircraft engine (4 and 6 cylinder) crank- cases halves	2 Simplex Multi- spindle head indexers 1 Duplex multi- spindle head indexer 9 Machining centers	\$10 mil.	Same as Allis Chalmers except some machines have a single position queue.

## APPENDIX B

### USER'S MANUAL

#### B.1 Introduction

The simulation of FMS is conducted in two stages by executing two separate programs viz. FMSSIM, the basic simulation package, and EMULAT, the graphical emulation package.

During the first stage of the simulation, the program FMSSIM collects all vital statistics on the various performance measures.. It also records the status of the various system components as the simulation proceeds through the occurrence of each event. This record is written onto a display status file. The information in this display status file can be retrieved to generate graphical animation by executing the second program EMULAT.

#### B.2 Description

The FMSSIM package consists of 71 subroutines, among which 12 are modified GASP subroutines. The EMULAT package consists of 12 subroutines linked with GLIB and SYSLIB from RT-11. A brief description of these subroutines is given in Appendix D. Different file extension codes are used to identify the different types of subroutines (e.g., FMS for FMSSIM subroutines; GSP for GASP subroutines and GRF for graphics subroutines).

Both packages are overlayed to reduce the computer storage requirements. The overlay structures are shown in Appendix F. The present simulator using up to 22 K words of memory for FMSSIM and 16 K words of memory for EMULAT can simulate a system confined to the following limits:

Maximum number of part types = 10

Maximum number of parts in the system = 20

Maximum number of operations for each part type = 10

Maximum number of alternate stations for each operation = 4

Maximum number of stations = 15

Maximum shuttle capacity (each type ) = 3

Maximum number of pallet types = 10

Maximum number of pallets = 20

Maximum number of cart types = 4

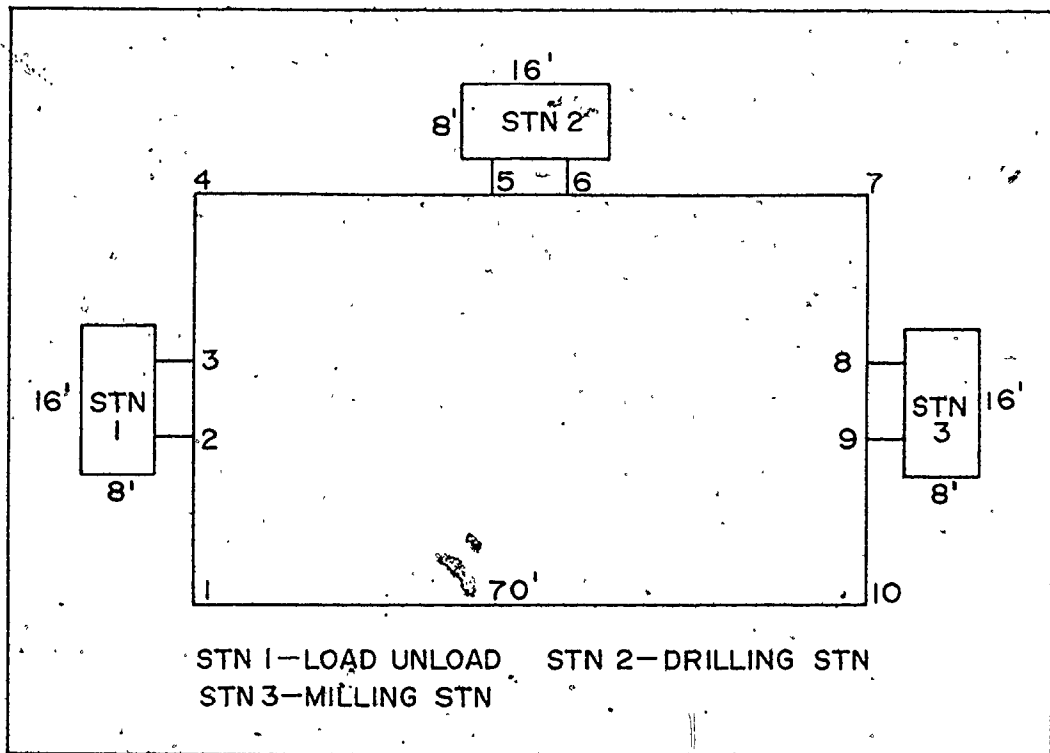
Maximum number of carts in the system = 10

Maximum number of track points = 40

### B.3 Simulation Procedure

The general procedure for a simulation is described as follows. A simple system with its specifications explained in Fig. B.1 is used for illustration.

- (A) Set up a data file according to the format presented in Table B.1 using any text editor available. All data files should be identified by the file extension code .DAT. Modifications of existing data files can also be done using the text editor.



SYSTEM LAYOUT

PART TYPES	PROCESS SEQUENCE (PROCESS TIME (SEC.) INDICATED IN THE BRACKET)
1.	LOADING (15) - DRILL (80) - UNLOAD (15)
2	LOADING (15) - MILL (200) - UNLOAD (15)
3	LOADING (15) - DRILL (60) - MILL (180) - UNLOAD (15)
	All part types have exponential arrival time
PALLET TYPE	PART TYPES THAT GO ON THE PALLET
1	PART TYPES 1 & 3
2	PART TYPES 2 & 3
CART TYPE	2 carts with 3 pallet positions each. Cart speed = 2 ft/sec.
DECISION RULES	<ol style="list-style-type: none"> <li>1. Introduce part with highest priority in order of part 2, 1, 3.</li> <li>2. Select parts from incoming shuttle according to FIFO rule.</li> <li>3. Select next operation in the order of given process sequence.</li> <li>4. Select idle station.</li> <li>5. Select idle cart.</li> <li>6. Cycle back if cart cannot unload.</li> </ol>

Fig. B.1 Description of Exemplary Case:

### Table B.1 Input Format for Data File

```

=====
STN NO. NO. OF POSITION TRACK POINT TRANSFER TIME FROM STATION STATION SIZE
      IN IN QUEUE AT QUEUE IN OUT COM TO TRACK TO MACHINE X-COOR Y-COOR X-DIMEN Y-DIMEN
=====

```

```

=====
**** DATA FOR PALLET TYPE ****

```

```

NUMBER OF PALLET TYPES (MAX =10)
=====

```

```

=====
PALLET NUMBER OF PART PART PART
TYPE PALLET TYPE TYPE TYPE
=====

```

```

=====
**** DATA FOR CART TYPE ****

```

```

NUMBER OF CART TYPES (MAX TYPE =4 ; MAX NO OF CARTS =10)
=====

```

```

=====
CART SPEED NO. OF NO. OF FEASIBLE TRACK POINTS
TYPE CARTS PALLET 1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14. 15. 16. 17. 18. 19. 20.
(MAX=3) 21. 22. 23. 24. 25. 26. 27. 28. 29. 30. 31. 32. 33. 34. 35. 36. 37. 38. 39. 40.
=====

```

Table B.1 (Cont'd)

NUMBER OF TRACK POINTS (MAX =40)

POINT NO	STATION NUMBER (0 IF NONE)	SUCCESSIVE TRACK POINTS (1) (2) (3) (4)	XCOR	YCOR	CONVEYOR SPEED TO SUCCESSIVE POINTS (1) (2) (3) (4)
1	0	1	0	0	0
2	0	1	0	0	0
3	0	1	0	0	0
4	0	1	0	0	0
5	0	1	0	0	0
6	0	1	0	0	0
7	0	1	0	0	0
8	0	1	0	0	0
9	0	1	0	0	0
10	0	1	0	0	0
11	0	1	0	0	0
12	0	1	0	0	0
13	0	1	0	0	0
14	0	1	0	0	0
15	0	1	0	0	0
16	0	1	0	0	0
17	0	1	0	0	0
18	0	1	0	0	0
19	0	1	0	0	0
20	0	1	0	0	0
21	0	1	0	0	0
22	0	1	0	0	0
23	0	1	0	0	0
24	0	1	0	0	0
25	0	1	0	0	0
26	0	1	0	0	0
27	0	1	0	0	0
28	0	1	0	0	0
29	0	1	0	0	0
30	0	1	0	0	0
31	0	1	0	0	0
32	0	1	0	0	0
33	0	1	0	0	0
34	0	1	0	0	0
35	0	1	0	0	0
36	0	1	0	0	0
37	0	1	0	0	0
38	0	1	0	0	0
39	0	1	0	0	0
40	0	1	0	0	0
41	0	1	0	0	0
42	0	1	0	0	0
43	0	1	0	0	0
44	0	1	0	0	0
45	0	1	0	0	0
46	0	1	0	0	0
47	0	1	0	0	0
48	0	1	0	0	0
49	0	1	0	0	0
50	0	1	0	0	0
51	0	1	0	0	0
52	0	1	0	0	0
53	0	1	0	0	0
54	0	1	0	0	0
55	0	1	0	0	0
56	0	1	0	0	0
57	0	1	0	0	0
58	0	1	0	0	0
59	0	1	0	0	0
60	0	1	0	0	0
61	0	1	0	0	0
62	0	1	0	0	0
63	0	1	0	0	0
64	0	1	0	0	0
65	0	1	0	0	0
66	0	1	0	0	0
67	0	1	0	0	0
68	0	1	0	0	0
69	0	1	0	0	0
70	0	1	0	0	0
71	0	1	0	0	0
72	0	1	0	0	0
73	0	1	0	0	0
74	0	1	0	0	0
75	0	1	0	0	0
76	0	1	0	0	0
77	0	1	0	0	0
78	0	1	0	0	0
79	0	1	0	0	0
80	0	1	0	0	

\*\*\*\*\* DATA FOR DOWNTIME STATISTICS \*\*\*\*\*  
(STATION)

(STATION)

\*TYPE OF BREAKDOWN DISTR

STATION	TIME BETWEEN	REPAIR TIME
1	10	10
2	10	10
3	10	10
4	10	10
5	10	10
6	10	10
7	10	10
8	10	10
9	10	10
10	10	10
11	10	10
12	10	10
13	10	10
14	10	10
15	10	10
16	10	10
17	10	10
18	10	10
19	10	10
20	10	10
21	10	10
22	10	10
23	10	10
24	10	10
25	10	10
26	10	10
27	10	10
28	10	10
29	10	10
30	10	10
31	10	10
32	10	10
33	10	10
34	10	10
35	10	10
36	10	10
37	10	10
38	10	10
39	10	10
40	10	10
41	10	10
42	10	10
43	10	10
44	10	10
45	10	10
46	10	10
47	10	10
48	10	10
49	10	10
50	10	10
51	10	10
52	10	10
53	10	10
54	10	10
55	10	10
56	10	10
57	10	10
58	10	10
59	10	10
60	10	10
61	10	10
62	10	10
63	10	10
64	10	10
65	10	10
66	10	10
67	10	10
68	10	10
69	10	10
70	10	10
71	10	10
72	10	10
73	10	10
74	10	10
75	10	10
76	10	10
77	10	10
78	10	10
79	10	10
80	10	10
81	10	10
82	10	10
83	10	10
84	10	10
85	10	10
86	10	10
87	10	10
88	10	10
89	10	10
90	10	10
91	10	10
92	10	10
93	10	10
94	10	10
95	10	10
96	10	10
97	10	10
98	10	10
99	10	10
100	10	10

```

PARAM 1, PARAM-2      PARAM 1  PARAM 2

```

\*\*\*\*\* DATA FOR DOWNTIME STATISTICS \*\*\*\*\*  
(CART)

(CART)

\*TYPE OF BREAKDOWN DISTR

Table B.1. (Cont'd)

```
=====
CART      TIME BETWEEN  REPAIR TIME
NO        BREAKDOWN,
PARAM 1  PARAM 2      PARAM 1  PARAM 2
=====
```

```
=====
**** DATA FOR DOWNTIME STATISTICS ****
      (TRACK POINT)
ONE SET OF DATA FOR ALL TRACK POINTS
=====
```

```
*TYPE OF BREAKDOWN DISTR
```

```
=====
TIME BETWEEN  REPAIR TIME
BREAKDOWN,
PARAM 1  PARAM 2      PARAM 1  PARAM 2
=====
```

```
=====
**** PRIORITY RULES ****
=====
```

```
=====
RULE(1)  RULE(2)  RULE(3)  RULE(4)  RULE(5)  RULE(6)
=====
```

Table B.1 (Cont'd)

The file name used for this example is FMSDT.DAT.  
 A printout of the data as they appear in the data file  
 is given in Table B.2.

(B) The basic simulation is performed by executing the  
 FMSSIM package. Turn the graphics terminal off and  
 run the program. The program will interact with the  
 user as shown below:

=====

DO YOU WANT A PRINTOUT OF THE FORMAT OF THE DATA FILE (Y IF YES) ?

DO YOU WANT A PRINTOUT OF THE DATA (Y IF YES) ?

DO YOU WANT TO PROCEED WITH THE SIMULATION (Y IF YES) ?Y

NAME OF THE DATA FILE (10 CHARACTERS)-----FMSDT.DAT

DURATION OF TIME TO BE SIMULATED-----1000.

NUMBER OF INTERVALS WHEN REPORTS ARE NEEDED--1

TIME WHEN YOU WANT THE DISPLAY TO START-----0.

TIME WHEN YOU WANT THE DISPLAY TO END-----0.

=====

(B) Subroutine for user-defined decision rule

A special subroutine called CHRUL has been incorporated into the FMSSIM package. It allows the user to specify self-defined decision rules.

The user may refer to Appendix C for the glossary of variable names. Many of the system status flags (such as station status, cart status, part status, etc.) can be obtained from the status arrays (such as SSTAN, SCART, SPART, etc.). The values for these arrays are transferred via the common blocks.

The following are illustrations of how each rule may be modified [(Refer to pg. 148 for program listing).]

Rule 1: Selection of part type to be introduced into the system

It can be altered by writing a program to arrange the priority of each part type (IPART(N,2)). Since there is a maximum of 10 part types, the range of the priority index should be from 1 to 10 (with 1 being the highest priority). This is illustrated in the example on page 148 by assigning priority to the different part types according to the number of operations. The fewest operations will have the higher priority.

Rule 2: Selection of next part to be machined

It can be altered by writing a subroutine to select the part from the incoming queue of the station and return the part number in IPT. This is illustrated in the example by using a random selection rule.

Rule 3: Selection of next operation for a part

If the operations do not have to follow the pre-determined sequence as given by the input data for each part type, a user-defined rule can be used. The part number is transferred to the subroutine by IPT in the argument list. The remaining operation can be checked from the completed list of operations and the required operations list for a specific part type. The next operation selected must be returned via IOP in the argument list.

Rule 4: Selection of next station for a part

It can be altered by writing a program to select the next alternate station knowing the part number IPT and operation number IOP. The alternate stations are listed in array IOPER. The station selected is returned via IST. This is illustrated in the example where the station with the shortest out-shuttle has the highest priority.

Rule 5: Selection of cart to pick up a part

It can be altered by writing a subroutine to select the cart. The cart number selected is then returned in ICT. This is illustrated in the example where the cart with the most empty slots available has the highest priority.

If any of the rules were altered, the CHRUL subroutine should be edited to include the new rule and a value zero should be given to the corresponding IRULE in the input data set, e.g., if Rule 5 is changed

IRULE (5) should be set to zero in the data file. The subroutine CHRUL.FMS is then recompiled and the entire package relinked using the command file FMS.COM. A listing of the command file is given in Appendix F.

The subroutine CHRUL.FMS in its original form as well as after the implementation of the above user-defined rules are shown on pg 147 and pg 148 respectively.

```

SUBROUTINE CHRUL(IST,IPT,NPT,ICT,IOP,IRUL)
*****
C
C      This is a user written subroutine
C      It specifies the new decision rules used by the user
C
COMMON/DATA1/NPATE,NPART,NSTAN,NPLTY,NPLET,NCATE,
INCART,NPOIN,NPSYS
COMMON/DATA2/IPART(10,5),IDSTR(10,10),IOPER(10,10,5)
1,ISTAN(15,6),IPEET(10,5),ITRAK(10,5),RPART(10,2)
2,RSTAN(15,2),ROPER(10,10,8),ICART(4,42),RCART(4)
3,RTRAK(40,6),IRULE(8)
COMMON/DATA3/FSTAN(15,4),FCART(1,4),SSTAN(15,12)
1,SCART(10,32),SFLET(20,25),SPLTY(10),SPATE(10)
2,SPART(20,20),STRAK(40),FTRAK(4)
COMMON/SELEC/IAPAR(6)
C
GO TO (100,200,300,400,500),IRUL
C
C      User's defined RULE 1
C
100    RETURN
C
C      User's defined RULE 2
C
200    RETURN
C
C      User's defined RULE 3
C
300    RETURN
C
C      User's defined RULE 4
C
400    RETURN
C
C      User's defined RULE 5
C
500    RETURN
      END

```

```

SUBROUTINE CHRUL(IST,IFT,NPT,ICT,IOP,IRUL)
C *****
C
C This is a user written subroutine
C It specifies the new decision rules used by the user
C
COMMON/ DATA1/ NPATE, NPART, NSTAN, NPLTY, NPLET, NCATE,
1 NCART, NPOIN, NPSYS
COMMON/ DATA2/ IPART(10,5), IDSTR(10,10), IOFER(10,10,5)
1, ISTAN(15,6), IPLET(10,5), ITRAK(40,5), RPART(10,2)
2, RSTAN(15,2), ROPER(10,10,8), ICART(4,42), RCART(4)
3, RTRAK(40,6), IRULE(8)
COMMON/ DATA3/ FSTAN(15,4), FCART(4,4), SSTAN(15,12)
1, SCART(10,52), SPLET(20,25), SPLTY(10), SPATE(10)
2, SPART(20,20), STRAK(40), FTRAK(4)
COMMON/ SELEC/ IAPAR(6)
GO TO (100,200,300,400,500),IRUL

C
C User decision rule to select part type to be introduced
C
100 RETURN

C
C Select parts randomly
C
200 CALL RANDU(IRAND1,IRAND2,XX)
IPS=IFIX(XX*NPT)+1
IPT=IAPAR(IPS)
RETURN

C
C Select operation with shortest processing time
C
300 ITYPE=SPART(IPT,1)
NOPLFT=SPART(IPT,9)
NOP=IPART(ITYPE,4)
NOPCOM=NOP-NOPLFT
TIME=1000000.
DO 350 N=NOPCOM,NOP
IF(ROPER(ITYPE,N,1).GT.TIME) GO TO 350
IOP=IOFER(ITYPE,N,1)
TIME=ROPER(ITYPE,N,1)
350 CONTINUE
RETURN

C
C Select the station with shortest out shuttle
C
400 ITYPE=IFIX(SPART(IRT,1))
NOP=IPART(ITYPE,4)
DO 420 N=1,NOP
IF(IOFER(ITYPE,N,1).EQ.IOP) GO TO 440
420 CONTINUE

C
440 KMIN=10
DO 460 L=2,5
KOUNT=0
IS=IOFER(ITYPE,N,L)
DO 450 I=7,9
IF(SSTAN(IS,I).LE.0.) GO TO 450
KOUNT=KOUNT+1
450 CONTINUE
IF(KOUNT.GT.KMIN) GO TO 460

```

```

      KMIN=KOUNT
      IST=IS
460   CONTINUE
      RETURN
C
C      Select the cart with fewest part on cart
C
500   KMIN=10
      DO 580 N=1,NCART
          KOUNT=0
          DO 560 L=4,6
              IF(SCART(N,L).LE.0.) GO TO 560
              KOUNT=KOUNT+1
560   CONTINUE
          IF(KOUNT.GT.KMIN) GO TO 580
          KMIN=KOUNT
          ICT=N
580   CONTINUE
C
      RETURN
      END

```

A printout of the data can be obtained if requested (Table B.3). The user can proceed with the simulation by typing in the name of the data file which contains the system data, the duration of time to be simulated, the number of intervals when intermediate system reports are required and the time span during which the graphical animation is to be performed.

An example of the system report is given in Table B.4.

(C) When the simulation is completed, one can proceed to examine the graphical output. The system status required for graphical animation are recorded in 4 separate display status files for 4 different types of entities in the system, viz. carts, station, pallets, and parts.

These display status files are direct access files assigned the same file name as the input data file but having different file extension codes DT1, DT2, DT3 and DT4, respectively. Therefore, the graphical outputs for different systems can be maintained in different files and examined later. Every time the input data file is modified and a new simulation run performed, the display status files will be overwritten by the results of the new simulation run. Hence in executing the graphical animation program we are always examining the latest run of the simulation for a particular input data file.

To execute the graphical animation program, turn the graphics terminal off and run the program EMULAT. The program will prompt for the data file name:

=====

TYPE IN THE FILE NAME: FMSDT.DAT

USE LIGHT PEN TO SELECT THE MODE OF DISPLAY

=====

The program sketches the layout of the machine shop as described in the data file. It also sets up the odometers for system clock and production figures as well as a set of menu as shown in Fig. B.2.

The user can interact with the program using the light pen to select one of the three menus provided: CONT (for continuous display), STEP (for single step display) and EXIT (for aborting the program). The graphical animation can be repeated without running the simulation again.

#### B.4 Error Diagnostics

Errors can arise due to bad input data or unrealistic system specifications (such as a track point without any successor point, a conveyor with no conveyor speed, etc.). Debugging facilities are incorporated into the program to assist the user to locate the error. A brief description of the error codes used is given in Appendix E.

Table B.2 : Data File Printout

\*\*\*\*\* DATA FOR STATION \*\*\*\*\*

NUMBER OF STATIONS	MACHINE SHOP LENGTH	WIDTH
3	140.00	100.00

STN NO	NO. OF POSITION IN QUEUE		TRACK POINT AT QUEUE		TRANSFER TIME FROM QUEUE		STATION LOCATION		STATION SIZE		
	IN	OUT	IN	OUT	COM	TO TRACK	TD STATION	X-COOR	Y-COOR	X-DIMEN	Y-DIMEN
1	3	3	2	3	0	1.00	0.50	34.00	45.00	8.00	16.00
2	3	3	5	6	0	1.00	0.50	75.00	76.00	16.00	8.00
3	3	3	8	9	0	1.00	0.50	115.00	45.00	8.00	16.00

\*\*\*\*\* DATA FOR PALLET TYPE \*\*\*\*\*

NUMBER OF PALLET TYPES
2

PALLET TYPE	NUMBER OF PALLET	PART TYPE	PART TYPE	PART TYPE
1	4	1	3	0
2	6	2	3	0

Table B.3 Echo Printout of Input Data

\*\*\*\*\* DATA FOR PART TYPE \*\*\*\*\*

NUMBER OF PART TYPES

3

PART TYPE	MAX. NO. IN THE SYSTEM	PRIORITY 1-HIGH 10-LOW	REQUIRED PRODUCTION	NUMBER OF OPERATIONS	INTERARRIVAL TIME	
					PARAM 1	PARAM 2
1	4	2	30	3	10.00	0.00
2	3	1	20	3	8.00	0.00
3	4	3	10	4	12.00	0.00

\*\*\*\*\* DATA FOR OPERATIONS \*\*\*\*\*

PART TYPE	FIX=1 NOR=2 EXP=3	OPER NO.	STN. NO.		STN. NO.	STN. NO.	PARAM 1 AT		PARAM 2 AT	
			(1)	(2)			(3)	(4)	(2)	(3)
1	2	1	1	0	0	0	15.00	0.00	0.00	0.00
1	1	2	0	0	0	0	80.00	0.00	0.00	0.00
1	2	3	1	0	0	0	15.00	0.00	0.00	0.00
2	2	4	1	0	0	0	15.00	0.00	0.00	0.00
2	1	5	3	0	0	0	200.00	0.00	0.00	0.00
2	2	6	1	0	0	0	15.00	0.00	0.00	0.00
3	2	7	1	0	0	0	15.00	0.00	0.00	0.00
3	1	8	2	0	0	0	60.00	0.00	0.00	0.00
3	1	9	3	0	0	0	180.00	0.00	0.00	0.00
3	1	10	1	0	0	0	15.00	0.00	0.00	0.00

Table B.3 (Cont'd)

\*\*\*\*\* DATA FOR CART TYPE \*\*\*\*\*

NUMBER OF CART TYPES

CART TYPE	SPEED	NO. OF CARTS	NO. OF PALLET (MAX-3)	FEASIBLE TRACK POINTS																			
				1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.
1	2.00	2.	3	1	2	3	4	5	6	7	8	9	10	0	0	0	0	0	0	0	0	0	0

\*\*\*\*\* DATA FOR TRACK POINTS \*\*\*\*\*

NUMBER OF TRACK POINTS  
10

TRACK NO	STATION NUMBER (0 IF NONE)	SUCCESSIVE DECISION POINTS				XCOR	YCOR	CONVEYOR SPEED TO SUCCESSIVE POINTS			
		(1)	(2)	(3)	(4)			(1)	(2)	(3)	(4)
1	0	2	0	0	0	40.00	20.00	0.00	0.00	0.00	0.00
2	1	3	0	0	0	40.00	40.00	0.00	0.00	0.00	0.00
3	1	4	0	0	0	40.00	50.00	0.00	0.00	0.00	0.00
4	0	5	0	0	0	40.00	70.00	0.00	0.00	0.00	0.00
5	2	6	0	0	0	70.00	70.00	0.00	0.00	0.00	0.00
6	2	7	0	0	0	80.00	70.00	0.00	0.00	0.00	0.00
7	0	8	0	0	0	110.00	70.00	0.00	0.00	0.00	0.00
8	3	9	0	0	0	110.00	50.00	0.00	0.00	0.00	0.00
9	3	10	0	0	0	110.00	40.00	0.00	0.00	0.00	0.00
10	0	1	0	0	0	110.00	20.00	0.00	0.00	0.00	0.00

Table B.3 (Cont'd)

\*\*\*\*\* DATA FOR DOWNTIME STATISTICS \*\*\*\*\*  
(STATION)

TYPE OF BREAKDOWN DISTR

3

STATION NO	TIME BETWEEN BREAKDOWN		REPAIR TIME	
	PARAM 1	PARAM 2	PARAM 1	PARAM 2
1	2500.00	0.00	150.00	0.00
2	3000.00	0.00	200.00	0.00
3	3500.00	0.00	250.00	0.00

\*\*\*\*\* DATA FOR DOWNTIME STATISTICS \*\*\*\*\*  
(CART)

TYPE OF BREAKDOWN DISTR

3

CART NO	TIME BETWEEN BREAKDOWN		REPAIR TIME	
	PARAM 1	PARAM 2	PARAM 1	PARAM 2
1	4000.00	0.00	300.00	0.00

Table B.3 (Cont'd)

\*\*\*\*\* DATA FOR DOWNTIME STATISTICS \*\*\*\*\*  
 (TRACK POINT)  
 ONE SET OF DATA FOR ALL TRACK POINTS

TYPE OF BREAKDOWN DISTR

3

TIME BETWEEN REPAIR TIME  
 BREAKDOWN  
 PARAM 1 PARAM 2 PARAM 1 PARAM 2  
 4500.00 0.00 500.00 0.00

\*\*\*\*\* PRIORITY RULES \*\*\*\*\*

RULE(1) RULE(2) RULE(3) RULE(4) RULE(5) RULE(6)  
 1 1 1 1 1 2

Table B.3 (Cont'd)

TYPICAL OUTPUT

SYSTEM REPORT AT TIME 0.10E+04 TIME UNITS

PRODUCTION SUMMARY OF COMPLETED PARTS

PART TYPE	PRODUCTION		THROUGHPUT TIME FOR		MAX
	PARTS SCHED	COMPL	PCT	AVE	
1	30	3	10.0	547.61	441.32
2	20	3	15.0	499.12	420.99
3	10	0			945.69
NO VALUE RECORDED					
TOTAL	60	6			

STATUS OF PARTS CURRENTLY IN SYSTEM--

PART NUMBER	PART TYPE	PRIOR NUMBER	PALLET NUMBER	CURRENT STAT	OPER	NEXT STAT	OPER	NO. OPER LEFT	IN SHUT(1)		OUT SHUT(2)		LIST OF OPERATIONS COMPLETED	TIME ENTER SYSTEM	
									IN	OUT	IN	OUT			
1	2	1	5	3	5	0	0	2	2	1	0	0	0	0	421.99
2	2	1	6	1	0	3	5	2	2	2	0	0	0	0	967.03
3	2	1	7	0	0	1	6	1	1	0	0	0	0	0	34.75
4	2	1	8	0	0	3	5	2	2	0	0	0	0	0	780.58
5	2	1	9	3	5	0	0	2	2	0	0	0	0	0	62.91
6	2	1	10	3	5	0	0	2	2	1	0	0	0	0	76.64
7	1	2	1	1	0	2	2	2	2	1	0	0	0	0	846.86
8	1	2	2	0	0	1	3	1	1	0	2	0	0	0	600.65
9	1	2	3	2	2	0	0	2	2	1	0	0	0	0	725.04
10	1	2	4	1	0	2	2	2	2	2	1	0	0	0	347.33

Table B.4 Typical System Output

## PALLET INFORMATION

PALL TYPE	NOW IN USE	NOW AVAIL	MAX USED	UTILISATION
1	4	0	4	2.21
2	6	0	6	4.76

## STATUS OF PALLETS--

PALLET NUMBER	PART NUMBER	PALLET TYPE
1	7	1
2	8	1
3	9	1
4	10	1
5	1	2
6	2	2
7	3	2
8	4	2
9	5	2
10	6	2

## STATION PERFORMANCE SUMMARY

STATION NUMBER	TIME BUSY	PCT	TIME IDLE	PCT	TIME DOWN	PCT	PERCENT OF TIME BUSY EXCLUDING DOWNTIME
1	318.31	31.9	680.69	68.1	0.00	0.0	31.86
2	198.67	39.9	600.33	60.1	0.00	0.0	39.91
3	902.67	90.4	96.33	9.6	0.00	0.0	90.36

Table B.4 (Cont'd)

## STATUS OF STATIONS--

STATION NUMBER	LAST START TIME(0:IDLE) DOWN-1 (-VE:COMPL) OCCUPY-2	UP-0	TIME AVAILABLE AFTER BREAKDOWN	IN-SHUTTLE	OUT-SHUTTLE	PART NUMBER IN QUEUE	COMMON-SHUTTLE
1	0.00	0	0.00	0	0	10	7
2	921.33	2	0.00	0	0	0	0
3	897.33	2	0.00	6	1	0	0

## SHUTTLE PERFORMANCE SUMMARY

STATION NUMBER	IN-SHUTTLE QUEUE SIZE	UTILI- MAX QUE	OUT-SHUTTLE QUEUE SIZE	UTILI- MAX QUE	COMMON UTILI- MAX QUE
1	3	0.009	1	3	2.426
2	3	0.026	1	3	0.229
3	3	2.211	3	3	0.468

## CART PERFORMANCE

CART NUMBER	MOVE		WAITING		DOWN		IDLE		TOTAL		NUMBER OF TRACK POINTS PASSED	NUMBER OF ASSIGNMENTS
	TIME	PCT	TIME	PCT	TIME	PCT	TIME	PCT	DISTANCE MOVED			
1	958.17	95.9	21.00	2.1	0.00	0.0	19.8	2.0	1940.00	81	23	
2	895.49	89.6	16.68	1.7	0.00	0.0	86.8	8.7	1820.00	77	18	

Table B.4 (Cont'd)

## STATUS OF CART--

CART NUMBER	CURRENT SPEED	PART NUMBER		UP-O DOWN-1	CART TYPE	TIME AVAILABLE AFTER BREAKDOWN	1-LOADING 2-UNLOAD 3-WAITING			SUCCESSIVE TRACK				POINTS
		1	2	3						7	8	9	10	
1	2.00	8	0	0	1	0.00	2			7	8	9	10	0
										0	0	0	0	0
										0	0	0	0	0
										0	0	0	0	0
2	2.00	4	0	3	1	0.00	2			3	4	5	6	0
										0	0	0	0	0
										0	0	0	0	0
										0	0	0	0	0
										0	0	0	0	0
										0	0	0	0	0

Table B.4 (Cont'd.)

CURRENT TIME: 0.00

PART TYPE     A       B       C

PART COMP     0       0       0

DISPLAY

MODE :

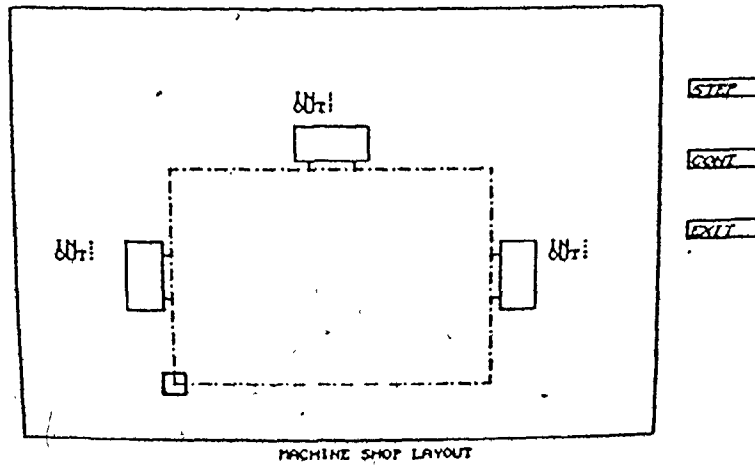


Fig. B.2 Graphical Display at Startup.

APPENDIX C  
GLOSSARY OF COMMON VARIABLES

<u>GASP Variables</u>	<u>Definition</u>	<u>Common Block</u>
ATRIB(I)	Attribute values of events ATRIB(1) - Event Time ATRIB(2) - Event Type ATRIB(3) - Part number for which event is scheduled	GCOM1
JEVNT	Code of time event to be processed	GCOM1
MFA	Relative address of first cell of NSET available	GCOM1
MEE(I)	Relative address of first entry in File I	GCOM1
MLE(I)	Relative address of last entry in File I	GCOM1
NNAPO	Number of attributes plus one	GCOM1
NNAPT	Number of attributes plus two	GCOM1
NNATR	Number of attributes per entry in QSET	GCOM1
NNFIL	Number of files	GCOM1
NNQ(I)	Current number of entries in file I	GCOM1

NNTRY	Maximum allowable number of entries	GCOM1
TNOW	Current time of simulation	GCOM1
TTBEG	Initial value of TNOW or time when simulation begins	GCOM1
TTFIN	Time to end simulation	GCOM1
EENQ(I)	Time integrated number of entries in File 1	GCOM2
VVNQ(I)	Time integrated square of number of entries in File 1	GCOM2
IINN(I)	Priority ranking indicator for event file lowest event time always has highest priority IINN(I) = 1	GCOM2
MMAXQ(I)	Maximum number of entries in file, I	GCOM2
QQTIM(I)	Time of last use of file I	GCOM2
SSOBV(I,J)	Array for storing statistics generated by COLCT (for part production statistics)	GCOM2
SSTPV(I,J)	Array for storing statistics generated by TIMST (for pallet and shuttle)	GCOM2

<u>FMS Variables</u>	<u>Definition</u>	<u>Common Block</u>
NPATE	Number of part types	DATA1
NPART	Total number of parts	DATA1
NSTAN	Number of station	DATA1
NPLTY	Number of pallet types	DATA1
NPLET	Total number of pallets	DATA1
NCATE	Number of cart types	DATA1
NCART	Total number of carts	DATA1
NPOIN	Number of track points	DATA1
IPART(I,J)	Description of parts	DATA2
	IPART(I,1) - Maximum number	
	IPART(I,2) - Priority	
	IPART(I,3) - Number of parts scheduled	
	IPART(I,4) - Number of operations required	
	IPART(I,5) - Type of distribu- tion for arrival pattern	
IDSTR(I,J)	Distribution of process time for operation J of part type I	DATA2
IOPER(I,J,K)	Description of operation	DATA2
	IOPER(I,J,1) - Operation number	
	IOPER(I,J,2) to IOPER(I,J,5) - Stations where the operation can be performed	

ISTAN(I,J)	Description of stations	DATA2
------------	-------------------------	-------

ISTAN(I,1) - Number of positions  
in incoming shuttle

ISTAN(I,2) - Number of positions  
in outgoing shuttle

ISTAN(I,3) - Number of positions  
in common shuttle

ISTAN(I,4) - Track point for in-  
coming shuttle

ISTAN(I,5) - Track point for out-  
going shuttle

ISTAN(I,6) - Track point for common  
shuttle

IPLET(I,J)	Description of pallet types	DATA2
------------	-----------------------------	-------

IPLET(I,1) - Number of pallets  
available

IPLET(I,2) to IPLET(I,5) - Part  
types that can be held  
by the pallet

ITRAK(I,J)	Description of track point	DATA2
------------	----------------------------	-------

ITRAK(I,1) - Station number where  
track point is joined

ITRAK(I,2) to ITRAK(I,5) - Successor  
points

RPART(I,J)	Description of part type	DATA2
------------	--------------------------	-------

RPART(I,1) - Mean arrival time

RPART(I,2) - Standard deviation of  
arrival time

RSTAN(I,J)	Description of station	DATA2
RESTAN(I,1)	- Transfer time from track to shuttle	
RSTAN(I,2)	- Transfer time from shuttle to station	
ROPER(I,J,K)	Process time for operation J of part type I at station K	DATA2
ICART(I,J)	Description of cart type	DATA2
ICART(I,1)	- Number of carts	
ICART(I,2)	- Number of pallets position on cart	
ICART(I,3) to ICART(I,42)	- Feasible track points where cart can travel	
RCART(I)	Cart speed for cart type I	DATA2
RTRAK(I,J)	Description of track point	DATA2
RTRAK(I,1)	- x-coordinate of track point I	
RTRAK(I,2)	- y-coordinates of track point I	
RTRAK(I,3) to RTRAK(I,6)	- Conveyor speed to successive track points	
IRULE(I)	Decision rules	DATA2
FSTAN(I,J)	Reliability statistics for station	DATA3
FCART(I,J)	Reliability statistics for cart	DATA3
FTRAK(I)	Reliability statistics for track points	DATA3

SSTAN(I,J)	Status vectors for station	DATA3
SSTAN(I,1)	- Last start time	
SSTAN(I,2)	- Status of station (free, down or occupied)	
SSTAN(I,3)	- Time when it will be available if down	
SSTAN(I,4) to SSTAN(I,6)	- Part no. in incoming shuttle	
SSTAN(I,7) to SSTAN(I,9)	- Part no. in outgoing shuttle	
SSTAN(I,10) to SSTAN(I,12)	- Part no. in common shuttle	
SCART(I,J)	Status vectors of carts	DATA3
SCART(I,1)	- Last track point passed	
SCART(I,2)	- Time of passing last track point	
SCART(I,3)	- Current speed of cart	
SCART(I,4) to SCART(I,6)	- Par no. on cart	
SCART(I,7)	- Status of cart (free, down, waiting)	
SCART(I,8)	- Cart type	
SCART(I,9)	- Time when it will be available if down	
SCART(I,10)	- Activity of cart (load- ing, unloading, waiting)	

SCART(I,11) - Destination of cart

SCART(I,12) to SCART(I,52) - Successive track point

SPLTY(I) - Number of pallets in use for pallet type I

DATA3

SPATE(I) - Stock level of part type I

SPART(I,J) - Status vector for part

SPART(I,1) - Part type

SPART(I,2) - Priority

SPART(I,3) - Pallet Number

SPART(I,4) - Cart Number

SPART(I,5) - Current station

SPART(I,6) - Current operation

SPART(I,7) - Next station

SPART(I,8) - Next operation

SPART(I,9) - Number of operations left

SPART(I,10) - Type of shuttle which part has entered

SPART(I,11) to SPART(I,19) - Operations completed

SPART(I,20) - Time when part enters the system

STRAK(I)

Status of track point (up or down)

DATA3

<u>FMS Variables</u>	<u>Definition</u>	<u>Common Block</u>
PCOMP(I)	Number of parts completed for part type I	BLOCK
TATSS(I,J)	Performance statistics for station I	BLOCK
	TATSS(I,1) - Time when last status change	
	TATSS(I,2) - Duration when station is busy	
	TATSS(I,3) - Duration when station is idle	
	TATSS(I,4) - Duration when station is down	
CSTAT(I,J)	Performance statistics for cart I	BLOCK
	CSTAT(I,1) - Time when last status change	
	CSTAT(I,2) - Duration when cart is moving	
	CSTAT(I,3) - Duration when cart is waiting	
	CSTAT(I,4) - Duration when cart is down	
MROUT(I,J)	Track points on generated route I	ROUTE
DROUT(I)	Distance for route I	ROUTE
IROUT(I)	Flag to indicate if route is blocked	ROUTE

TROUT(I)	Time delay for route to resume service	ROUTE
NLOAD	Number of loading station	LODNG
ISLOD(I)	Loading station number	LODNG
IRAND1, IRAND2	Seeds of random number	STATS
KSTAN	Type of reliability distribution for station	BREAK
KCATE	Type of reliability distribution for cart	BREAK
KTRAK	Type of reliability distribution for track	BREAK
TSTA	Time when graphical display starts	RTIME
TEND	Time when graphical display ends	RTIME

<u>Graphics Variables</u>	<u>Definition</u>	<u>Common Block</u>
NRCC	Pointer for record file of cart	RECOD
NRCP	Pointer for record file of pallet	RECOD
NRCS	Pointer for record file of station	RECOD
NSTEP	Number of updating for graphics record	RECOD
IBUF	Buffer array in display file	DFILE
CRTL	Cart dimension	DRAW
XOCRT(I)	x-coordinate for cart I	DRAW
YOCRT(I)	y-coordinate for cart I	DRAW
OFFSET	Spacing for lettering	DRAW
SPLN	Length of machine shop	SKETCH
SPWID	Width of machine shop	SKETCH

RSTAT(I,J)	Description of station	SKETCH
RSTAT(I,1)	- x-coordinate of station location	
RSTAT(I,2)	- y-coordinate of station location	
RSTAT(I,3)	- Length of station	
RSTAT(I,4)	- Width of station	

APPENDIX D  
DESCRIPTION OF SUBROUTINES  
AND FUNCTIONS

GASP SUBROUTINES

1. GASP      Executive routine for advancing time and status
2. DATIN     Initialises GASP variables and calls user written functions INTLC and STATE
3. EVNTS     Subroutine for decoding events
4. SET       Initialise file pointers and file statistics arrays
5. CLEAR     Initialises statistical arrays (SSOBV and SSTPV) and allows the user to collect statistics starting at any time during the simulation
6. COLCT(XX, ICLCT) If ICLCT > 0, records value XX as an observation on variable number ICLCT; If ICLCT = 0, computes and reports statistics on all NNCLT variables, if ICLCT < 0, computes and reports statistics on variable - ICLCT
7. TIMST  
   (XX, T, ISTAT) If ISTAT > 0, integrates variable number ISTAT assuming the value during the interval up to time T is the value of XX at the last call to TIMST for variable ISTAT; XX is the value variable ISTAT will have during the

next interval; if ISTAT<0, computes and reports statistics on variable - ISTAT

8.    RMOVE  
      (NTRY,IFILE)    Removes entry NTRY from file IFILE
9.    INTLS  
                     It initialises state variables and non-GASP variables, called in subroutine DATIN after all GASP variables have been initialised
10.   FILEM(IFILE)    File an entry into IFILE
11.   COPY(NTRY)      Puts attribute of entry NTRY into buffer storage array ATRIB without removing the entry
12.   NFIND  
      (NTRY,XVAL,  
      MCODE, IFILE,  
      JATT, TOL)      Locate an entry in file IFILE whose JATT attribute is related to the value XVAL according to the specification given by MCODE as shown below  
                     MCODE = 1: maximum value but greater than XVAL  
                     MCODE=2: minimum value but greater than XVAL  
                     MCODE=3: maximum value but less than XVAL  
                     MCODE=4: minimum value but less than XVAL  
                     MCODE=5: value equal to XVAL  $\pm$  TOL  
                     NTRY is set equal to the first cell number of the entry desired, the I<sup>th</sup> attribute of the entry is located in QSET(IC) where IC=NFIND + I; if no entry is found, NFIND is set to zero

FMS SUBROUTINES

START	Introduces starting events (arrival event for each part type, first breakdown event for each system components; station, cart and track point)
REPOT	It produces the system output
BREAK	It decodes the type of components for which breakdown event is scheduled and simulated the breakdown event
REPAR	It decodes the type of components for which repair event is scheduled and simulates the repair event
MANUAL	It produces a manual for input data format
READIN	It is a subroutine which provides an initial dialogue with the user to determine the duration of simulation and data file names period when graphical outputs are required
UNLCA	It simulates the unload cart event
OU SHU	It simulates the event when the part enters the out shuttle
LODCA	It simulates the load cart event
INSHU	It simulates the event when the part enters the shuttle
INSTN	It simulates the event when the part enters the station
TOCAR	It simulates the event when the part enters the cart and is ready to move on to its next destination

ARIVE	It simulates the arrival of raw parts
DISPLY	It collects the status of the system required for graphical display
DSPLT	It collects the status of pallets for display
DSSTN	It collects the status of station for display
DSCRT	It collects the status of the cart for display
RPPRT	It analyses and reports on the production statistics of all part types
RPPLT	It analyses and reports on the utilisation of all pallet types
RPSTN	It analyses and reports on the utilisation of all stations
RPCRT	It analyses and reports on the utilisation of all carts
RPSHT	It analyses and reports on the utilisation of shuttles
MLPRT	It prints the manual for inputting the part type data
MLSTN	It prints the manual for inputting the station data
MLCRT	It prints the manual for inputting the cart type data
MLRUL	It prints the manual for inputting the decision rules
MLSTS	It prints the manual for reliability data
STATS	It reports on the status of the system

NXTPA	It selects the next part to be processed
OPCOM	It simulates the operation complete event
CONVY	It simulates the moving of parts from one track point to another on a conveyor
RDDATA	Read in the input data
PDONE	It simulates the completion of a part
NXTOP	It selects the next operation for a part
GCART	It selects the cart to transfer a part
FSTAT	It selects the next station to go to
STUSA	It reports on the status of parts and stations
STUSB	It reports on the status of carts and pallets
INTRO	It introduces a part into the system whenever there is a pallet available
PSLCT	It selects the part according to the specified rule
MOVCA	It simulates the movement of carts
OPSTA	It simulates the starting of an operation on a station
ROUTE	It generates all possible routes between two track points
POSCA	It finds the current position of carts
TCROS	It finds the time when a cart passes through a track point
RBLCK	It checks the blocked route and the time when a blocked route will be freed
HRUL	User-defined decision rule it describes

GRAPHICS SUBROUTINES

EMULAT	Executive program for graphical output
SKETCH	It displays the system layout on the graphic terminal
MOTION	It simulates the movement of parts through the system
SKSHP	It displays the <u>shop</u> and sets up the odometer for system time and the production figure. It also displays the various text strings
SKTRK	It displays the MHS and locates all the stations
SKCRT	It displays the carts in their initial position
SHSTN	It displays the current status of the station
SHCRT	It displays the current status of the cart
SHPLT	It displays the current status of pallets on conveyor
LPHIT	It checks the light pen interaction
SQUARE	It displays a square with given dimensions at a given location to represent the cart and the station
LLBXY	It finds out the locations for labelling the in- and out-shuttle of each station

APPENDIX E  
ERROR DIAGNOSTICS

ERROR CODE	ERROR MESSAGES	POSSIBLE CAUSES	OCCURRENCE
102	Part cannot be found in out-shuttle	Error in station input data out-shuttle capacity larger than 3	OUSHU
103	Part cannot be found in in-shuttle	Error in station input data in-shuttle capacity larger than 3	INSHU
104	Part cannot be found on cart which is unloading the part	Error in cart input data maximum number of pallets larger than 3	INSHU
105	Part cannot be found in in-shuttle	Error in station input data in-shuttle capacity larger than 3	INSTN
106	Part cannot be found in out-shuttle	Error in station input data out-shuttle capacity larger than 3	TOCAR
109	No pallet position available on cart	Error in cart input data maximum number of pallets less than or equal to zero	TOCAR
110	Completed operation more than scheduled	Error in operation input data	OPCOM
111	No station found for an operation	Error in operation input data	OPCOM
112	Cart not found	Error in cart input data	GCART
115	No feasible route	Error in track input data	MOVCA
116	Open ended track	Error in track input data	ROUTE
119	Operation not found	Error in operation input data	PSLCT
120	Station not found	Error in operation input data	PSLCT
201	Negative entry in file	Refer to GASP User's Manual [16]	GASP

202	Number of entry is negative	Error 202 - 208 - Refer to GASP User's Manual	SET
203	Negative pointer		FILEM
204	Number of file less than 1		FILEM
205	Negative entry		COPY
206	Negative pointer		NFIND
207	Negative entry		RMOVE
208	Negative pointer		RMOVE

## APPENDIX F: OVERLAY STRUCTURES FOR FMSSIM &amp; EMULAT

This is a linker for the simulation package

RU LINK

Root segment

FMSSIM,FMSSIM=FMSSIM,0ASP-ERROR//

Overlay region 1

DATIN/0:1

START/0:1

EVENTS/0:1

Overlay region 2

SET/0:2

REPT/0:2

CLEAR/0:2

BREAK/0:2

REPAR/0:2

MANUAL/0:2

READIN/0:2

UNLCA/0:2

OUSHU/0:2

LODCA/0:2

INSHU/0:2

INSTN/0:2

TOCAR/0:2

AKIVE/0:2

DISPLY/0:2

Overlay region 3

RPPRT/0:3

RPPLT/0:3

RPSTN/0:3

RPCRT/0:3

RPSHT/0:3

MLPRT/0:3

MLSTN/0:3

MLCRT/0:3

MLRUL/0:3

MLSTS/0:3

DTPRT/0:3

DTSTN/0:3

DIOPR/0:3

DTPLT/0:3

DTCRT/0:3

DTIRK/0:3

DTSTS/0:3

DTROL/0:3

STATS/0:3

NXTPA/0:3

DSPLT/0:3

DSSIN/0:3

DSCRT/0:3

OPCOM/0:3

CONVY/0:3

POOR COPY

COPIE DE QUALITEE INFERIEURE

## Overlay region 4

RDDATA/0:4  
PDONE/0:4  
NXTOP/0:4  
GCART/0:4  
FSTAT/0:4  
STUSA/0:4  
STUSB/0:4  
INTRO/0:4  
PSLCT/0:4

## Overlay region 5

COLCT/0:5  
TIMST/0:5  
RMOVE/0:5  
INTLC/0:5  
MOVCA/0:5  
OPSTA/0:5

## Overlay region 6

FILEM/0:6  
ROUTE/0:6  
POSCA/0:6  
RBLCK/0:6  
PRIOR/0:6

## Overlay region 7

COPY/0:7  
TCROS/0:7  
NFIND/0:7  
ORDER/0:7  
CHRUL/0:7

! This is a linker for the emulation package.

RU LINK

! Root segment

EMULAT,EMULAT=EMULAT,RKO:GLIB,RKO:SYSLIB//

! Overlay region 1

READIN/U:1

SKETCH/U:1

MOTION/O:1

! Overlay region 2

DTPRT/O:2

DTOPR/O:2

DTSTN/O:2

DTPLI/O:2

DTCRT/O:2

DTTRN/O:2

DTSTS/O:2

DTRUL/O:2

SKSHF/O:2

SKTRN/O:2

SKCRT/O:2

SKPLT/O:2

SHSTN/O:2

SHCRT/O:2

SHPLT/O:2

! Overlay region 3

SQUARE/O:3

LLBXY/O:3

//

POOR COPY  
COPIE DE QUALITEE INFERIEURE

APPENDIX G: SAMPLE INPUT AND ITS ECHO-PRINTOUT

[illegible]

Table G.1. Sample Data File



\*\*\*\*\* DATA FOR PART TYPE \*\*\*\*\*

NUMBER OF PART TYPES

PART TYPE	MAX.NO.IN THE SYSTEM	PRIORITY 1-HIGH 10-LOW	REQUIRED PRODUCTION	NUMBER OF OPERATIONS	INTERARRIVAL TIME			
					DISTR	PARAM 1	PARAM 2	
1	10	2	500	7	0	0.00	0.00	
2	10	2	150	7	0	0.00	0.00	
3	10	2	80	7	0	0.00	0.00	
4	10	2	200	8	0	0.00	0.00	
5	10	2	100	7	0	0.00	0.00	
6	10	2	50	8	0	0.00	0.00	

\*\*\*\*\* DATA FOR OPERATIONS \*\*\*\*\*

PART TYPE	FIX=1 NOR=2 EXP=3	OPER NO.	STN. NO.				PARAM 1 AT				PARAM 2 AT			
			(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
1	1	1	1	0	0	0	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	1	2	2	3	5	0	11.00	11.00	11.00	0.00	0.00	0.00	0.00	0.00
1	1	3	1	0	0	0	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	1	4	4	0	0	0	1.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	1	5	1	0	0	0	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table G.2 Echo Printout of Data File.



\*\*\*\*\* DATA FOR STATION \*\*\*\*\*

NUMBER OF STATIONS      MACHINE SHOP  
LENGTH      WIDTH

6      400.00      350.00

STN NO	NO. OF POSITION		TRACK POINT		TRANSFER TIME FROM		STATION LOCATION		STATION SIZE	
	IN	OUT	IN	OUT	TO QUEUE	TO TRACK	X-COOR	Y-COOR	X-DIMEN	Y-DIMEN
1	3	3	3	4	0.10	0.10	210.00	80.00	30.00	20.00
2	3	0	6	7	0.10	0.10	60.00	180.00	20.00	30.00
3	3	0	9	10	0.10	0.10	110.00	280.00	30.00	20.00
4	3	0	11	12	0.10	0.10	210.00	280.00	30.00	20.00
5	3	0	14	15	0.10	0.10	270.00	280.00	30.00	20.00
6	3	0	17	18	0.10	0.10	340.00	180.00	20.00	30.00

\*\*\*\*\* DATA FOR PALLET TYPE \*\*\*\*\*

NUMBER OF PALLET TYPES

PALLET TYPE	NUMBER OF PALLET		PART TYPE		PART TYPE	
	IN	OUT	IN	OUT	IN	OUT
1	3	3	3	4	0.10	0.10
2	3	0	6	7	0.10	0.10
3	3	0	9	10	0.10	0.10
4	3	0	11	12	0.10	0.10
5	3	0	14	15	0.10	0.10
6	3	0	17	18	0.10	0.10

Table G.2 (Cont'd.)

```

1 2 3 4 5 6
3 3 3 3 3 3
1 2 3 4 5 6
0 0 0 0 0 0

```

\*\*\*\*\* DATA FOR CART TYPE \*\*\*\*\*

NUMBER OF CART TYPES

0

\*\*\*\*\* DATA FOR TRACK POINTS \*\*\*\*\*

NUMBER OF TRACK POINTS

18

TRACK NO	STATION NUMBER (0 IF NONE)	SUCCESSIVE DECISION POINTS (1) (2) (3) (4)	XCDR	YCDR	CONVEYOR SPEED TO SUCCESSIVE POINTS (1) (2) (3) (4)
1	0	2	0	0	320.00 100.00
2	0	3	0	0	230.00 100.00
3	1	4	0	0	220.00 100.00
4	1	5	0	0	200.00 100.00
5	0	6	0	0	80.00 100.00
6	2	7	0	0	80.00 170.00
7	2	8	0	0	80.00 170.00
8	0	9	0	0	80.00 260.00
9	3	10	0	0	100.00 260.00
10	3	11	0	0	120.00 260.00
11	4	12	0	0	200.00 260.00

Table G.2 (Cont'd.)

```

=====
**** DATA FOR DOWNTIME STATISTICS ****
(STATION)

TYPE OF BREAKDOWN DISTR

12 4 13 0 0 0 220.00 260.00 100.00 0.00 0.00
13 0 14 0 0 0 230.00 260.00 100.00 0.00 0.00
14 5 15 0 0 0 260.00 260.00 100.00 0.00 0.00
15 5 16 0 0 0 280.00 260.00 100.00 0.00 0.00
16 0 17 0 0 0 320.00 260.00 100.00 0.00 0.00
17 6 18 0 0 0 320.00 190.00 100.00 0.00 0.00
18 6 1 0 0 0 320.00 170.00 100.00 0.00 0.00
=====

```

```

=====
**** DATA FOR DOWNTIME STATISTICS ****
(STATION)

```

TYPE OF BREAKDOWN DISTR

1

```

=====
STATION   TIME BETWEEN   REPAIR TIME
NO        BREAKDOWN
PARAM 1  PARAM 2      PARAM 1  PARAM 2
=====
1  5000.00  0.00  100.00  0.00
2  2500.00  0.00  200.00  0.00
3  2500.00  0.00  200.00  0.00
4  3000.00  0.00  350.00  0.00
5  2500.00  0.00  200.00  0.00
6  3000.00  0.00  350.00  0.00
=====

```

```

=====
**** DATA FOR DOWNTIME STATISTICS ****
(TRACK POINT)
ONE SET OF DATA FOR ALL TRACK POINTS

```

TYPE OF BREAKDOWN DISTR

1

Table G.2 (Cont'd.)

# REPAIR TIME

TIME BETWEEN  
BREAKDOWN

PARAM 1 PARAM 2 PARAM 1 PARAM 2

8000.00 0.00 100.00 0.00

## \*\*\*\*\* PRIORITY RULES \*\*\*\*\*

RULE(1) RULE(2) RULE(3) RULE(4) RULE(5) RULE(6)

1 1 1 2 1 1

Table G/2 (Cont'd.)

195.

APPENDIX H: DATA STRUCTURE

## ORGANIZATION OF DESCRIPTION DATA

NO. OF PART TYPES		NO. OF STATION		NO. OF PALLET TYPES			NO. OF CART TYPES			NO. OF TRACK PTS.				
PART DESCRIPTION (one record for each part type)		MAX. NO IN SYSTEM	PRIORITY	NO. OF PARTS SCHEDULED	NO. OF OPERATIONS	DISTR. FOR ARRIVAL TIME		PARAM 1* ARRIVAL TIME	PARAM 2* ARRIVAL TIME					
OPERATIONS DESCRIPTION		OPERATION NO.	STATION NO. 1	STATION NO. 2	STATION NO. 3	STATION NO. 4	TIME AT STN. 1	TIME AT STN. 2	TIME AT STN. 3	TIME AT STN. 4				
STATION DESCRIPTION		CAPACITY IN-SHUTTLE	CAPACITY OUT-SHUTTLE	CAPACITY COMMON SHUTTLE	TRACK PT AT IN- SHUTTLE	TRACK PT AT OUT- SHUTTLE	TRACK PT AT COMMON SHUTTLE	TRANSFER TIME TRACK TO SHUTTLE	TRANSFER TIME SHUTTLE TO SHUTTLE					
X-COOR. OF STATION		Y-COOR. OF STATION	LENGTH OF STATION	WIDTH OF STATION										
PALLET DESCRIPTION	NO. OF PALLETS	PART TYPE	PART TYPE	PART TYPE										
CART DESCRIPTION	NO. OF CARTS	NO. OF PALLETS IT CAN HOLD	FEASIBLE TRACK POINTS											
	PT9	PT10	PT11	PT12	PT13	PT14	PT15	PT16	PT17	PT18				
	PT19	PT20	PT21	PT22	PT23	PT24	PT25	PT26	PT27	PT28				
	PT29	PT30	PT31	PT32	PT33	PT34	PT35	PT36	PT37	PT38				
	PT39	PT40												
CART SPEED														
STATION RELIABILITY	TIME LEADING TO BREAKDOWN		TIME FOR REPAIR											
	*PARAM 1	PARAM 2	PARAM 1	PARAM 2										

ORGANIZATION OF DESCRIPTION DATA - Cont'd.

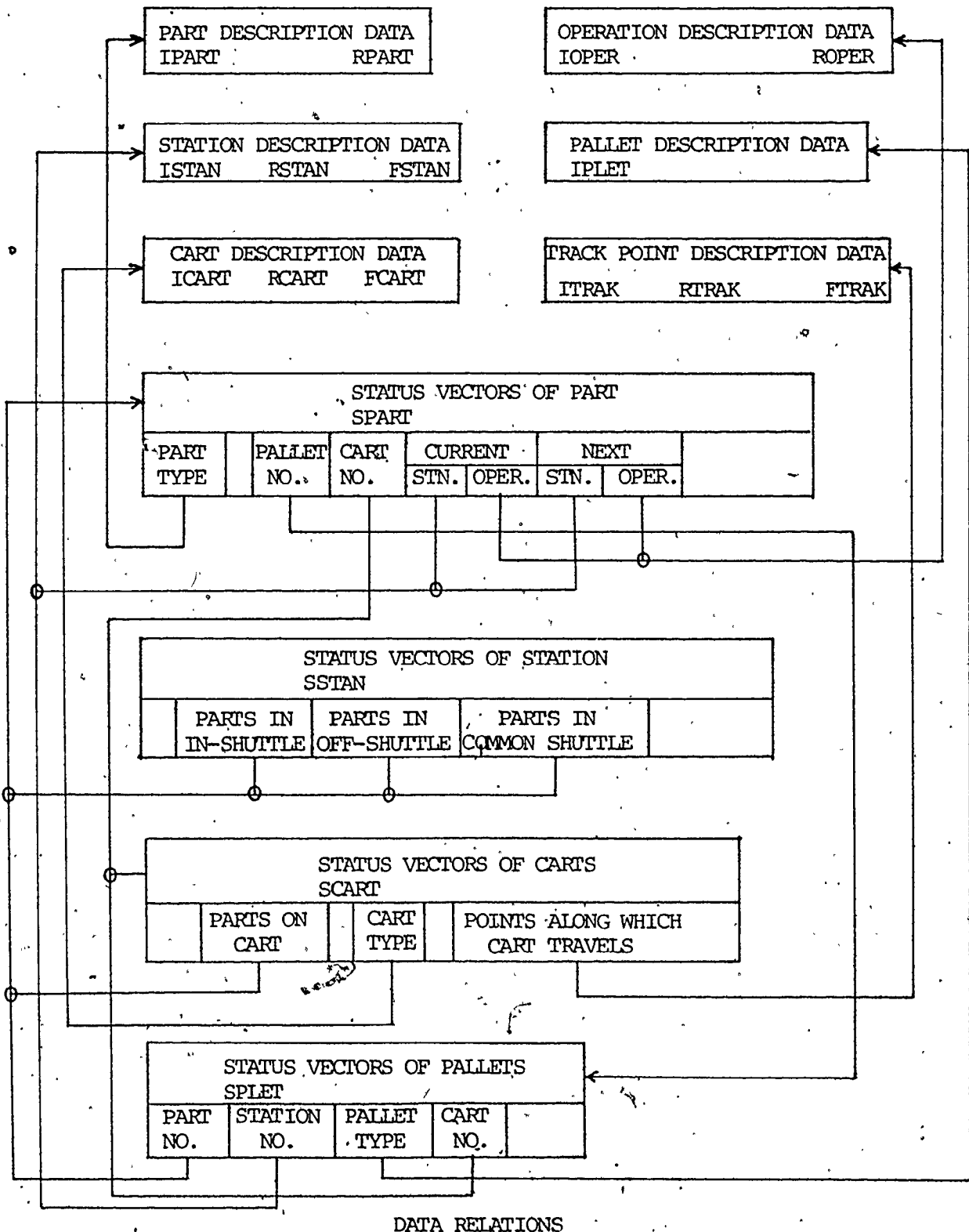
CART RELIABILITY	TIME LEADING TO BREAKDOWN		TIME FOR REPAIR	
	PARAM 1	PARAM 2	PARAM 1	PARAM 2
* PARAM 1				
TRACK RELIABILITY	TIME LEADING TO BREAKDOWN		TIME FOR REPAIR	
	PARAM 1	PARAM 2	PARAM 1	PARAM 2
* PARAM 1				

\* PARAM 1 - Mean for Normal Distribution and Exponential Distribution.

\* PARAM 2 - Standard Deviation for Normal Distribution.

## ORGANIZATION OF STATUS VECTORS

PART STATUS	PART TYPE	PRIORITY	PALLET NO.	CART NO.	CURRENT STATION	CURRENT OPERATION	NEXT STATION	NEXT OPERATION	NO. OF OPERATION LEFT	SHUTTLE TYPE
OPERATION NUMBER COMPLETED										
1		2	3	4	5	6	7	8	9	TIME ENTER SYSTEM
PALLET STATUS	PART NO.	STATION NO.	PALLET TYPE	LAST PT PAST	TIME OF PASSING	CURRENT SPEED	CART NO.	SUCCESSIVE TRACK		
	PT4	PT5	PT6	PT7	PT8	PT9	PT10	PT11	PT12	PT13
	PT14	PT15	PT16	PT17	PT18	PT19	PT20	PT21	PT22	PT23
	PT24	PT25	PT26	PT27	PT28	PT29	PT30	PT31	PT32	PT33
	PT34	PT35	PT36	PT37	PT38					
CART STATUS	LAST POINT PASSED	TIME OF PASSING	CURRENT SPEED	PART NO. ON CART		BREAKDOWN FLAG		CART TYPE	TIME AVAILABLE IF DOWN	ACTIVITY
				1	2	3				
SUCCESSIVE TRACK POINTS										
DESTINATION	PT1	PT2	PT3	PT4	PT5	PT6	PT7	PT8	PT9	
PT10	PT11	PT12	PT13	PT14	PT15	PT16	PT17	PT18	PT19	
PT20	PT21	PT22	PT23	PT24	PT25	PT26	PT27	PT28	PT29	
PT30	PT31	PT32	PT33	PT34	PT35	PT36	PT37	PT38	PT39	
STATION STATUS	LAST START TIME	STATUS FLAG	TIME WHEN AVAILABLE IF DOWN	PART NUMBER (IN-SHUTTLE)		PART NUMBER (OFF-SHUTTLE)		PART NUMBER (COMMON SHUTTLE)		
				1	2	3	1	2	3	
NUMBER AVAILABLE										
PALLET TYPE STATUS										
PART TYPE STATUS	STOCK LEVEL									

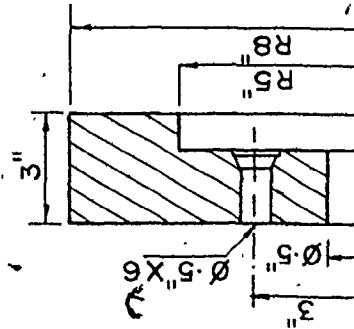


APPENDIX J

PROCESS PLANS FOR ALL PART  
TYPES USED IN CASE STUDY

PROCESS PLAN			
PART NAME	TYPE 1 WEAR PLATE	PART NO. 1	MATERIAL CAST STEEL

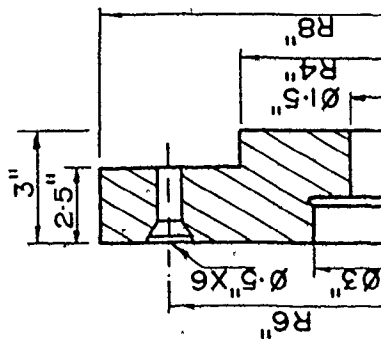
OPERATION NO.	DESCRIP-TION	STATION	S.F.P.M.	I. P. R.	I. P. M.	PROCESS TIME (MIN)	
						INDIV.	TOTAL
1	LOADING	LOADING	-	-	-	1.00	1.00
2	BORING TOOL CHANGE INTER- NAL FACING	LATHE	105.0	0.014	0.58	3.96	11.03
			-	-	-	0.10	
			105.0	0.014	0.42	4.66	
3	REFIX- TURING	LOADING	-	0	-	1.00	1.00
4	DRILL- ING TOOL CHANGE COUNTER- SUNK	DRILL- ING	105.0	0.012	8.60	0.79	1.39
			-	-	-	0.10	
			105.0	0.004	8.60	0.50	
5	REFIX- TURING	LOADING	-	-	-	1.00	1.00
6	TURNING FACING	LATHE	105.0	0.014	0.34	8.70	15.49
			105.0	0.014	0.68	6.69	
7	UNLOAD	LOADING	-	-	-	1.00	1.00
TOTAL PROCESS TIME						31.91	



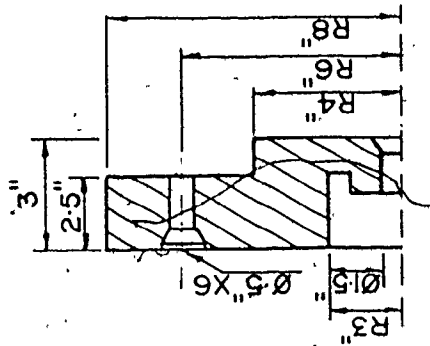
PROCESS PLAN				PART NO. 2		MATERIAL CAST STEEL	
PART NAME: TYPE 2 WEAR PLATE							
OPERATION NO.	DESCRIP-TION	STATION	SFPM	I.P.R.	I.P.M.	PROCESS TIME (MIN)	
						INDIV.	TOTAL
1	LOADING	LOADING	-	-	-	1.00	1.00
2	INT. BOR-ING	LATHE	105.0	0.014	1.69	2.25	
	INT. FAC-ING		105.0	0.014	0.68	5.14	
	TURNING		105.0	0.014	0.34	7.27	17.23
3	REFIXTUR-ING	LOADING	-	-	-	1.00	1.00
4	DRILLING	DRILLING	105.0	0.012	8.60	1.05	
	TOOL CHANGE		-	-	-	0.10	
	COUNTER-SINK		105.0	0.014	8.60	0.67	1.82
5	REFIXTUR-ING	LOADING	-	-	-	1.00	1.00
6	FACING	LATHE	105.0	0.014	0.53	6.56	
	TURNING		105.0	0.014	1.14	0.44	
	FACING		105.0	0.014	1.74	0.56	7.56
7	UNLOAD	LOADING	-	-	-	1.00	1.00
TOTAL PROCESS TIME						30.61	

3"  
2.5"  
0.5" X 6"  
R6"  
R4"  
R5"  
R8"

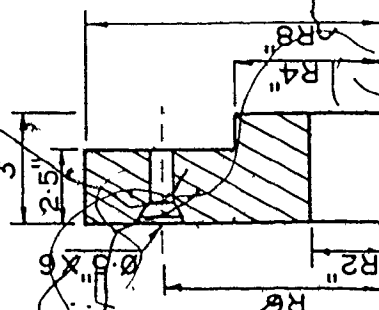
PROCESS PLAN		PART NO. 3		MATERIAL CAST STEEL			
PART NAME: TYPE 3 WEAR PLATE							
OPERATION NO.	DESCRIP- TION	STATION	SFPM	I.P.R.	I.P.M.	PROCESS TIME (MIN.)	
						INDIV.	TOTAL
1	LOADING	LOADING	-	-	-	1.00	1.00
2	INT. BOR- ING	LATHE	105.0	0.014	0.86	1.26	
	TOOL CHANGE		-	-	-	0.10	
	GROOVING		105.0	0.014	0.86	0.14	
	TOOL CHANGE		-	-	-	0.10	
	FACING		105.0	0.014	0.86	1.46	
	TOOL CHANGE		-	-	-	0.10	
	TURNING		105.0	0.014	0.43	1.34	4.50
3	REFIXTUR- ING	LOADING	-	-	-	1.00	1.00
4	DRILLING	DRILLING	105.0	0.012	8.60	1.05	
	TOOL CHANGE		-	-	-	0.10	
	COUNTER- SUNK		105.0	0.014	8.60	0.67	1.82
5	REFIXTUR- ING	LOADING	-	-	-	1.00	1.00
6	FACING	LATHE	105.0	0.014	0.86	1.72	
	TURNING		105.0	0.014	0.43	3.50	
	FACING		105.0	0.014	1.14	0.88	6.10
7	UNLOAD	LOADING	-	-	-	1.00	1.00
TOTAL PROCESS TIME						16.42	



PROCESS PLAN							
PART NAME: TYPE 4 WEAR PLATE		PART NO. 4		MATERIAL CAST STEEL			
OPERATION NO.	DESCRIPTION	STATION	SFPM	I.P.R.	I.P.M.	PROCESS TIME (MIN)	
1	LOADING	LOADING	-	-	-	1.00	1.00
2	INT. BORING TOOL CHANGE FACING TOOL CHANGE	LATHE	105.0 - 105.0 -	0.014 - 0.014 -	1.76 - 0.86 -	2.26 0.10 3.46 0.10	
3	TURNING REFIX-TURING	LOADING	105.0 -	0.014 -	0.43 -	3.50 1.00	9.52 1.00
4	DRILLING TOOL CHANGE COUNTER-SUNK	DRILLING	105.0 - 105.0	0.014 - 0.014	8.60 - 8.60	0.79 0.10 0.50	1.39
5	MILLING	MILLING	105.0	0.014	3.70	2.96	2.96
6	REFIX-TURING	LOADING	-	-	-	1.00	1.00
7	FACING TURNING FACING	LATHE	105.0 105.0 105.0	0.014 0.014 0.014	0.86 0.43 1.14	1.72 3.50 1.22	6.44
8	UNLOAD	LOADING	-	-	-	1.00	1.00
TOTAL PROCESS TIME							24.21



PROCESS PLAN		PART NO. 5		MATERIAL CAST STEEL		
PART NAME TYPE 5 WEAR PLATE						
OPERATION NO.	DESCRIPTION	STATION	SFPM	I.P.R.	I.P.M.	PROCESS TIME (MIN) INDIV. TOTAL
1	LOADING	LOADING	-	-	-	1.00 1.00
2	INT. BORING TOOL CHANGE	LATHE	105.0	0.014	1.38	5.94 0.10
3	TURNING REFIX-TURING	LOADING	105.0	0.014	0.86	4.56 1.00
4	DRILLING TOOL CHANGE COUNTER-SUNK	DRILLING	105.0	0.014	8.60	0.79 0.10 1.39
5	REFIX-TURING	LOADING	-	-	-	1.00 1.00
6	FACING TURNING FACING	LATHE	105.0 105.0 105.0	0.014 0.014 0.014	0.53 1.14 1.74	3.75 1.32 1.44 6.51
7	UNLOAD	LOADING	-	-	-	1.00 1.00
TOTAL PROCESS TIME						18.00





APPENDIX K: FLOW CHARTS

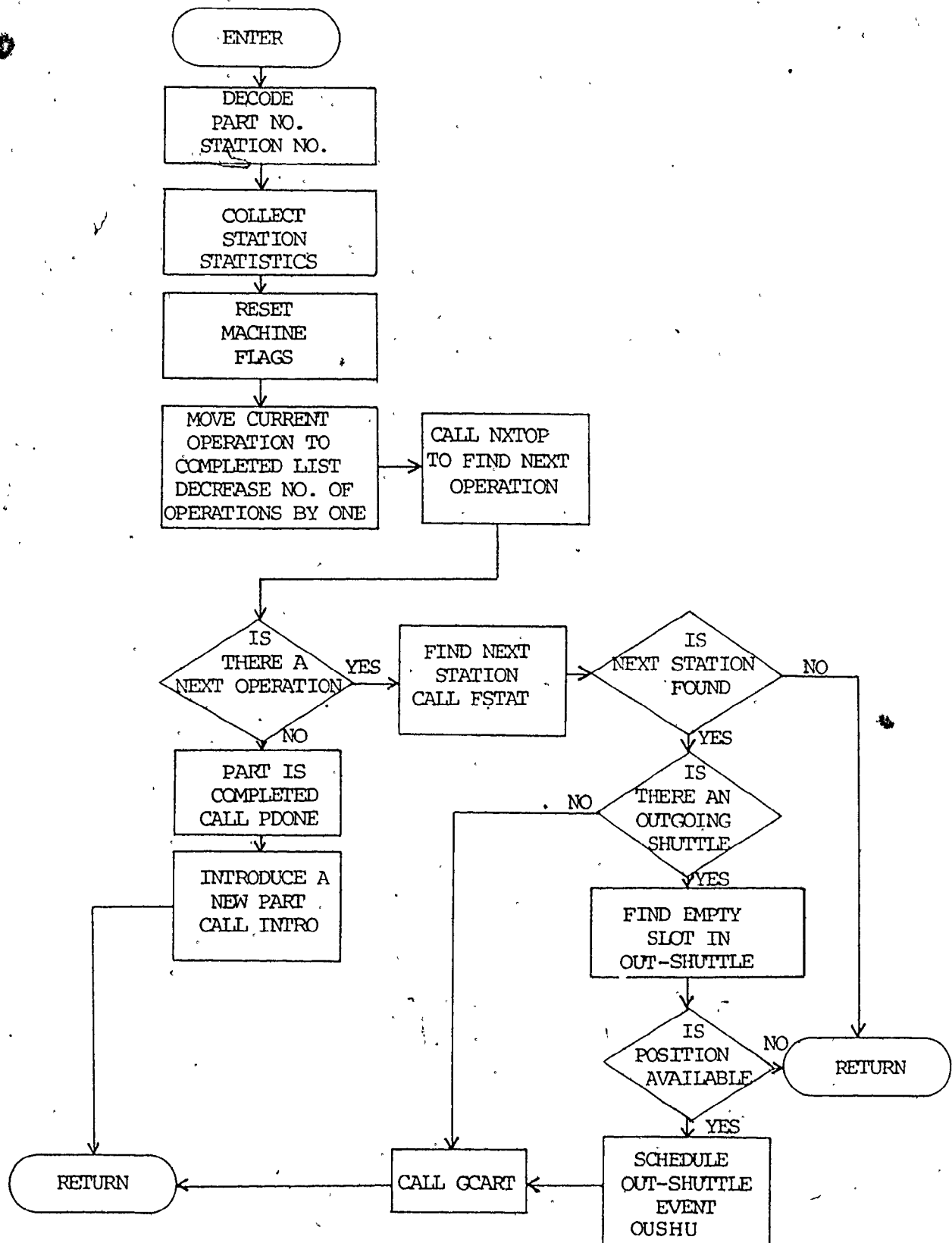


Fig. K.1 Flowchart for Subroutine OPCOM.

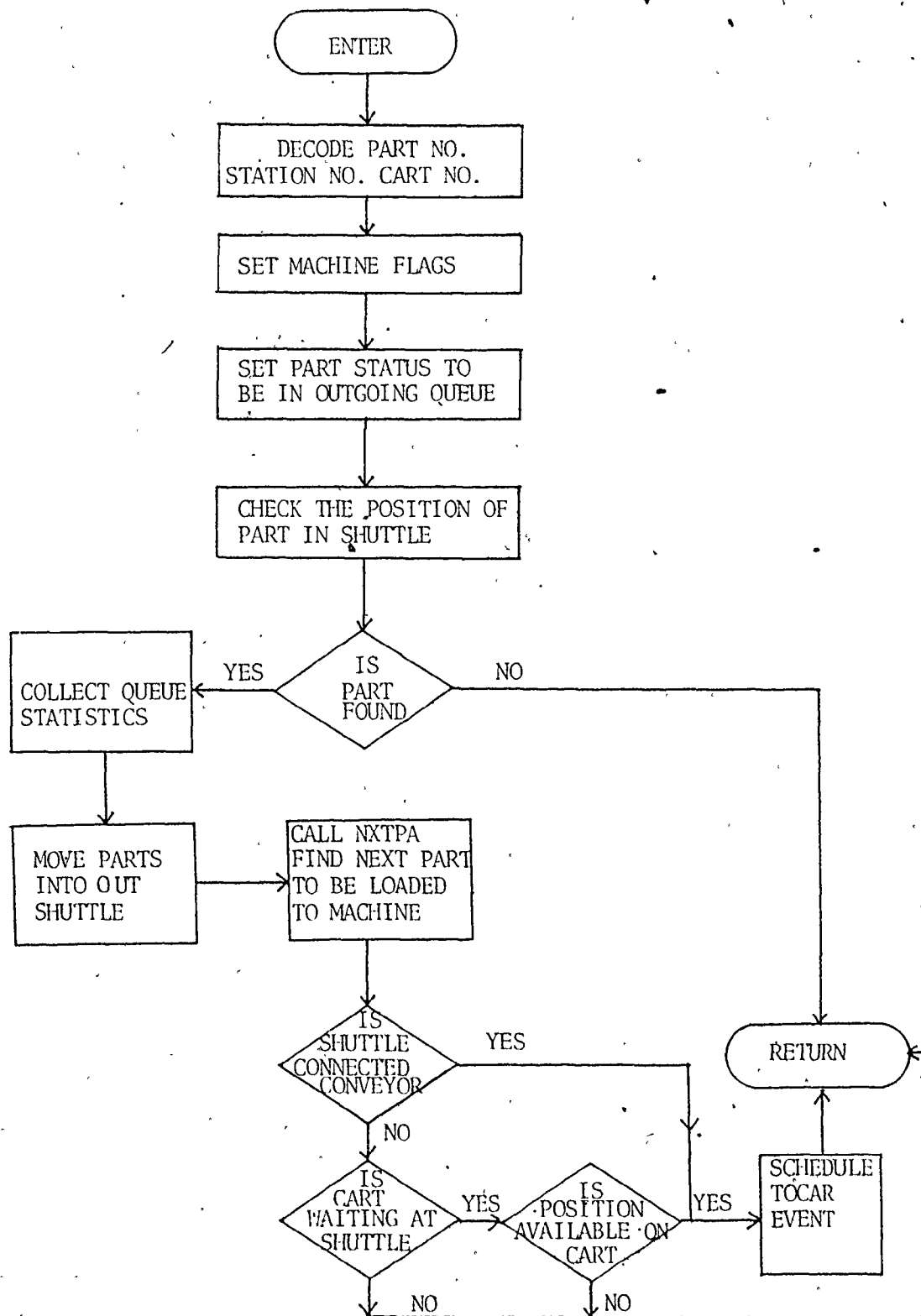


Fig. K.2 Flowchart for Subroutine OUSHU.

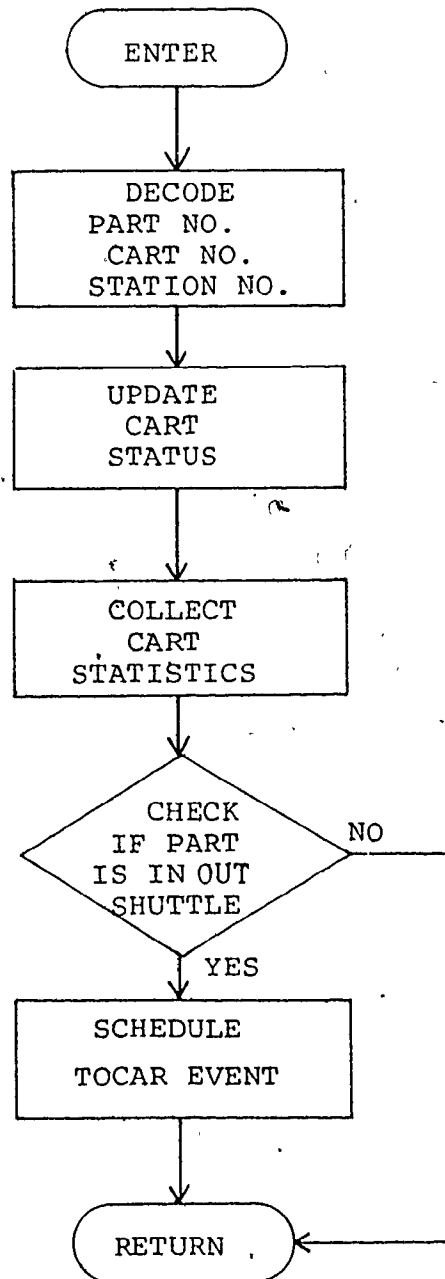


Fig. K.3 Flowchart for Subroutine LODCA.

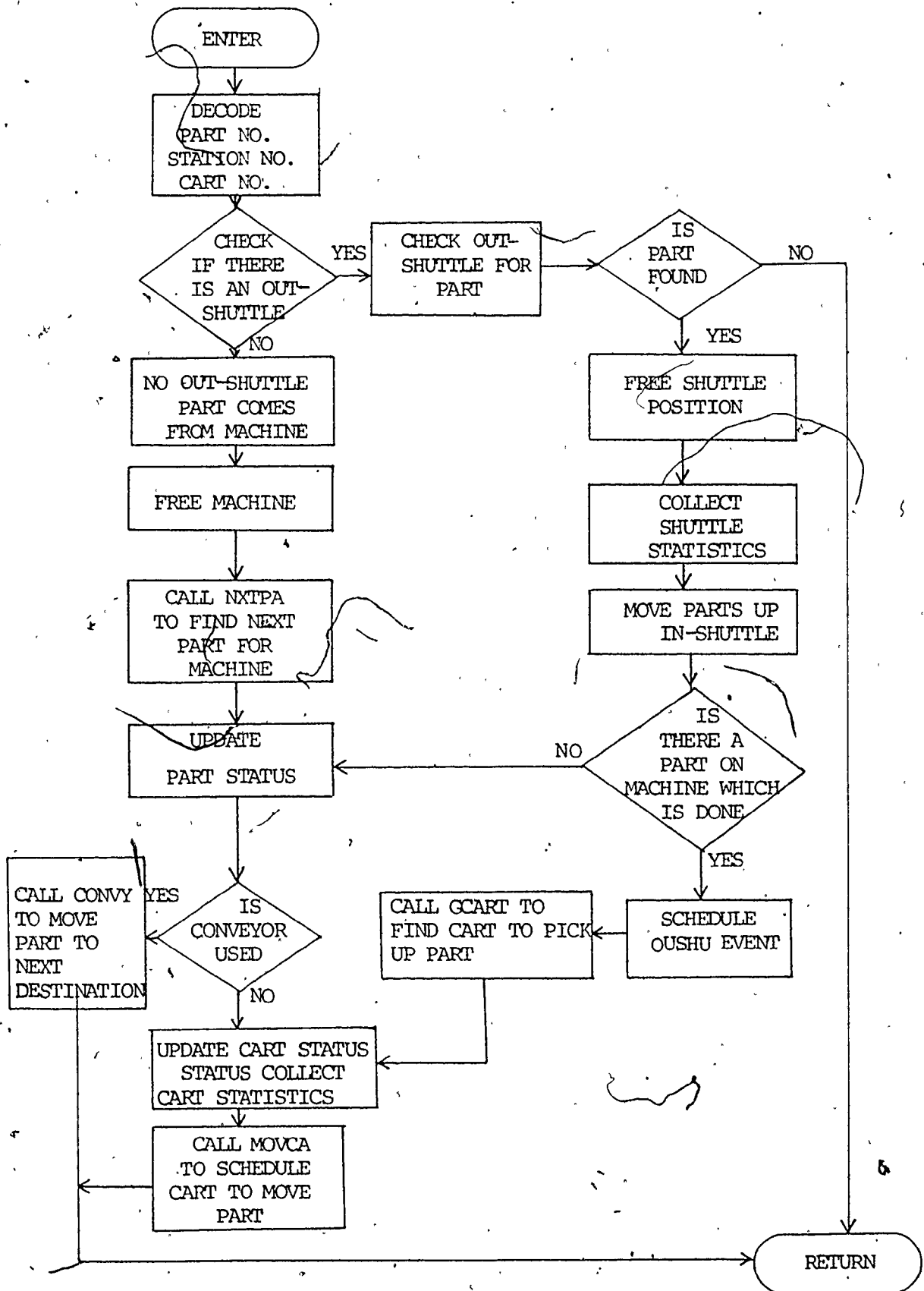


Fig. K.4 Flowchart for Subroutine TOCAR.

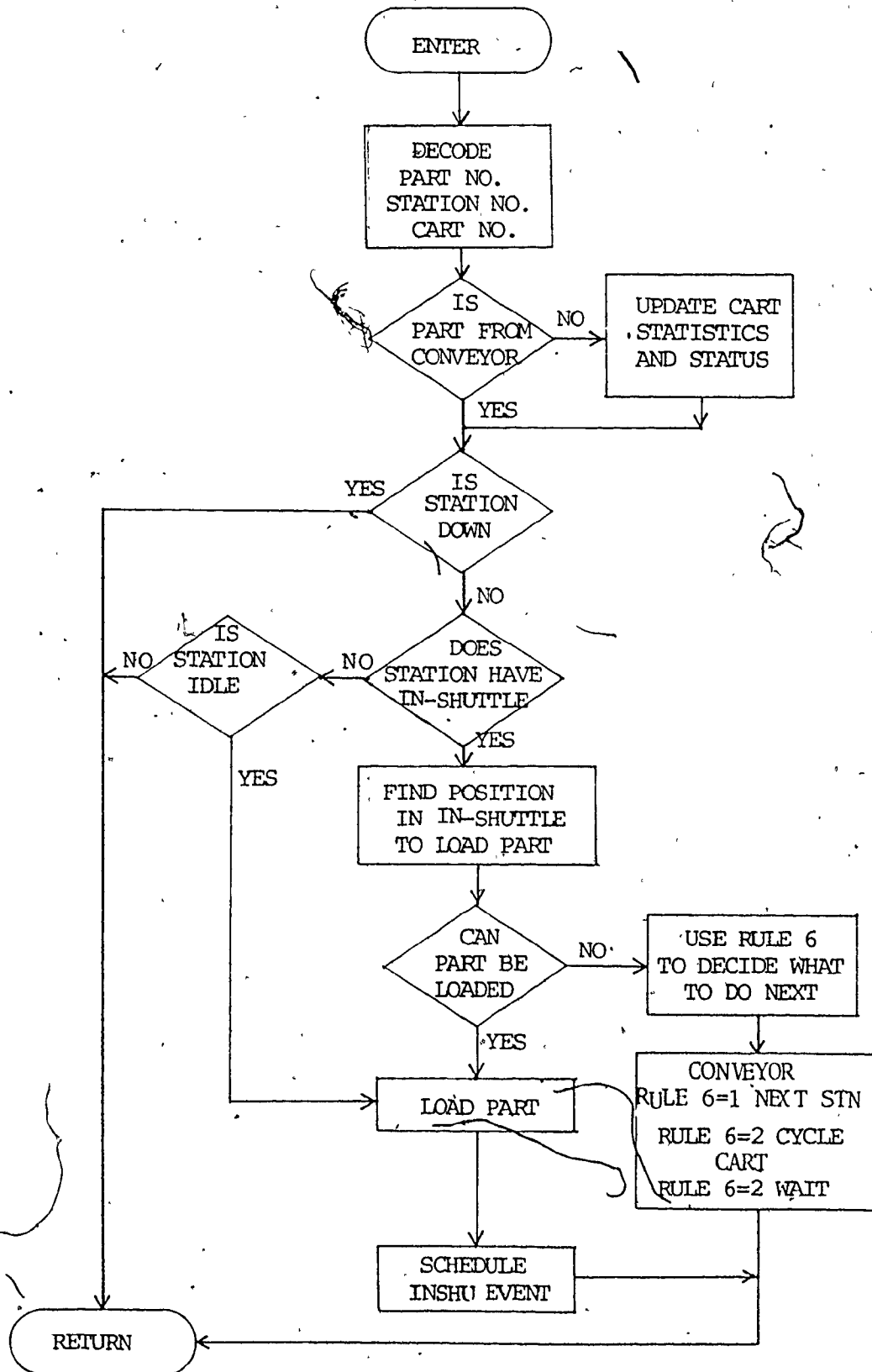


Fig. K.5 Flowchart for Subroutine UNLCA.

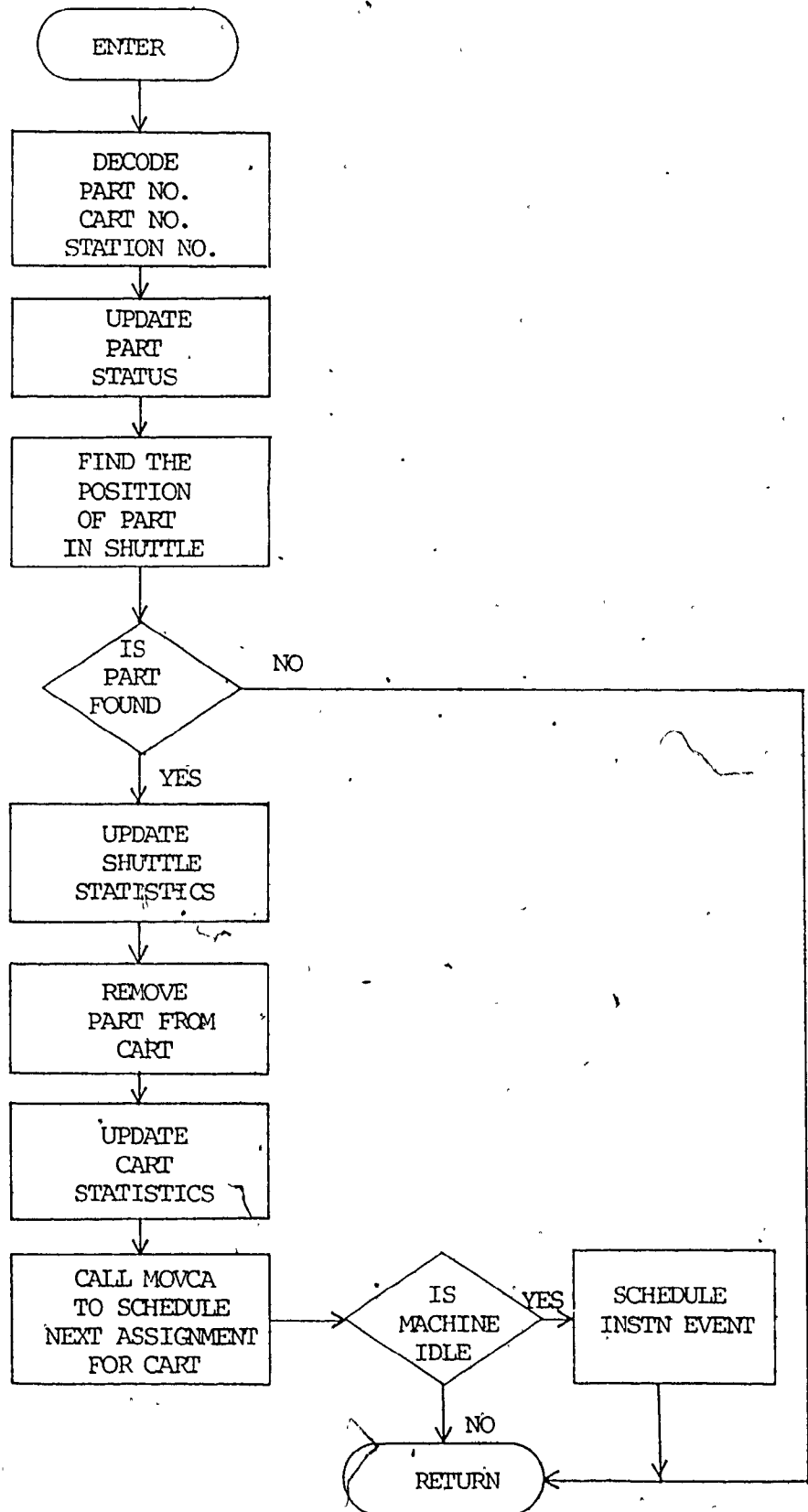


Fig. K.6 Flowchart for Subroutine INSHU.

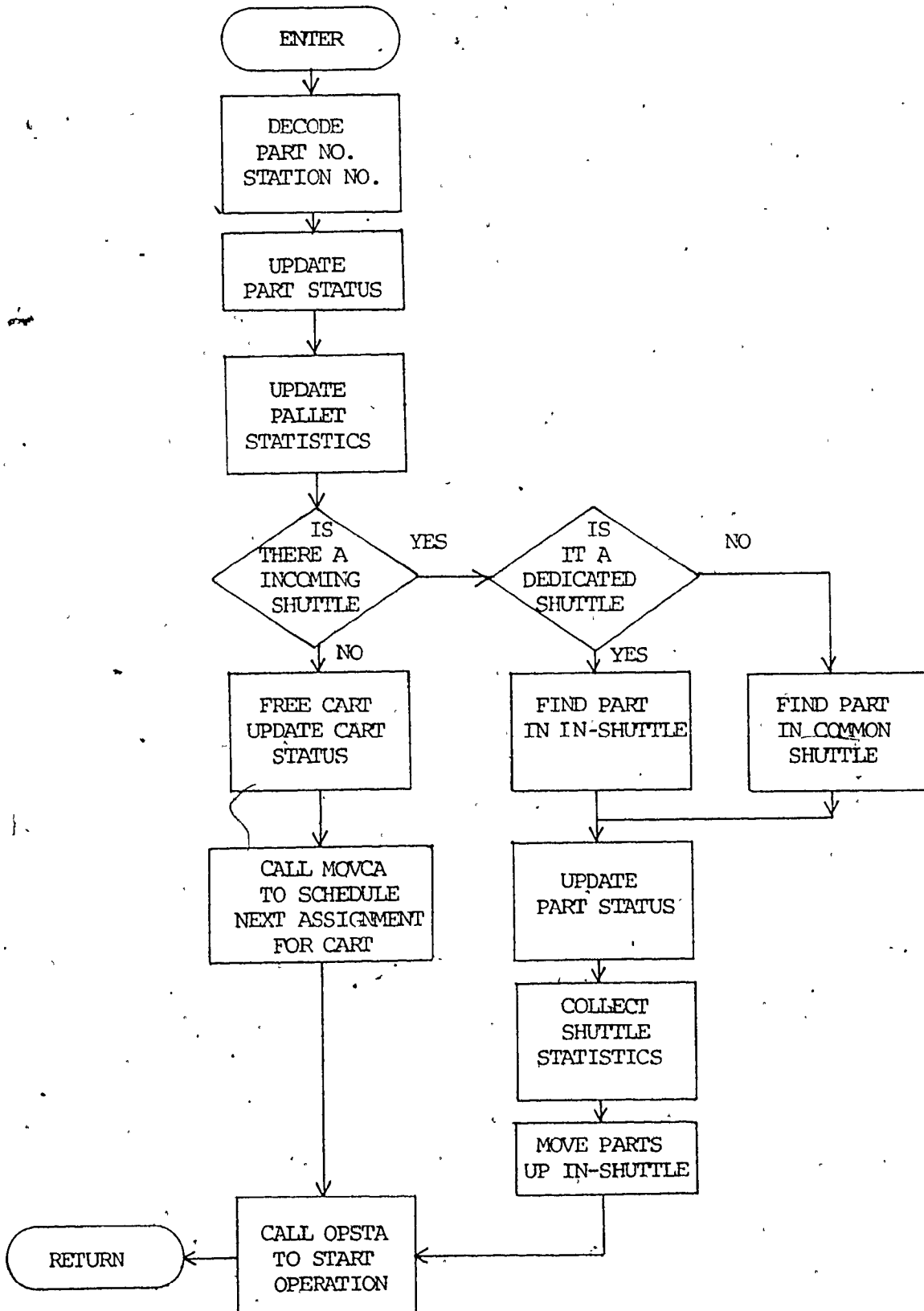


Fig. K.7 Flowchart for Subroutine INSTN.

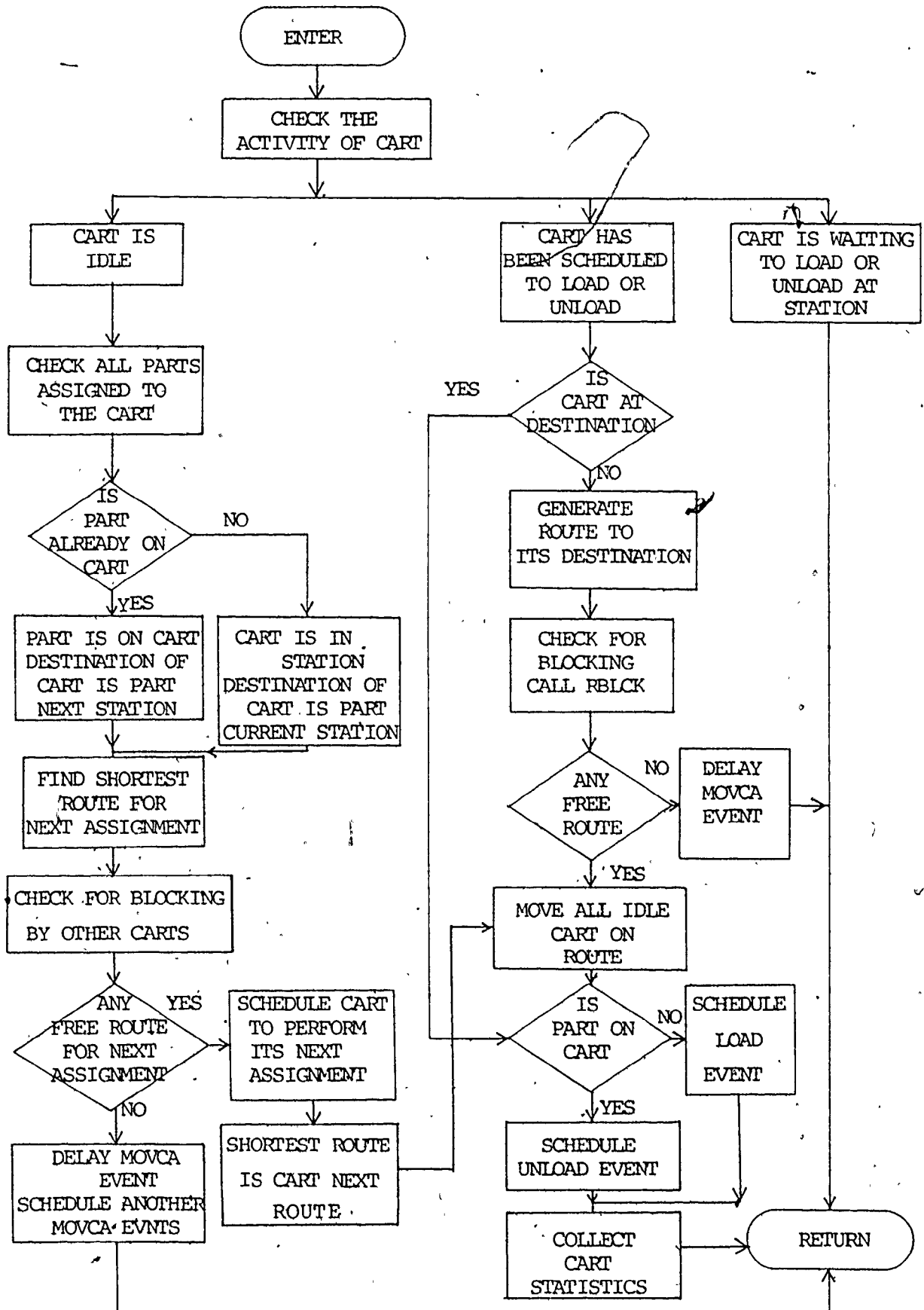


Fig. K.8 Flowchart for Subroutine MOVCA,

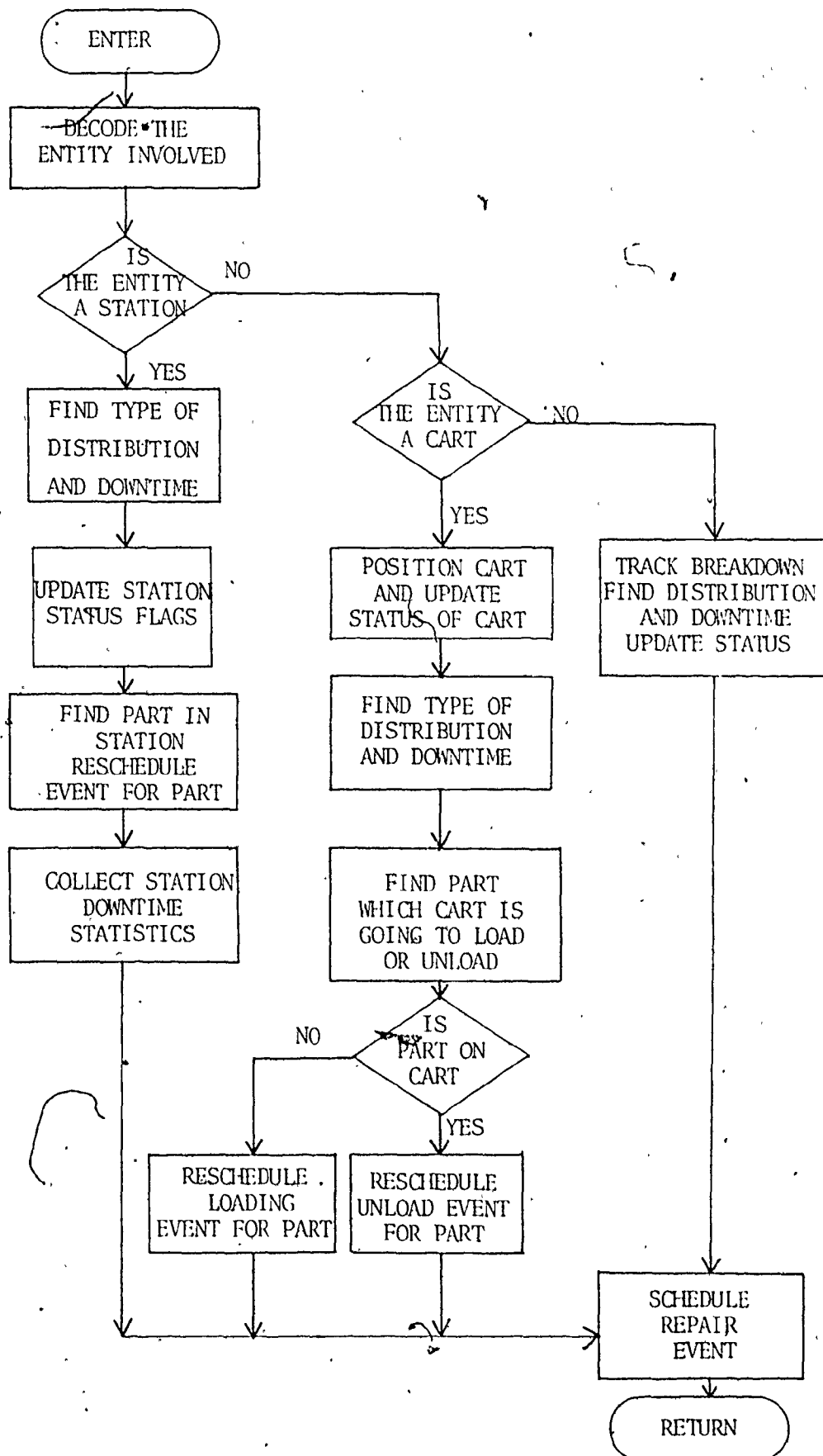


Fig. K.9 Flowchart for Subroutine BREAK.

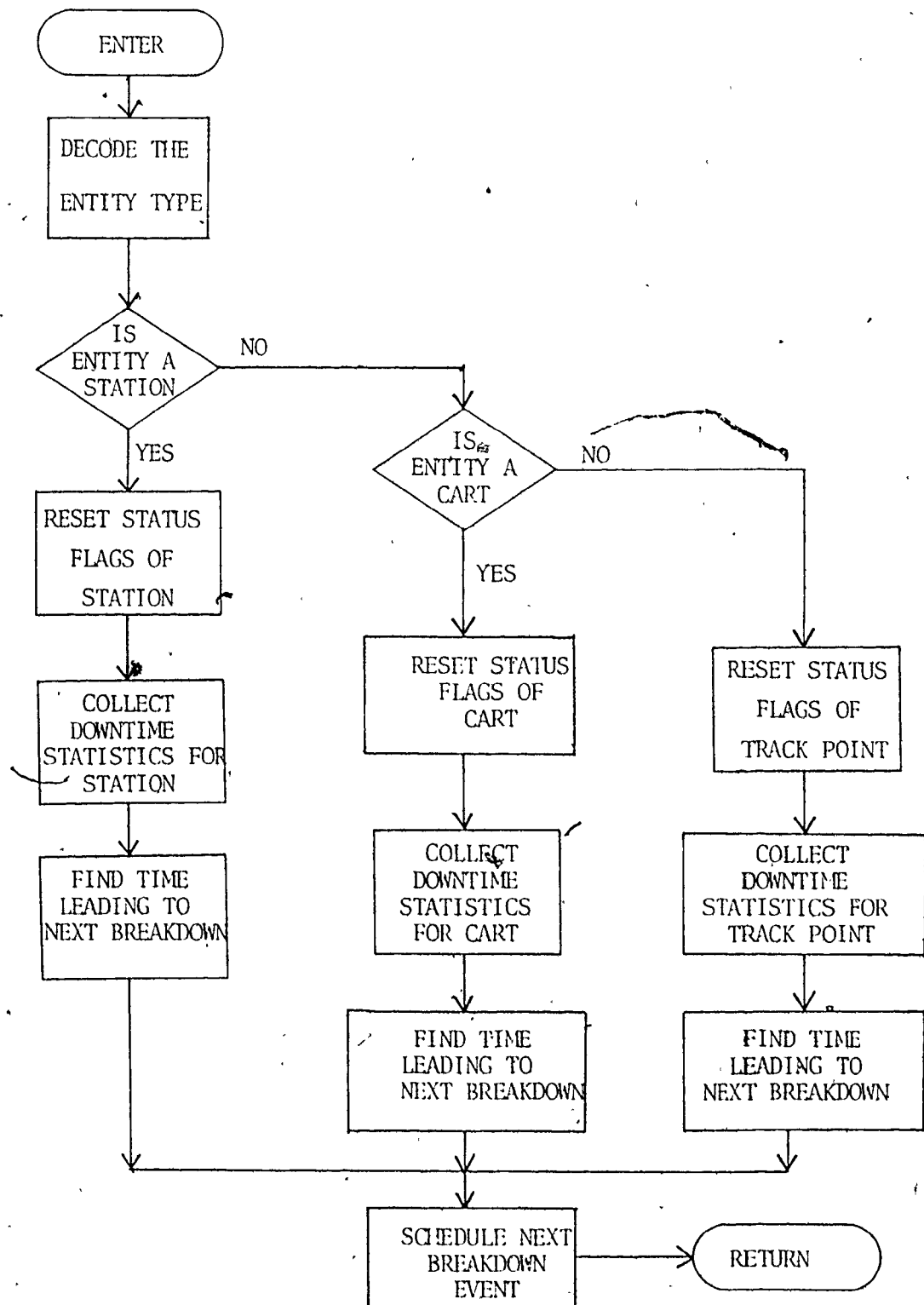


Fig. K.10 Flowchart for Subroutine REPAR.

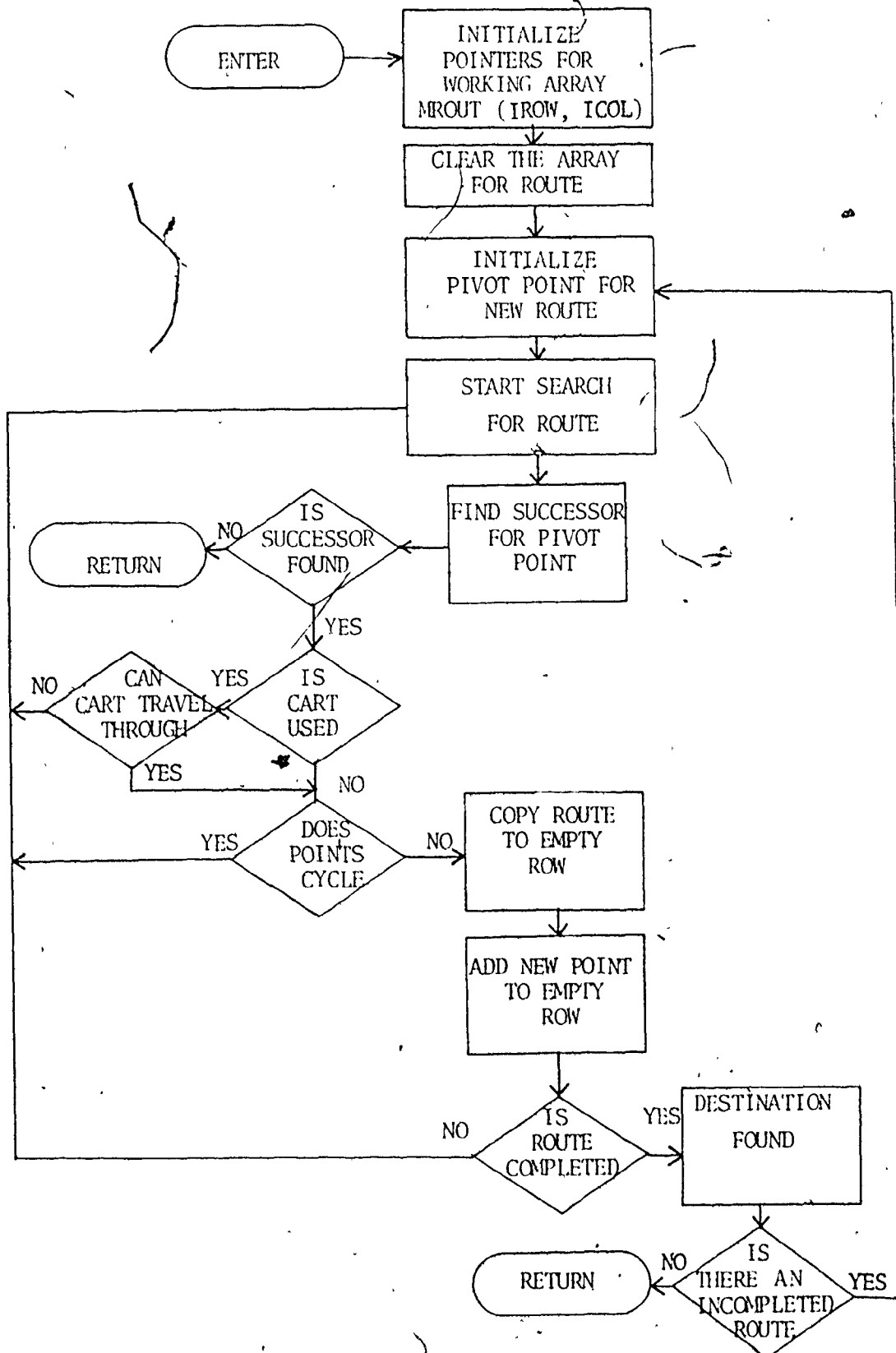


Fig. K.11 Flowchart for Subroutine ROUTE.

APPENDIX L  
SAMPLE OUTPUT FOR CASE STUDY

### PRODUCTION SUMMARY OF COMPLETED PARTS

1001 58

STATUS OF PAKIS CURRENTLY IN SYSTEM--

PORT NUMBER	PORT TYPE	PRIOR NUMBER	CURRENT STAT	CURRENT OPER	NEXT STAT	NEXT OPER	NO OPER LEFT	IN 'SHUT(1) OUT SHUT(2)	LIST OF OPERATIONS COMPLETED	TIME ENTER SYSTEM
1	1	2	5	6	0	0	2	0	1 2 3 4 5 0 0 0 0	537.00
2	1	2	0	0	2	2	6	0	1 0 0 0 0 0 0 0 0	597.60
3	1	2	3	2	0	0	6	0	1 0 0 0 0 0 0 0 0	560.20
4	2	2	2	9	0	0	6	0	8 0 0 0 0 0 0 0 0	581.90
5	2	2	0	0	2	9	6	0	8 0 0 0 0 0 0 0 0	574.70
6	2	2	6	0	3	13	2	0	8 9 10 11 12 0 0 0 0	531.80
7	3	2	3	20	0	0	2	1	15 16 17 18 19 0 0 0 0	552.10
8	3	2	3	20	0	0	2	1	15 16 17 18 19 0 0 0 0	546.90
9	3	2	2	16	0	0	6	1	15 0 0 0 0 0 0 0 0	584.10
10	4	2	5	23	0	0	7	1	22 0 0 0 0 0 0 0 0	360.30
11	4	2	0	0	6	26	4	0	22 23 24 25 0 0 0 0	128.20
12	4	2	2	23	0	0	7	1	22 0 0 0 0 0 0 0 0	13.10
13	5	2	13	1	24	0	3	0	30 31 32 33 0 0 0 0	545.50
14	5	2	5	35	0	0	2	1	30 31 32 33 34 0 0 0 0	543.50
15	5	2	1	32	0	0	2	1	30 31 0 0 0 0 0 0 0	577.30
16	6	2	2	38	0	0	7	14	37 0 0 0 0 0 0 0 0	17.00
17	6	2	3	38	0	0	7	1	37 0 0 0 0 0 0 0 0	217.40
18	6	2	3	38	0	0	7	1	37 0 0 0 0 0 0 0 0	327.00

PALLET INFORMATION

PALL TYPE	NOW IN USE	NOW, AVAIL	MAX USED	UTILISATION
1	3	0	3	2.12
2	3	0	3	2.06
3	3	0	3	1.98
4	3	0	3	2.56
5	3	0	3	2.00
6	3	0	3	2.30

STATUS OF PALLETS--

PALLET NUMBER	PART NUMBER	PALLET TYPE
1	1	1
2	2	1
3	3	1
4	4	2
5	5	2
6	6	2
7	7	3
8	8	3
9	9	3
10	10	4
11	11	4
12	12	4
13	13	5
14	14	5
15	15	5
16	16	6
17	17	6
18	18	6

STATION PERFORMANCE SUMMARY

STATION NUMBER	TIME BUSY	PCT	TIME IDLE	PCT	TIME DOWN	PCT	PERCENT OF TIME BUSY EXCLUDING DOWNTIME
1	370.90	61.9	228.10	38.1	0.00	0.0	61.92

2	583.30	97.4	15.70	2.6	0.00	0.0	97.38
3	579.90	96.8	19.10	3.2	0.00	0.0	96.81
4	147.20	24.6	451.80	75.4	0.00	0.0	24.57
5	573.50	95.7	25.50	4.3	0.00	0.0	95.74
6	15.00	2.5	584.00	97.5	0.00	0.0	2.50

STATUS OF STATIONS--

STATION NUMBER	LAST START TIME(0:10:10)	UP-0 DOWN-1 (-VE:COMPL) OCCUPY-2	TIME AVAILABLE AFTER BREAKDOWN	IN-SHUTTLE	OUT-SHUTTLE	PART NUMBER IN QUEUE	COMMON-SHUTTLE
1	599.10	2	0.00	15	0	0	0
2	593.40	2	0.00	16	12	9	0
3	591.90	2	0.00	17	18	7	0
4	0.00	2	0.00	0	0	0	0
5	589.50	2	0.00	10	8	14	0
6	0.00	2	0.00	0	0	0	0

SHUTTLE PERFORMANCE SUMMARY

STATION NUMBER	IN-SHUTTLE QUEUE SIZE	UTILI- SATION	MAX QUE	OUT-SHUTTLE QUEUE SIZE	UTILI- SATION	MAX QUE	COMMON UTILI- SATION	MAX QUE
1	3	0.385	3	3	0.048	1	0	0.600
2	3	2.729	3	0	0.000	0	0	0.000
3	3	2.660	3	0	0.000	0	0	0.000
4	3	0.033	1	0	0.000	0	0	0.000
5	3	2.553	3	0	0.000	0	0	0.000
6	3	0.001	1	0	0.000	0	0	0.000

End of Station and File