A DESIGN METHODOLOGY FOR OPERATIONAL CONTROL ELEMENTS FOR AUTOMATIC GUIDED VEHICLE BASED MATERIAL HANDLING SYSTEMS

by

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In memory of my brothers,

Ebere and Celestine

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CHAPTER 1

MATERIAL HANDLING IN MANUFACTURING

1.1 INTRODUCTION

The typical manufacturing system consists of workstations arranged in some order and linked together by one or more types of material handling devices. The movement of parts between the workstations is accomplished using the material handling equipment. Therefore, the selection of a particular type of handling equipment affects the flow characteristics of the items of manufacture within the system. Such characteristics include flow velocity, flow volume, flow path, tractability and product security (i.e. protectiveness or damage level) as they are transported from station to station. The role of material handling in a manufacturing environment cannot be overlooked if economic manufacture is to be realized. In certain factories, material handling cost may represent as much as 80% of factory labor dollar [45]. In view of the above statistic, it is logical to say that a properly designed and implemented material handling system could provide the disciplined environment that results in lower manufacturing cost through reduced handling of work-in-process, improved flow pattern and product tractability, and reduced product damage. Of course the actual demand for additional manpower to obtain a desirable level of control in a particular manufacturing environment varies with the degree of complexity of the manufacturing operations and handling activities.

Material handling systems in operation today combine several types of equipment which can generally be categorized into:

a) fixed path handling equipment,

b) limited or wide area handling equipment, and

c) mobile or variable path equipment [57].

Examples of the first class of equipment include conveyors of all types, and elevators. The second category includes cranes and hoists while the variable path equipment covers all forms of industrial trucks and perhaps towline systems. The traditional attitude that material handling cost is an overhead item has resulted in the treatment of material handling activities as problems and not as another important factor of production [43]. It is difficult to argue that this attitude has retarded the realization by management and systems analysts of the vital contribution of material handling in ensuring that a desirable level of production throughput is achieved.

The negative view toward material handling systems is changing rapidly. There are now an increasing number of manufacturing organizations that recognize material handling as a distinct and important function within the organization [43]. Existing equipment is being modified to perform more complex functions, and new product innovations are translated to operational systems [43]. There has been a tremendous surge in material handling technology, covering such areas as storage and retrieval, product labelling and identification, computer control of fixed path equipment, wide area equipment and variable path equipment, and the interfacing of various equipment types within the manufacturing environment. The effect of these technological advancements is a lower cost product and a more productive manufacturing environment [61]. The brief descriptions below show some of the recent technological innovations.

1.2 ADVANCES IN MATERIAL HANDLING SYSTEMS USING COMPUTER CONTROLS

The primary function of the computer or controller in a material handling system is the management of material flow and the optimization of the operations of material handling machinery [44]. Such computers operate on a real time environment, responding instantly to operational requirements such as the control of sortation, storage and retrieval of parts for manufacture, transportation of parts and the tracking of every part or group of parts held together as they progress through the various manufacturing stages.

Computer applications to raw material, work-in-process, and finished goods handling resulted in the advent of Automatic Storage and Retrieval Systems (AS/RS). An AS/RS is essentially an automated warehouse where the storage units (or parts) are stored and retrieved from storage cells automatically. The storage and retrieval process is usually accomplished through computer controlled stacker cranes or self-guided stock or order selectors with varying degrees of human intervention. Item contents within the warehouse reside in the memory of the computer. These information items are entered into the computer through input terminals or automatic sensors and readers along the input/output paths of the AS/RS. Fully automated systems make load or part routing decisions on a regular basis, confirming task executions and automatic adjustment of inventory [44,58].

In the area of part identification and tracking, several identification systems are now available that use magnetic or optical sensors or decoders for reading labels, cartons or other items. Some decoding devices are insensitive to the physical location of the labels [68]. In addition, computer controlled printers are also available that print labels in real time. Many systems are also capable of handling inventory and order-entry transactions, permitting instant audit of inventory or of the status of an order being picked [68].

With regard to material flow within the shop floor, computer controlled conveyor systems are not uncommon. Information on parts loaded onto a conveyor is received by the computer. Parts are automatically moved from machine center to machine center based on a prescribed routing. Computer control is also achieved through the use of industrial robots which draw their resemblance to the wide area handling equipment. Industrial robots are general purpose numerical control machines utilized for parts handling. They possess certain anthropometric characteristics that allow them to emulate the human operator. These motions are often distinguished into body motion, arm motion and wrist motion [42]. Monotonous and dangerous manual handling tasks are easily performed by these versatile machines.

Technological advancements in alternative forms of horizontal transportation have also emerged [81] as in Sweden, resulting in more productive use of available floor space and flexibility in product flow distribution. Computer controlled, robot vehicles that are generally identified as Automatic Guided Vehicle (AGV) systems are one example. Currently, AGV systems are predominantly used in warehousing environments [44]. Applications have been reported on the use of AGVs for carrying mail in offices [76,77], for transporting items in pharmaceutical plants, and for moving in-process parts in a manufacturing facility [35,76]. The initial cost of installing an AGV system is competitive; direct labor cost is low. An AGV system provides flexibility that few other systems can parallel. It is the recognition of the flexibility, versatility, and cost saving potentials in the application of AGVs in manufacturing systems that motivated this study.

1.3 RESEARCH OBJECTIVE

The objective of this research is to develop a methodology for the identification, study, and characterization of the effects of operational design and control factors on the performance of an Automatic Guided Vehicle based material handling systems. Simulation will be used to facilitate the study. The simulation model so developed will provide the tools for evaluating various factors that are considered to play vital roles in the successful operation of an AGV system. Operational aspects of interest include the management and control strategies of an AGV systems, the effect of the size of unit loads employed for the transport of materials, and the management and control of jobs at workcenters. Techniques for the analysis of the performance of an AGV based material handling system under the effects of two or more operational control strategies will be demonstrated. This includes the examination of any interaction effects present among the control parameters. Another product of the research is that the simulation model developed can be used for the design of AGV systems. Apart from the specification of operating rules, the simulation model is useful for the design of the configuration of an AGV guidance network and the location of machining centers and their pickup/delivery stations. It can also be used for determining the required number of vehicles to sufficiently service a shop.

Several performance measures can be used to evaluate the effectiveness of an AGV based material handling system. Performance measures made available through the simulation model and will be used in the analyses that are presented in the later chapters of this manuscript include one or more of the following:

1. average unit load travel times between workstations,
2. vehicle utilization,
3. job flow time,
4. machine utilization,
5. job waiting time at each machining center,
6. average queue characteristics at each machining center,

7. total vehicle blocking or interference time per production shift resulting from congestion on the guide path, guide path intersections and pickup and delivery stations,
8. unit load throughput rate, and
9. total time vehicles travel empty or unloaded.

1.4 BENEFITS OF THE RESEARCH

The benefits of the research can be classified as follows:

1) Operational,
2) Design, and
3) Educational.

From the operational point of view, the methodology developed can be used

a) as a means for identifying potential bottlenecks in a material flow process,
b) to evaluate the effect of alternative unit load designs on job flow, machine utilization, and frequency of traffic conflicts since unit load sizes are directly related to the frequency of material moves.
c) as a tool for evaluating the combined effects of unit loads and job dispatching rules on machining center behavior as it relates to queue size, machine utilization, number of setups and job flow times,
d) for selecting an appropriate combination of vehicle management policy, unit load design, and job dispatching rules to improve system performance.

From the system design aspects, the procedure is useful for

a) comparing alternative AGV guide path configurations and arc orientations as they affect such system performance measures as vehicle blocking times, vehicle response times, and total time vehicles travel while loaded,

b) specifying an adequate number of vehicles necessary to perform satisfactorily a given material handling operation, and

c) selecting alternative vehicle control schemes.

Educationally, the developed analyses techniques have the potential to provide valuable insight for

a) ranking the performance of alternative vehicle management strategies in the areas of vehicle dispatching, traffic control at intersections, or resolution of traffic conflicts, and

b) identifying manufacturing conditions favorable to the adoption of a particular design of unit loads, vehicle control measures, and the combinations of unit loads and vehicle management policies.

1.5 ORGANIZATION OF PRESENTATION

The remainder of this manuscript is organized into eleven major chapters. Chapter 2 presents a detailed description of an AGV system. This includes a categorization of Automatic Guided Vehicles (AGVs) by function and the various types of control systems currently available. The section gradually leads to the definition of the class of AGVs modeled in this study and to the presentation of an outline of the advantages of an AGV system application.

Chapter 3 identifies the main factors to be considered for AGV system design and discusses how these factors, operating alone or interactively, can affect the performance of AGV system applications. In chapter 4, the literature in each of the main design factors identified in chapter 3 is reviewed. The early section of chapter 5 defines the type of manufacturing system to which this study is addressed. This is followed by the development of models describing the various aspects of the manufacturing system in the context of the application of AGV systems.

The process of assigning tasks to idle vehicles in an AGV system is an operational control problem. In chapter 6, models describing various vehicle dispatching rules are presented. In chapter 7, a broad description of the simulation routines developed to model the various components of AGV systems discussed in chapters 5 and 6 is presented. Chapter 8 employs the simulator developed in chapter 7 to characterize the behavior of an AGV system to vehicle dispatching rules at various operating conditions. The last section of chapter 8 through chapter 11 illustrate the use of experimental procedures in ranking levels of operating rules where alternative forms of accomplishing a task exist. The factors addressed include vehicle dispatching, unit load size specification, unit load sequencing, shop loading, and network control. Chapter 12 summarizes and concludes the study.

CHAPTER 2

AUTOMATIC GUIDED VEHICLE SYSTEM

2.1 INTRODUCTION

An Automatic Guided Vehicle (AGV) System features driverless vehicles that operate on a network of wire-guided paths. The vehicles are electronically controlled and programmable for automatic pickup, travel and delivery of materials. The guide wire is embedded beneath the floor surface along the desired travel path. The guide wire is energized with a low voltage, low current, constant frequency signal source; and through on-board electronic sensors, the vehicle tracks the path of the emitted signal to a prescribed destination. On arrival at a destination point, appropriate controls are activated to stop the vehicle, and have the load transfered to a load stand automatically or manually depending on the method of control. The vehicle is then reprogrammed to undertake another assignment.

Vehicle movement can be controlled by directly entering the load movement commands via an on-board vehicle programmable panel, or indirectly through a fixed station remote programming panel. Load movements in a complex AGV system is managed through a central computer.

In simpler systems where on-board or remote programming panels are used, a vehicle is dispatched to one or more pickup and delivery stations by an operator activating the appropriate switches. The programming panels are equipped with switches, each corresponding to a delivery or pickup station.

A computer controlled AGV system can be 1) open-loop computer controlled, and 2) closed-loop computer controlled. The closed-loop systems are the ultimate in automatic control. The central computer receives load movement commands through a variety of input devices including fixed-station remote programming panels, load presence sensors, Lanyard and pushbutton switches, CRT or other data terminal input, and on-line connection to other automatic processes [19].

Closed-loop computer control systems have two-way communication capabilities. Not only are they responsible for assigning missions to vehicles, dispatching and routing them to appropriate destinations; but they can also communicate with input devices, automated processes and other computers. The computer can be programmed to permit on-line interrogation of vehicles on a scheduled basis to obtain information on vehicle destination, identity and location. Other vehicle status that can be queried include running, holding for blocking, delivering or picking up load. Ability to monitor vehicle alarm conditions on loss of guide signal, loss of blocking signal, low battery, emergency bumper actuation and generation of management reports on load movements and vehicle and station productivity and utilization are in the province of closed-loop computer control systems. No load tracking and reporting capability exists in an open-loop system. For a detailed discussion of the material above and how they relate to other aspects of an AGV System, the reader is referred to references [9,19,49,67].

2.2 GUIDED VEHICLE CLASSIFICATION

Automatic Guided Vehicle Systems can be classifed into:

1. Automatic Horizontal Transportation System and
2. Automatically Positioned Stock Selectors.

Within the Automatic Horizontal Transportation Systems are four subgroups of vehicles, namely

a) towing vehicles,
b) unit load transporters,
c) guided pallet trucks, and
d) light load transporters.

As the name suggests, towing vehicles are automatic guided vehicles with towing capability. They are equipped to tow trailers and pallet lift trucks which themselves may be load bearing. Devices for loading towing vehicles include hand pallet trucks, lift trucks and cranes. Shuttle transfer and pusher arm devices are available to transfer loads onto and off trailers equipped with non-powered roller beds. Automatic loading and unloading requires powered conveyors and trailer roller beds.

Loads are carried on-board the vehicle for the case of unit-load transporters. Manual and automatic loading and unloading unit transporters are available. Manual transfer devices include cranes, hoists, lift trucks and hand trucks. Automatic loading and unloading devices include powered-roller conveyors, pusher arms and lift/lower vehicle beds.

Automatic guided pallet trucks have programming capabilities for automatic delivery of pallets but have to be manually operated for loading purposes. They also have the capability to pickup and drop-off loads at ground level.

Light load transporters are used mostly in light manufacturing and office environments and have load capacity of up to 1000 pounds. The method of loading and unloading is commonly manual.

Automatically Positioned Stock Selectors are the only class of automatic guided vehicle system with movement capability in both horizontal and vertical directions. They are primarily employed for order picking.

Despite the general features of each category, current guided vehicles come in different makes and sizes. The variety of makes are expected to increase in the near future as interest in AGV System application rises. Custom-made vehicles for special applications increase the diversity among vehicles. Generally, automatic guided vehicles are battery powered with most using four or six 6-volt batteries. Common vehicles travel at speeds of up to 3 miles per hour and have load bearing decks that measure 48 x 48 square inches [19].

Unit load transporters will form the basic family of vehicles modeled in this research. Examples of unit load transporters in the market today are Barrett's Unicar 240, Eaton Kenway's Robocarrier and Raymond's Electote System. Figure 2.1 shows a typical unit load transporter in action. Furthermore, for convenience of analysis, the Unicar 240 is selected to model the entire family.

The Unicar 240 is a unit load transporter with a load capacity of 4000 lbs. and a normal operating speed of 200 feet per minute. It is battery powered and requires a voltage source of 24 volts. When unloaded, the vehicle weighs 3000 lbs (including batteries). Load pickup and delivery is accomplished automatically by lifting or lowering its powered load platform under a variety of load stands. The platform can be lowered/lifted a total of four inches of vertical height. A turning radius of four feet is required when in motion. Other features of the Unicar 240 include two, 6 inch safety bumpers, one on each end, warning lights and start and stop switches on both ends [9].

2.3 ADVANTAGES OF AUTOMATIC GUIDED VEHICLE SYSTEMS

The advantages of an AGV System in manufacturing and warehousing is manifested by their growth in application in recent years [19]. System flexibility is a key factor for the justification of AGV systems. AGVS can be interfaced manually or automatically with other machinery and handling equipment. They can interface with automatic storage and retrieval systems, conveyor systems and production lines.

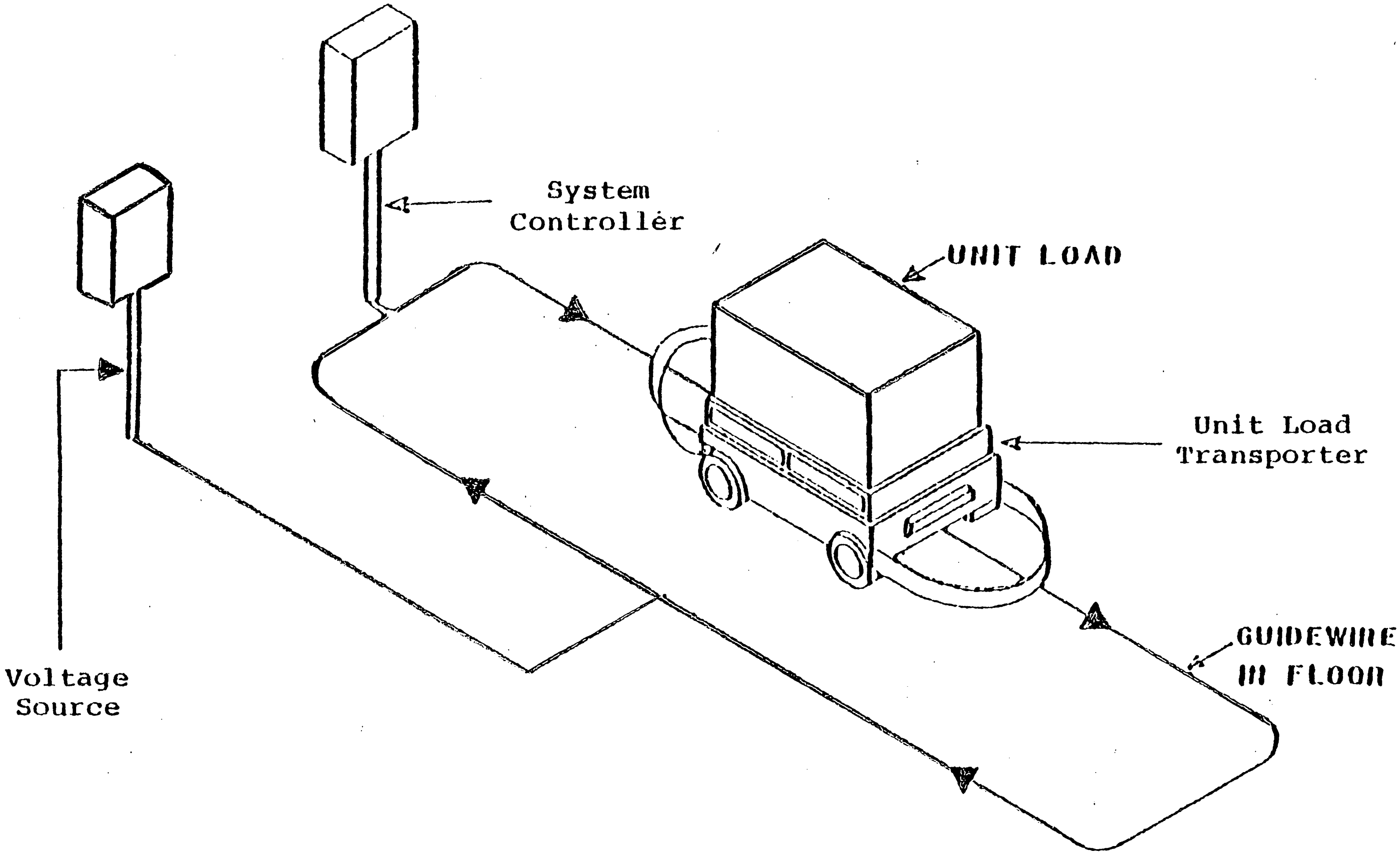


Figure 2.1 Automatic Guided Vehicle System

Parts handling, pickup and delivery is fast, accurate and safe and are especially adapted for long distance in-plant handling.

Because of the ease in installation, the guide path can be expanded, contracted or reconfigurated as the need arises. The tracking of load movements in a computer controlled system provides real time inventory control. Maintainability of environmental quality is part of the benefits for employing an AGV System. Vehicles leave the manufacturing or warehouse floor virtually unchanged. A typical system is energy efficient and produces very little noise or other forms of pollutants [19].

CHAPTER 3

DESIGN CONSIDERATIONS FOR AGVS APPLICATIONS

3.1 INTRODUCTION

The successful implementation of an automatic guided vehicle system in a manufacturing facility is affected by several design factors which can broadly be classified into physical and operational factors. The physical factors include the environment in which the vehicles operate, aisle width available for vehicle movement and turns, floor surface conditions, ramps, fire doors, elevators, draw bridges and other special requirements. The factors of interest in this study are mainly operational. These physical factors though equally important [19,82] will not be covered in detail in this study.

The operational factors discussed at length here include (a) characteristics of production system, (b) layout design, (c) unit load design, and (d) scheduling (dispatching) policy for material control. Detailed considerations of these operational factors are discussed below.

3.2 PRODUCTION SYSTEM CONSIDERATIONS

The installation of an automatic guided vehicle system does not alleviate all material handling problems. Certain characteristics of a manufacturing facility are more adaptable to AGV System applications than others. Depending on the annual production volume, a production system can be classified as a (1) job production, (2) batch production, or (3) continuous production [33]. The production system type, along with production and demand frequencies and product characteristics, determine the appropriate combinations of material handling equipment.

Job production systems involve the manufacture of products to meet special customer order requirements. The annual production volume is relatively small. Job production systems are further divided into three levels according to frequency of production, (a) a small number of parts produced only once, (b) a small number of parts produced intermittently as needed, and (c) a small number of parts produced on a scheduled basis and at known time interval.

In batch production, a number of identical items are produced per machine setup to either satisfy customer order or meet a continuous demand. Batch production systems involve a diverse product mix. The three subdivisions of batch production are: (a) a batch produced only once, (b) a batch produced at irregular intervals only on need, and (c) a batch produced at scheduled intervals to meet continuous product demand.

Continuous production systems involve large volumes of output and large annual demands. Production equipment is fully dedicated to the production of a specific item. Mass production and flow production are the two subsystems of continuous production.

Handling for continuous systems typically require conveyor equipment. Job production systems are more adaptable to the use of simple handling devices such as non-powered trucks. Powered trucks and automatic guided vehicles could be used as the volume and frequency of production tend toward batch production. Table 3.1 shows the interaction of volume of output, frequency of manufacture, production system type and the frequency of product demand. The table indicates combinations where the application of AGV System are considered Aappropriate. The checked (X) cells (i.e. production/demand frequency combinations) as shown on the table are considered candidate conditions for AGV System aplication. The unmarked cells indicate production/demand frequency combinations unsuitable for AGV System application.

In addition, an AGV System should be considered in situations involving long distance handling within a facility. The use of powered trucks for such handling can be uneconomical since both the operator and the equipment are simultaneously tied up on a task that can be automated. Lift trucks are more economical for short distance handling.

3.3 LAYOUT DESIGN CONSIDERATIONS

Most current applications of an AGV System employ unidirectional flow of traffic along the aisles. This is done for simplicity of control and for ease of system management. This suggests that there are relationships between 1) guide path network layout and the distribution of vehicles in the network, 2) network layout and handling distance, 3) handling distance and vehicle utilization, 4) handling distance and

Table 3.1: Classification on the Interactions Between Demand and Production Frequencies and Their Effect on Material Handling Equipment Selection

Legends: 1 = once
2 = intermittent/irregular
3 = periodic/regular
4 = continuous

		PRODUCTION FREQUENCY						
		Small No. of Pieces			Batch			Continuous
		1	2	3	1	2	3	4
DEMAND FREQUENCY	1					X	X	
	2					X	X	X
	3				X	X	X	X
	4				X	X	X	

material throughput rate, 5) handling distance and vehicle response time to calls, 6) network layout and space utilization, and 7) network layout and the location of departments. Figure 3.1 shows a relationship diagram between the elements outlined. Further discussions on some of these relationships will be presented in the next subsequent subsections.

3.3.1 Network Layout and Traffic Distribution.

In a system of unidirectional guide paths, there is a distinct vehicle entry aisle and a corresponding exit aisle for every pickup and delivery station. This has the effect of reduced traffic congestion on any aisle compared to the potential congestion in a two-way guide-path system. On the other hand, unidirectional paths result in longer travel distances between points.

3.3.2 Network Layout and Handling Distance.

One of the classical criterion used in facility layout problems is the minimization of handling cost via distance optimization. This is done by minimizing the Euclidean, rectilinear or squared Euclidean distance between the departments [36]. In an AGV system, handling distance cannot be optimized by minimizing the Euclidean or the rectilinear distances between stations as illustrated in Figure 3.2. Suppose a load is to be moved from point A to point B as in Figure 3.2. Using the Euclidean distance criterion, the path from A to B is P_{AB} = ACB. Using the rectilinear distance measure, $\bar{P}_{AB}$ = ADB. However, using

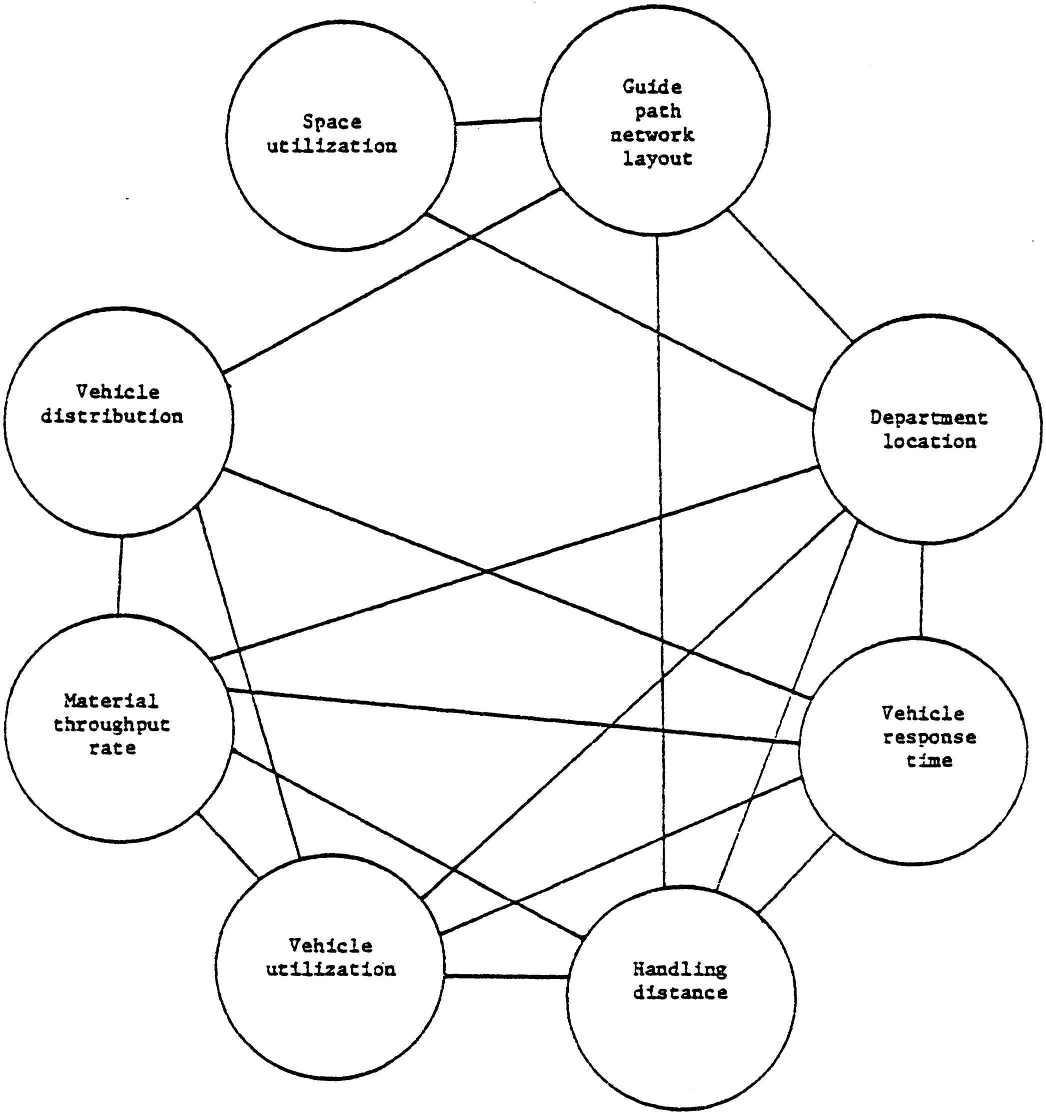


Figure 3.1: Factor Relationships Dependent on Facility Layout Design.

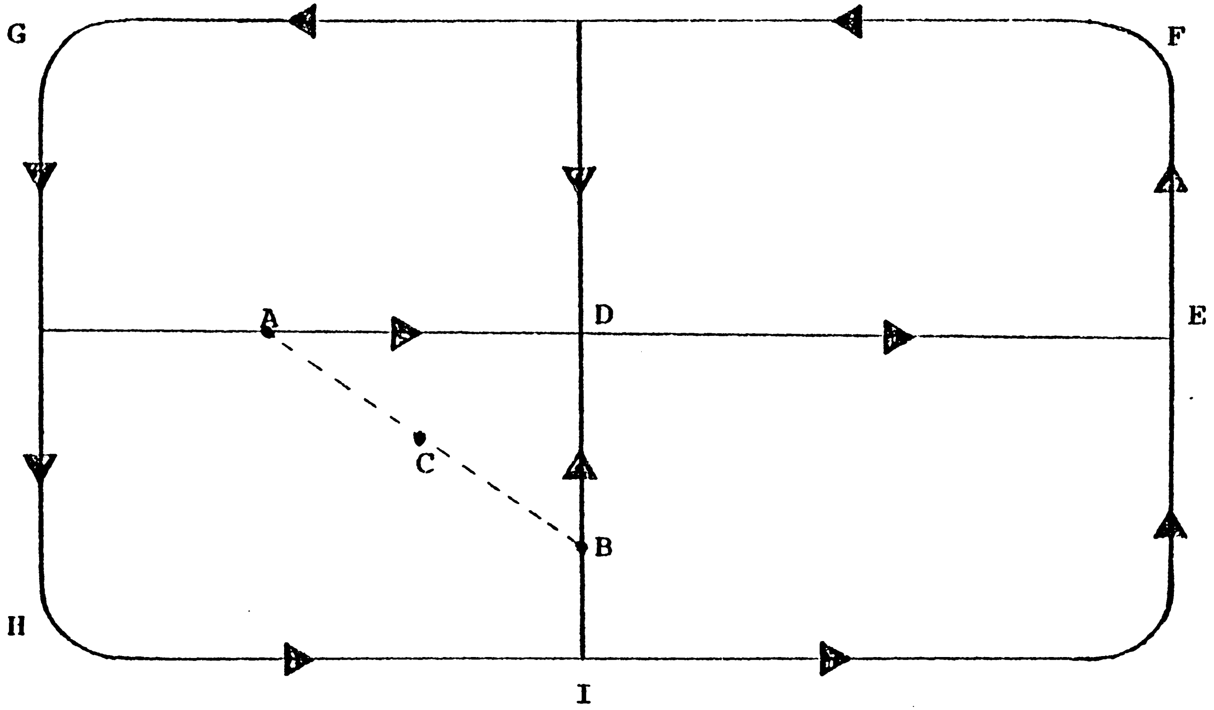


Figure 3.2: AGV System Guide Path

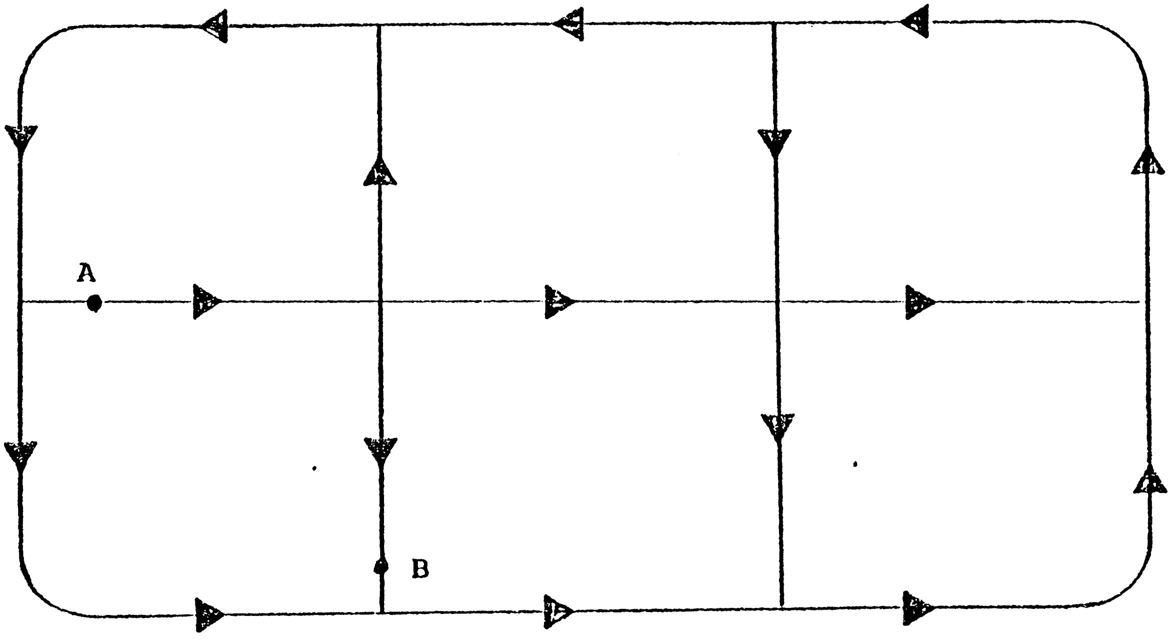


Figure 3.3: Network 1

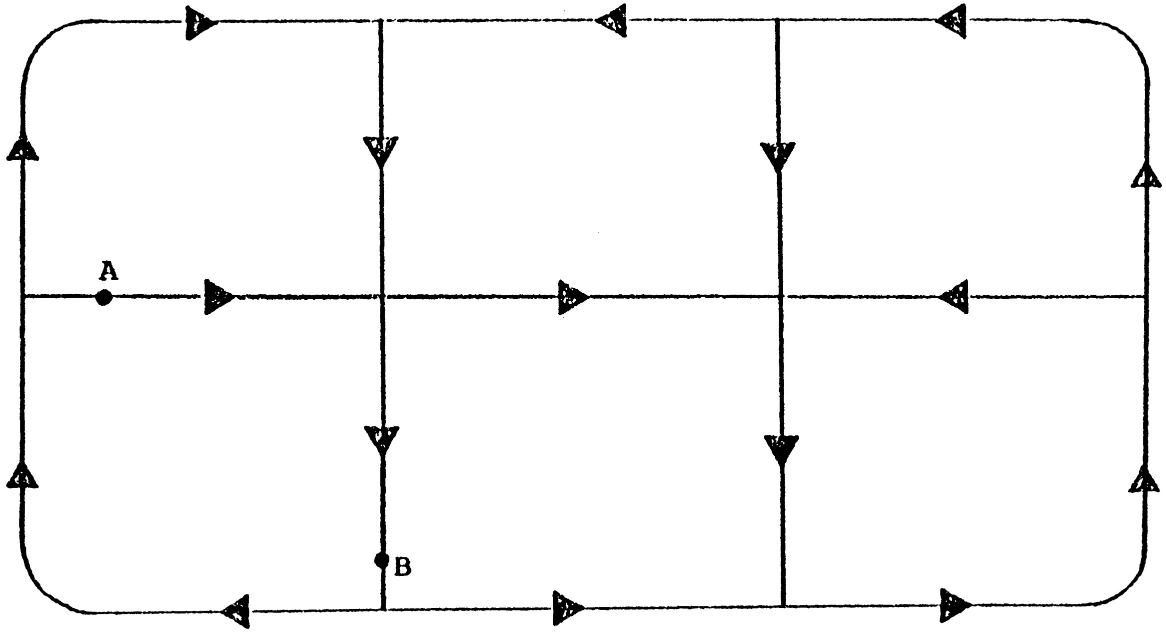


Figure 3.4: Network 2

the AGVS prescribed layout, where the arrows indicate the direction of traffic flow, $\bar{\bar{P}}_{AB}$ = ADEFGHIB. If d_{AB} measures the distance from A to B using the path P_{AB}, it is easy to show that $d_{AB} < \bar{d}_{AB} < \bar{\bar{d}}_{AB}$. An improperly laid out guide wire network results in an unnecessary increase in total move-travel distance.

3.3.3 Vehicle Handling Time, Utilization, Material Throughput Rate and Vehicle Response Time.

A poorly designed guide path network can reduce the overall effectiveness of an AGV system if vehicle travel time is not adequately controlled. This possibility is demonstrated using Figures 3.3 and 3.4. Suppose networks 1 and 2 are two guide path layouts serving two identical and equal facilities. When an empty vehicle at point B is demanded at point A, the time required to travel empty from B to A is much smaller in network 2 than in network 1. Thus better vehicle utilization and quicker response to demand results. Since the vehicle arrives at its destination faster in network 2 than in network 1, the load in network 2 is removed faster than the load in network 1; thus affecting system throughput rate.

3.3.4 Network Layout and Space Utilization.

A unidirectional network requires unique entry and exit aisles for every pickup and delivery station. This requirement may lead to unnecessary duplication of aisles. By properly locating stations, aisle sharing by multiple stations is possible.

3.3.5 Network Layout and Department Location:

The quadratic assignment problem is concerned with the location of facilities to sites such that the cost of item movements (i.e. exchanges between workstations) is minimized. In an AGV system context, the facilities represent the workstations where deliveries and pickups take place. Quadratic assignment models require as input the annual handling cost for locating workstation i in site k and workstation j in h, denoted by C_{ikjh} [36]. Estimates of the C_{ikjh} are commonly obtained assuming that the distance from site k to site h, d_{kh}, is equivalent to d_{hk}. This same assumption is used in constructing computerized layout planning systems such as CRAFT [36]. In designing AGV systems, quadratic assignment model and other related models cannot be used as design tools in their current versions. The use of a symmetric distance model in locating departments in an AGV system assumes that guide paths are bidirectional; an assumption that does not generally hold. Such an assumption inaccurately estimates the actual distance traveled by a vehicle between workstations. The problem with CRAFT exemplifies the shortcomings of current analytical tools when it comes to the design of AGV systems.

3.4 UNIT LOAD DESIGN CONSIDERATIONS

The objective of installing AGVs in a production facility is to move materials more efficiently. For unit load transporters, the materials moved are transported in unit loads. A unit load, as defined in reference [72], 'is a single item, a number of items, or bulk material which is so arranged or restrained that the mass can be picked up and moved between locations as a single object.' A frequently overlooked but important design factor is the form in which production parts are unitized for economic handling between workstations. The effect of unit load design on the specification and selection of design components for AGV system application requires careful consideration. Unit load characteristics including dimensions, weight and stability must be selected and analyzed within the constraints of automatic handling. This includes the analysis and selection of containers, pallets or skids.

To obtain a design that meets production requirements, estimates of the number of unit loads to be handled per production shift is required and this includes the number of unit load exchanges between workstations. Knowledge of the expected exchanges between various work centers are important network design parameters as they affect the orientation of the guide paths.

An important factor in designing unit loads is the interactive effects between unit load sizes, equipment selection, and scheduling rules for sequencing unit loads for machining. In conditions where unit load splitting is not permissible (i.e. a unit load is also a machining unit), large unit loads mean larger machining time per unit load. Previous studies have shown that certain job dispatching rules accelerate the flow times of some jobs at the expense of others [25]. It is intuitive to expect that larger unit loads tend to worsen the flow times of those jobs whose flow times are already increased due to the adopted dispatching rule. Similarly, smaller unit loads tend to improve the flow time of those jobs already favored by the dispatchng rule. However, the effect on handling frequency is inverse. The smaller the size of the unit loads, the greater the number of material moves required to accomplish the same level of a handling task. This increase in move requirements will generally increase the handling cost.

Unit loads leave a workstation upon completion of their machining requirements. In any given workstation, the time required to machine a larger unit load is greater than that required to machine a smaller unit load of the same product type. A large unit load size lowers the frequency of machining completion, and the corresponding frequency of unit load entries and departures from workstations. Fewer unit load departures from machining centers lead to the following:

a) a reduction in job lapping,

b) a backlog of unit loads queueing for machining at some workstations and at the same time machines in other stations are kept idle because of insufficient supply of materials. The lack of quick replenishments of unit loads is the result of unit loads being held up in preceding workstations upstream of the job route, and

c) a backlog of unit loads queueing for machining and a corresponding lack of material to transport. These conditions lead to underutilization of vehicles and machines.

The negative effects of specifying large unit loads should not be interpreted as favoring smaller unit loads over large ones. Small unit loads lead to more frequent machine schedules and setups. For instance, suppose that there are K unit loads of J distinct job types awaiting processing in a machining center with one machine. Furthermore, each job type j has $m_j \geq 2$ unit loads (i.e. $K = m_1 + m_2 + \ldots m_{J-1} + m_J$). The total number of setups in machining the K unit loads ranges from J to K. K setups are required if the commonly applied First Come - First Serve (FCFS) job disptaching rule is adopted and no two consecutive unit loads in the queue are of the same job type. J setups take place when unit loads of the same job type are processed consecutively without regard to their relative position in the job queue. This involves a two-stage unit load dispatching rule. The first stage is to select unit loads from the queue based on the job type just completed and the second stage is to line up the unit load of the job type on a FCFS basis. When the total number of unit loads in a queue, K, is large, the difference in setup costs resulting from the K-J excess setups could be very significant.

In summary, the unit load assignment rule must recognize the relationship between unit load size and queue capacity requirements, unit load size and number of machine setups required, unit load size and equipment utilization, unit load size and job throughput rate and unit load size and network demand, including traffic flow and traffic distribution in the network. The design policy must account for these various factors.

3.5 NETWORK DEMAND CONSIDERATIONS

The guide path network is the artery of an AGV system. The demand for network use by vehicles is affected by the operational characteristics of the facility such as production volume, frequency of vehicle calls for load pickup and delivery, and the method of dispatching and routing vehicles.

The demand for network use is orchestrated in one of four ways:

1) a vehicle is called to remove completed unit loads,
2) a vehicle is called to deliver new materials,
3) an empty vehicle is routed to a parking zone or a circulatory loop, and
4) an empty vehicle is circulated in a prescribed loop.

Congestion level in the guide path network depends on whether vehicle calls are scheduled or unscheduled. In scheduled calls, vehicles are dispatched to pickup stations at regular intervals. If a load is present at the station, it is picked up by the scheduled vehicle and delivered to the next appropriate station. Otherwise, the vehicle proceeds to another station or returns to a parking area or circulatory loop until rescheduled during the subsequent schedule period. Scheduled vehicle dispatches have a tendency to result in congested passageways due to the simultaneous surge in network demands. This can lead to more conflict resolutions for right of way and blockings between vehicles.

In contrast, unscheduled calls are individually generated by workstations on demand. The time of calls are not preplanned. The calls are activated by a need to remove loads waiting in a queue. Therefore, since vehicle dispatching policies affect the total blocking times experienced by a vehicle, the adoption of any dispatching and vehicle management policy should be carefully weighed during the design stage of an AGV system.

In the next chapter, a review of the current state of the art on some of the issues raised in this chapter will be provided.

CHAPTER 4

REVIEW OF LITERATURE

4.1 INTRODUCTION

The review of the literature covers the following areas:

A. design of Automatic Guided Vehicle systems,

B. unit load design system, and

C. job scheduling and vehicle management systems.

Job scheduling has received a considerable amount of research attention over the last three decades as the volume of literature available can testify [25]. The effect of unit loads in production and distribution systems has long been recognized by different classes of users, namely: air transporters, water transporters, and land based carriers with freight transportation drawing the highest attention as demonstrated in [48,66]. Research on unit loads in the area of in-plant application is beginning to grow. The history of modern Automatic Guided Vehicle System is recent. The first Automatic Guided Vehicle System dates back to 1953 [19] and its application consists of a modified towing truck pulling a trailer in a grocery warehouse. An overhead wire network constituted the guide path. Automatic Guided Vehicle (AGV) application, as it is known today, was first reported in Sweden. Volvo employed these vehicles to convey automobiles from production lines through final assembly [81].

With the above highlight, the approach for the rest of the review is to discuss in detail each of the following areas:

a) Automatic Guided Vehicle System,

b) Unit load design, and

c) Job scheduling and vehicle management.

The separability of the review is a matter of convenience and is not intended to connote that the subject matters are separable. Where appropriate, correlations will be cited.

4.2 AUTOMATIC GUIDED VEHICLE SYSTEMS

Most of the research on AGV systems have concentrated on hardware development rather than on the design of operational control elements. Reports on hardware design are difficult to obtain due to corporate confidentiality and proprietorship. Materials available in the open literature are mostly success stories written in trade journals [1,28,29,30,52,63,77,78,80]. Such materials always discuss the functional capabilities of AGV systems rather than developing and discussing models that contribute to operating performance. Technical publications in the analysis and design of AGV systems is almost nonexistent. However, there is indication of this trend changing.

It can be argued that given the history of AGV system, though short, a reasonable volume of literature would have been available by now if AGV system is that important for solving many material handling problems. The lack of interest in AGV system research is technology oriented. The capabilities of earlier AGV systems were very limited. Recent advances in electronic and computer technology have enhanced and expanded the applications of AGVs [82].

The limited literature on AGV system design include two papers by Maxwell [54,55]. The material presented in [54] dealing with the use of AGVs in production was an outgrowth of the work reported in [55]. A static integer programming model is formulated. The objective of the model is to determine the number of vehicles needed to meet the handling requirements of an assembly operation. Vehicle requirement is determined by first obtaining the material flow volume between workstations. The total flow distance for all unit loads is then estimated based on the shortest path algorithm. A heuristic vehicle dispatching rule is presented. The paper by Zornig [82] is hardware oriented and is more futuristic in nature. The purpose of the study is the description of the state of the art in industrial vehicular robot design and the exploration of ways to improve or enhance existing designs.

Related to AGV systems are Automatic Guideway Transit (AGT) systems. While the AGV system environment is a production system, a warehouse or an office, the areas of applications of AGTs are urban centers. Automatic Guideway Transit system is defined as automated (mass transit) vehicles on fixed guideways along an exclusive right of way [47]. Even more related to AGV system is the Personal Rapid Transit (PRT) system [47,62] which can be viewed as an automated taxicab operation. According to [82], during the past decade a number of attempts have been made to implement AGT system in a number of urban centers. Federal interest in AGT system has been substantial and reasonable amount of research have been undertaken [82]. The similarities between AGV system and AGT system operations suggests that the possibility exists for borrowing some of the findings in AGT system and applying them, with modifications, to AGV system applications.

Research areas investigated in AGT system that have some mapping with AGV system include control methods [13,47,62], guideway design, service concepts, vehicle management, routing and dispatching, reliability and dependability, and economic feasibilty studies [27,47,62]. In an AGV system context, the design of the guideway system is analogous to the design of the guide path. The process of unit load pickup, transportation, and delivery is equivalent to the services provided to the human passengers in an AGT system. Vehicle management involves the specification of appropriate rules for resolving conflicts between vehicles at intersections, setting up operational conditions, and ensuring safe flow of vehicles.

The technique with which road networks are designed in the field of transportation engineering can also be used to seek optimum guide path configuration in an AGV system. Several design models have been developed for planning the road system of regions [2,10,23,51,59,70]. Major disadvantages with these models are that they are static and are very difficult to solve to obtain optimum solutions [2,10,59,70]. For small scale network design problems typical in AGV systems, the computational cost involved in using the models to seek optimum configuration may be very prohibitive to outweigh the benefits sought. Moreover, since the traffic condition in an AGV system is dynamically changing over time, the optimum network found for any period has very limited interpretation as it may not apply in subsequent time periods. The optimum configuration at a peak production period may differ from that which applies when production is at a low level or when the product mix changes. It is therefore intuitive to argue that in a system with dynamically fluctuating traffic condition, an approximate guide path layout may be sufficient.

Thus far, attention has been directed to AGVs only. Other entities that flow through the traffic network are unit loads of manufactured products. In the next section, a review of unit load research is presented.

4.3 UNIT LOAD DESIGN

Handling activities occur at all levels of production. They extend from the procurement of raw materials through manufacturing, packaging, and storage to shipping of finished products to consumers. Depending on the physical characteristics of the materials transported, handling is facilitated by the use of some form of containers. One or more units of the items to be transported are placed in these containers. The resulting entity (i.e. container and the item in it) constitute a <u>unit load</u>. Because of their wide range of applications, the design and the selection of unit loads affect production performance at all levels. This performance factor has long been recognized in production systems involving handling. Such systems include manufacturing and freight transportation such as shipping through water, air, land, and rails. The selection of a particular design of unit loads has a direct relationship to utilization of container space, warehouse space, and carrier space. In manufacturing, it affects the specification of material handling equipment, buffer zones, and material throughput rates.

In his book on the design of material handling systems, Apple [4] devoted a chapter on the concepts of unit loads. The concepts discussed include methods of selecting unit loads, parts configuration in containers and unit load size selection. Although his approach is qualitative in nature, his work does provide a good starting point. Unit load design for better storage space seem to be the current trend in unit load research. Tables on the stacking of unit loads have been developed by the U.S. Navy [71] to achieve better space utilization. Amongst other published work in the area of space utilization are those of Peleg [60], Steudel [71] and Tanchoco et. al. [72]. Peleg's study, which resulted in the development of a computer program, seeks to determine an appropriate dimension for a container suitable to a particular application. The study also seeks to find the appropriate stacking pattern of unit loads to achieve a high unit load space utilization. Steudel's work seeks to establish a loading pattern on a rectangular base unit load such that space wastage is reduced. Dynamic programming technique is employed as a solution methodology. The model by Tanchoco et. al. develops a relationship between unit load selection and the selection of material handling equipment such as industrial trucks, conveyor systems and palletizers. Other reported studies are those of Saxena [69] and Apple Jr. [5]. In [69], a regression model is developed for predicting storage space requirements as a function of unit load characteristics. Considerations for storage space requirements for work-in-process is part of the discussions in [5]. Factors such as load size and container types as well as storage mode are cited as reasons for poor material control in industry.

The size of unit loads has also been used to determine the optimum production quantity to schedule for manufacture. In Tanchoco et. al. [73], a mathematical model is developed for minimizing total production cost through optimum selection of production quantity, unit load dimensions, weight, and part content. Cost components of the model are the total setup cost as a function of annual demand and production quantity per setup, inventory holding cost, backorder cost, and transportation cost as a function of number of unit loads transported. The smaller the part content of a unit load, the more the number of unit loads generated from a batch, and the higher the transportation cost.

In the design of storage systems, the size and weight of unit loads to be stored are explicit design factors. This is testified by the work by Kay [50] where a set of mathematical models for warehouse handling have been developed. The models explicitly consider storage cells' dimensions and locations to determine storage patterns and locations. Specification of cell sizes are a function of unit load dimension and live weight. The effect of unit load sizes on the design of high rise storage systems is addressed in [6].

Handling and storage are integral parts of a Materials Requirements Planning (MRP) system. The determination of appropriate unit load size and configuration for in-plant handling in conjunction with alternative MRP lot-sizing procedure is addressed in [40].

Published technical materials in the design of unit loads for in-plant application have been few compared to the magnitude of the design problem itself. However, trade journals in material handling occassionally feature issues in the selection of unit loads [18,20,74,75]. Studies on the economy of unit load design in the area of freight handling has been addressed more than that of in-plant handling [48,66]. This suggests that there is yet a pool of unaddressed issues in the design of unit loads for in-plant applications. Such areas as the effect of unit load specification on job flow times, batch lapping, equipment requirements, and equipment utilization have not been addressed. The interactions between unit load specification, job flow times and job lapping were discussed in the last chapter. In the next section job scheduling policies and the management of material handling vehicles, including their roles in accelerating job completions through the machine shop are reviewed. The interactions between material handling system and job scheduling policies are cited wherever it is appropriate.

4.4 JOB SCHEDULING AND MANAGEMENT OF MATERIAL HANDLING SYSTEMS

The advantages of operating within the framework of a planned production schedule has been a well recognized condition in the production cycle. This is testified by the volume of literature available in the area [25]. While it is unquestionable that "several aspects of scheduling have been addressed over the past thirty years, very little has been done to integrate the effects of job dispatching policies at workstations to the operations of material handling systems that provide the support for workstations." Job scheduling and material handling systems have each developed to a study area that suggest a complete lack of relationship between them. "The common tie between job dispatching rules and the policies for operating material handling system is that both are intended to provide the drive necessary to keep jobs flowing through the manufacturing system." It is a common practice that when the effects of job dispatching rules on a machine shop are evaluated, the effects of material handling system are assumed negligible [22,25] or given." "Dispatching policies are judged by their abilities to accelerate the jobs through the machine shop at zero transit times between workstations." The job flows are also assumed to occur in whole entities (i.e. jobs are not split into transportable sizes). However," the realization of the impact of a job dispatching rule is dependent on the reliability of the material handling system that supports it. Jobs have to be delivered at workstations before any application of a dispatching rule is put into effect."

Dispatching rules and machining rates provide the driving force that controls the flow of jobs (or unit loads if a batch system is assumed) through a machining center. It is the rate of unit load completions that determine the frequency of moves in a manufacturing system. Move frequency is always considered in designing any material handling system. Likewise, the material handling system provides the flow potential when jobs or unit loads are in transit. In situations where limited queue capacities exist at workstations, machine blocking is a possibility unless completed unit loads are removed in a timely manner. The removal rate of completed jobs therefore depends on the capacity of the material handling equipment selected and the policies governing their operations. The policies surrounding the operation of a material handling system include: 1) determining which equipment to be dispatched for unit load pickup, 2) setting up priorities for determining the order unit loads are to be picked, and 3) setting the pattern for scheduling material handling missions. "For manufacturing systems employing continuously operating conveyor systems, the scheduling of the unit load to be transported is a trivial matter. But where variable path or fixed path equipment, especially AGVs, are used, the scheduling of which unit load to transport and when to transport it is a non-trivial task." "Unless an adequate vehicle management policy is implemented, the benefits of any job dispatching rule, even though efficient by itself, may not be realized." The current separability approach pursued in the study of job dispatching rules and material handling system management policies are reviewed below to illustrate the missing gap highlighted above.

The material is organized into three subheadings, namely:

1. static or deterministic job scheduling,
2. dynamic or stochastic job scheduling, and
3. vehicle management.

The case of static model is presented first.

4.4.1 Static Scheduling Models

Due to the enormous amount of literature available on static job scheduling, exhaustive discussion of all available work is fruitless. Only the most relevant studies are cited.

The objective in static scheduling models is to determine the optimum sequence on each machine to schedule the jobs to optimize a single or a combination of the following criteria [25,39]:

a) maximum tardiness,

b) weighted sum of tardiness,

c) weighted sum of completion times,

d) total cost of tardiness,

e) total penalty if jobs are dependent on one another,

f) setup times or setup cost for sequence dependent setups,

g) makespan,

h) flow times, etc.

Despite the fact that the listed criteria are all related to time in one form or the other, no consideration is given to optimize the time required of the jobs or unit loads to travel from one workstation to another. Ensuring that jobs are available at the right workstations and at the right times is a function of the material handling system. The static models generally assume that material handling time is negligible and that jobs are instantaneously available at the proper sites and at the required time [25,39].

Classes of problems considered under static scheduling fall under the following categories:

a) N jobs and a single machine,
b) N jobs and M identical machines,
c) N jobs and uniform and related parallel machines,
d) job shops, and
e) flow shops.

These classes of problems usually assume single part jobs [22]. This precludes any multi-component jobs as well as batch jobs. The elimination of batch jobs also mean the elimination of unit load consideration for the nontrivial handling cases. As it is observable in most manufacturing systems, batch production accounts for about 75% of total manufacture [35]. Batch jobs are usually broken down and transported in portable size units. Therefore, it is possible to find unit loads of a given batch at different workstations simultaneously. This suggests that given the assumptions built into static scheduling models, only trivial manufacturing environments can fit the description.

Mathematical modeling and solution methodology employed for solving static scheduling problems precludes the inclusion of additional factors that complicate the models. Solution techniques currently in use include linear programming, dynamic, integer, convex, and quadratic programming. Other techniques include network flows, combinatorial methods, reliable heuristics or controlled enumeration, and Monte Carlo sampling [7,22,25,39]. Given the possible solution techniques listed above, it is not difficult to understand why the effect of material handling system is generally assumed away. Consideration of material handling will tremendously complicate the models. The degree of complication is even more so if jobs can be split into unit loads or lap-phasing is permitted. “The current models represent a pursuit to attaining mathematical tractability rather than an attempt to recognize the effects of material handling time in scheduling.”

Additional materials on static scheduling models can be found in the book by Conway, Maxwell and Miller [22] and the more recent book by Baker [7]. The survey paper by Graham et.al. [39] provides a good reference guide to the literature on static models. The survey itself requires some mathematical sophistication. Also very informative is the review paper on sequencing research by Day et.al. [25]. It too has a very large literature listing. The review of dynamic scheduling and its assumptions on material handling aspects of production is presented next.

4.4.2 Dynamic Scheduling Models

There are similarities between dynamic scheduling models and static scheduling models. Both have received considerable amount of research attention as their literatures show [25]. The model objectives are in most cases functions of time. Both suffer the same shortcoming when it relates to material handling and unit load systems considerations. But due to the solution methodology employed for dynamic models, some of the assumptions in the static models are relaxed. As subsequent discussions below will illustrate, even though the analysis tool generally employed for investigating dynamic models would have made it easier to incorporate unit loads and material handling systems into the analysis, there are no known studies by the author that considers simultaneously the joint effects of unit loads, material handling and job dispatching rule on the performance of a production system. Monte Carlo simulation is the principal tool for studying dynamic schedules.

In dynamic scheduling models, jobs are assumed to be continuously arriving and leaving the manufacturing systems as their service requirements are satisfied. On arrival, a job is initially assigned to a machining center and it takes zero time for the job to travel from the arrival dock to the assigned center. Thereafter, the flow of the job is controlled by an $Mx(M+1)$ transition matrix, where M is defined as the number of machining stations in the system. The elements across the rows of the matrix specify the transition probabilities and must sum to unity. A transition to the (M+1) column represents a completion and departure of a job from the system [25]. To avoid long cycling by jobs, an upper limit is usually imposed on the number of allowable transitions a job can make [21]. Transition is terminated if the limit is reached.

As it can be inferred from the above paragraph, the transitions represent the movement of jobs from one workstation to another. It is easy to understand that the matrix controlled flow process is not a workable technique for batch or multi-component jobs as pursued in this study. Since the job route is not predefined, there is no guarantee that unit loads belonging to the same batch will necessarily follow the same job route. In batch systems, unit loads make the transitions instead of whole jobs. Therefore, a different technique for specifying job routes has to be implemented for batch scheduling.

Furthermore, by assumming that transition from one machining center to another is instantaneous, the models obviously eliminate the role of material handling equipment in the system. This elimination is unjustified if it is realized that a typical part in manufacture spends about 70% of its time in handling [5]. The current study recognizes that 70% is too high a proportion to be ignored. In practice, instances exist where the causes of bottlenecks at a machining station are due to the inability of the handling system to remove completed jobs from workstations in a timely manner. Machine blocking will result more frequently if the handling system is inefficient.

The objective in most dynamic scheduling studies is to optimize on some system or job related performance measure(s). Such measures are in most cases a variation of time measurement. Common measures of performance are [7,22,25,26]:

a) frequency with which jobs assigned due dates are met,

b) job tardiness,

c) average tardiness

d) mean flow time,

e) jobs makespan,

f) work-in-process inventory,

g) job waiting times at each machining center and for the manufacturing system in general,

h) number of jobs in the system,

i) machine utilization, and

j) machine setup times for setup dependent schedules.

Unfortunately, despite the emphasis placed on the effective utilization of time by the criteria, it can be seen that such emphasis is only isolated since it does not integrate both machining and handling times. Optimizing the completion time of a job or unit load at a machining center is a worthwhile effort only if the completed unit load is delivered timely to its subsequent destination.

There are currently more than twenty priority rules cited in [25] for dispatching jobs from queues for machining. Individual circumstances necessitate the definition of other rules as the conditions warrant. The rules are predominantly heuristic with First Come-First Serve (FCFS) being the most commonly applied. The different rules cited in [25] can be classified into

a) arrival order rules,

b) lateness rules,

c) job characteristics based rules, and

d) random rules.

Studies have been conducted to investigate the effect of combining two or more rules at certain circumstances [12]. On the other hand, there is a complete lack of any documented rules designed to investigate the sequence for moving completed jobs waiting at a workstation. There is a parallel relationship between jobs or unit loads waiting for processing at a machining center and those already completed but waiting to be moved from that center. One set is competing for limited machine resource while the other is associated with limited handling resource. It is the combined effect of this two-stage resource competition that actually determine when a unit load leaves a workstation. A weakness anywhere in the flow link (i.e machining and handling) produces a control problem over the entire production system. Manufacturing systems where dynamic scheduling models have been investigated include cellularly-divided group technology manufacturing systems [41], flow shops, job shops, and parallel processors manufacturing systems. In all the applications, the link between job dispatching policy and material handling system management is missing.

Thus far, attention has been focused on the review of job dispatching models and their relationships to material handling systems in a manufacturing environment. In the next section, current policies in the scheduling and routing of material handling equipment is presented. The presentation focuses primarily on the management of mobile (i.e variable path) material handling equipment since they are more related to Automatic Guided Vehicles (AGVs) than any other families of equipment. No further attempts will be made to relate vehicle management policies to job scheduling.

4.4.3 Vehicle Management

Unlike job scheduling, there are not enough reported work known to the author that suggests careful studies have been conducted to investigate the effects of various rules for dispatching and routing mobile material handling equipment in a manufacturing system. The rarity of such reports suggest that current practices in the scheduling and routing of industrial vehicles are merely rules of thumb. Fortunately, the lack of standard practices as cited above is not completely shared by other fields that share relationships with in-plant material handling. For example, the search for an optimum schedule and routing of a fleet of vehicles is a common design problem in the fields of physical distribution and transportation. Since the activities of physical distribution and transportation are merely a macroscopic representation of the operations of an in-plant industrial vehicle handling system, much can be derived from these fields for the advancement of the design of an industrial vehicle handling system. Commonly employed criteria for evaluating the effectiveness of a schedule or routing of a fleet of vehicles in the fields of physical distribution and transportation are [15,47,56,65]:

a) total travel distance,

b) total travel time, and

c) total travel cost.

The vehicle scheduling problem was first posed by Dantzig and Ramser [24] in 1959, and was recognized as a special form of the well known traveling salesman problem. The problem is described as follows: a set of customers each with a known location and known demand for some commodity, is to be supplied from a central depot by delivery vehicles of known capacity. The problem is to design the routes of these vehicles to optimize on some measures of performance, given that all deliveries are met. The optimum solution is that which minimizes the number of vehicle routes (and hence the number of vehicles), and for them, the total distance, time or cost involved. The problem as described has its equivalence in the operation of a fleet of industrial vehicles. The central depot represents the warehouse or an AS/RS that supports a manufacturing operation. The customer demand locations are equivalent to workstations or departments while the demanded materials are the unit loads traveling between the warehouse and the departments. The route selection is equivalent to specifying the aisles and paths of vehicles traveling in and out of the warehouse.

Extensions of the scheduling models include cases with multiple depots and multiple delivery points [56]. This extension also has an equivalence in a manufacturing system. Separate warehouse for raw materials, work-in-process inventory and finished products are not uncommon in manufacturing operations. Partly completed unit loads are brought from in-process inventory and transported to workstations for processing. On completion, they are returned to the finished goods inventory or transported to another workstation. In this case, a machining center acts as a depot as well as a demand center since it can receive and send unit loads from and to other locations in the system.

The vehicle scheduling models described are static and deterministic. Studies have also been reported on scheduling and routing of vehicles where demand time is assumed to be stochastic. The reported studies are mostly in the area of scheduling urban mass transit systems. Blair's [10] paper whose abstract appeared in the ORSA-TIMS bulletin (1980) describes a material handling system with stochastic demands for unit load pickups. His solution technique is optimization through simulation. Dantzig et. al. in their static model employed integer linear programming to seek optimum solution. Since then, solution methodologies have been refined and extended. Current techniques include branch and bound, heuristic algorithms, and iterative methods [15,16,37,38,56]. Even the more recent study by Maxwell [55] on the selection of routes for an AGV system is static and employs integer programming technique. None of the solution technique guarantees optimality for very large problems. Because of the iterative nature of some of the techniques, lengthy computational time and large computer storage requirements are involved.

The problem of routing and distributing motor vehicles evenly on a network of streets have been studied in the area of traffic engineering. This problem is equivalent to distributing and routing industrial vehicles through the aisles of a manufacturing plant. The only noticeable difference is, of course, in the magnitude of the problem. In traffic engineering, the objective of such studies is to spread the motor vehicles throughout the street network so as to minimize total network travel times for all vehicles [53], or to reduce traffic congestion at some regions of the transport network [47]. The studies require an origin-destination (O-D) flow matrix for the network. The matrix provides information on network demand and the load (traffic density) of each network segment and intersection. The O-D matrix is equivalent to the From-To Chart of material handling trips or unit loads that travel between machining centers in a manufacturing system. Three measures are used in altering the flow pattern of vehicles in a network:

a) traffic signal control,

b) traffic management schemes (such as bans on certain turns, imposition of one-way streets), and

c) route control devices (such as advisory or mandatory route signs) [3].

Measures (b) and (c) are accomplished in AGV system through proper design of the guide path and the controlling software. Installation of traffic signals at selected intersection of an AGV system is meaningless since all vehicles at an intersection are under the guidance of the same controller. Through appropriate marriage of the hardware and software, stops at an intersection can be signaled to an approaching AGV as the needs arise instead of adopting the rigid intersection control schemes as found in a road system.

Of even greater relevance to this study is the direct relationships that exist between the design of an AGV system and that of an Automated Guideway Transit (AGT) system. Both have automatic vehicles operating under the control of computers. While unit loads are the items transported in an AGV system, people take the role of unit loads in the AGT system. AGT systems have been previously cited in this review.

4.5 SUMMARY

In this chapter, a review on the level of research on AGV system, unit load design, job scheduling, and vehicle management were presented. These areas have been identified in an earlier chapter as design factors in the installation and operation of a successful Automatic Guided Vehicle material handling system. With the emphasis on the operational issues, each factor is reviewed in the context of available literature in the area of manufacturing systems and in related fields such as physical distribution, and transportation and traffic engineering. As the review is presented, references are made , where appropriate to the other factors. The review attempts to establish the position that the design factors are interrelated and that despite the current practice of studying each factor independently of the others, they all have to be integrated in setting the controls and strategies required to operate an effective or unified handling system. In the next chapter, an integrated model of an Automatic Guided Vehicle System is developed. Using a modular approach, the model incorporates the various aspects of manufacturing as reviewed, building into each module the trigger mechanisms that relates it to the other modules.

CHAPTER 5

MODEL DEVELOPMENT

5.1 INTRODUCTION

The system modeled in this research represents a typical production facility where the installation of an automatic guided vehicle material handling system is required. The economic justification procedure required for the acquisition of an AGV system is outside the scope of the present study. Because of the several subsystems modeled in this chapter, a brief outline of its composition and scope is appropriate.

The chapter is begun with a description of the type of production environment to which this research is focused. This is followed by a mathematical formulation of the different subsystems that describe an AGV based system. These mathematical models are modularly developed to show clearly the multi-component nature of the type of production system of interest. Finally, a brief description of a simulation model that integrates the various mathematical models developed is presented.

5.1.1 The Description of the Shop Environment

The production environment is a manufacturing shop. Within the shop are various types of machines or people organized in groups according to specialized functions. Batch jobs are dynamically arriving into the shop for processing. On arrival, the batch is broken up into unit loads. The number of unit loads that makeup a batch is a function of the batch size, unit load size and parts characteristics. Unit loads are the transportable items in the shop. Each batch has a known machining route that depends on the job type. On completion of its last required operation, a unit load is transported to storage or warehouse via automatic guided vehicles. The guided vehicles also transport the unit loads between machining centers within the shop. At each machining center, the unit loads are individually scheduled for processing through an established dispatching rule. Even though they are machined as an entity, the actual machining time required by a unit load is a function of its size and the characteristics of the parts and job type contained in it. Since each unit load is transported and machined independently, it is possible to find unit loads from the same batch at different manufacturing stages. Thus, the problem of scheduling control arises.

5.2 MODELING APPROACH

Due to the complex and interactive nature of the manufacturing environment modeled in this study, a simulation methodology is applied. Solution through mathematical programming is currently intractable. The size of a mathematical model can be very large for realistic production environments. To cope with the stochastic, highly interactive, exogeneously and endogenously driven system, digital simulation is adopted. Simulation analysis is the most desirable and often the only available systems analysis technique for studying complex manufacturing facilities such as the one considered in this research [61].

5.2.1 The Shop Model

The general shop model is composed of submodels that describe portions of the total system. The submodels basically fall into

a) Physical System Design
   i) Guide path network specification

b) System Operational Design
   i) the job arrival process to the shop,
   ii) the unit load assignment process,
   iii) the machining process, and
   iv) the vehicle-unit load transport system.

Details on these models are presented in subsequent sections of this chapter.

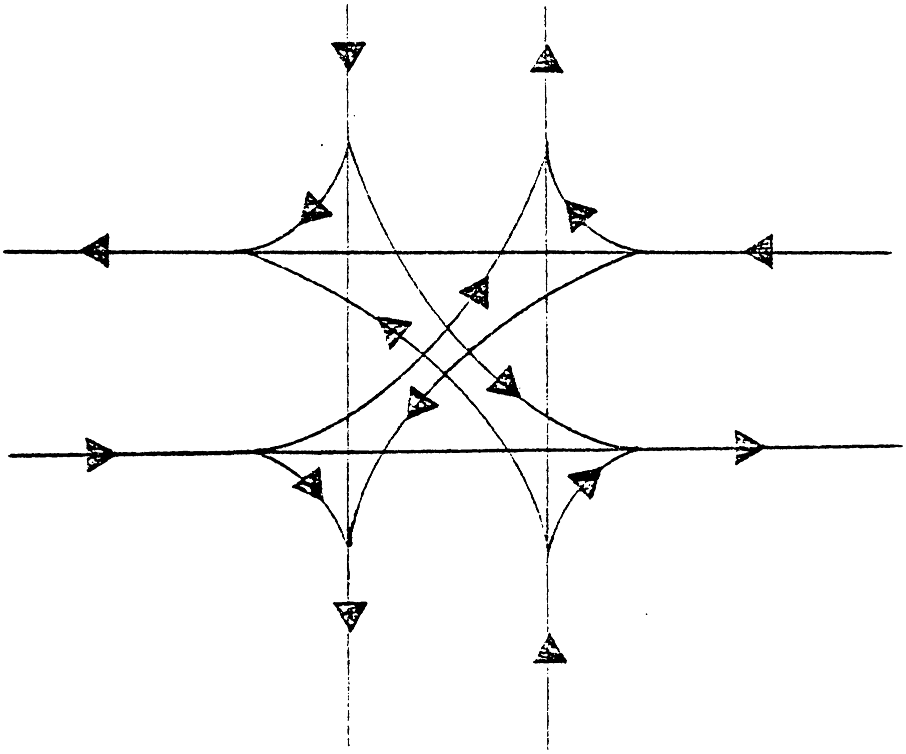
5.3 PHYSICAL SYSTEM DESIGN (GUIDE PATH NETWORK SPECIFICATIONS)

The layout of the guide wires constitute the guide path network system. Consideration of the paths dictates the direction of traffic flows. Flow of traffic can be unidirectional or bidirectional. There are currently no reported bidirectional traffic flows along the main aisle of an AGV system in the true sense of bidirection flows. There are, of course, bidirectional vehicles. The use of bidirectional vehicle movement is limited to ingress and egress to pickup and delivery stations, and to a few selected guide paths with low traffic densities.

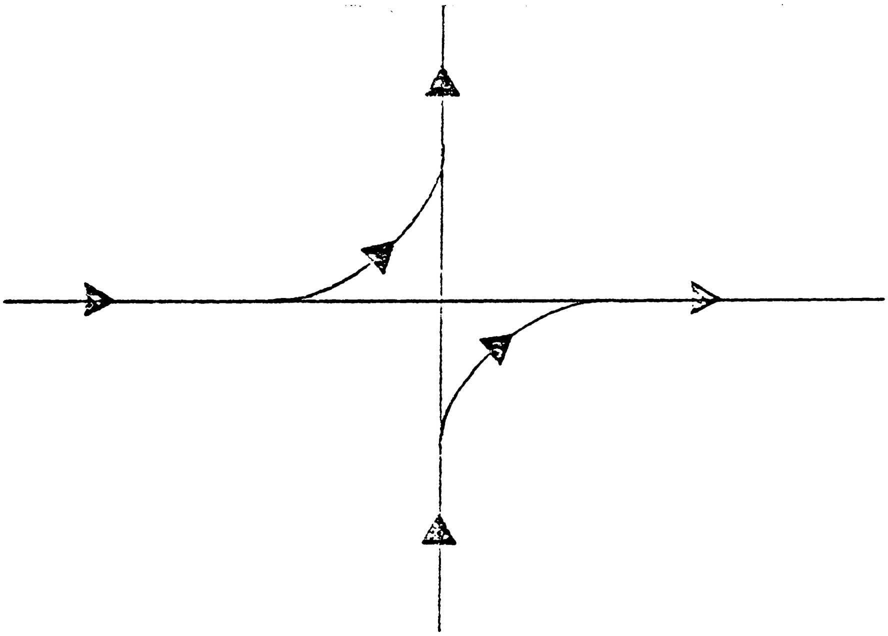
AGV systems employing two-way flows currently do so only in apparent form through modifications. Two methods are used for the modification [67]. One approach is to layout parallel guide wires along an aisle such that guidance signals along the wires are sent in opposite directions. The wires must be sufficiently separated in space with enough clearance to take two vehicles. Therefore aisles with parallel guide paths must be sufficiently wide. The alternative approach is to have vehicle controls at entry points of aisles. The control holds a vehicle entering an aisle until an exiting vehicle is cleared.

There are advantages and disadvantages associated with each type of layout. The advantages of one-way systems are aesthetics, simplicty of control and economics [47]. A larger plant area is served and is less expensive to install. Intersection controls are less demanding and require smaller computers than two-way layouts. Even for a detailed graphical representation of intersections as in Figure 5.1, two-way intersections are much more robust and complex [47]. A weakness of the one-way system is that a vehicle may travel a longer distance before it gets to its destination even if its source and destination are not that far apart. Furthermore, a faster moving vehicle may be blocked or slowed down if a slower moving vehicle is traveling ahead of it.

In this study, a one-way traffic flow system is adopted. This is due in part to their current dominance in industrial applications and partly due to their benefits which currently outweigh two-way systems.



Two-Way System Intersection Interchange



One-Way System Intersection Interchange

Figure 5.1 Intersection Interchange

A typical unidirectional guide path system is shown in Figure 5.2. It consists of path segments and intersections. The intersections are the points in the guide path system where two or more segments of the guide wires meet. This includes points of wire crossings, merges and diverges. The segments of the guide paths is that portion of the wire system between two intersections.

The guide path system is modeled as a network. The nodes of the network are the intersections (i.e. crossings, merges and diverges). The network arcs are the guide path segments as shown in Figure 5.2. An arc has a source node and a terminal node. By specifying the nodes that bound an arc, an arc is uniquely identified. The arc specification also indicates the orientation of the arc. For example, an arc that originates in node α and terminates in node β is represented as arc(α, β). In a unidirectional system, arc(α, β) $\neq$ arc(β,α). No two or more arcs can have a common source and terminal nodes simultaneously. U-shaped arcs are not permitted.

Positions within the network are identified using the cartesian-coordinate system. For every node, a point location is provided in terms of (x,y) coordinates. The point location is useful for purposes of zoning, measuring distances between points, specifying congested areas of the network due to traffic, and identifying node and arc locations. All delivery and pickup stations are also modeled as nodes except that they are located off main tracks as Figure 5.2 illustrates.

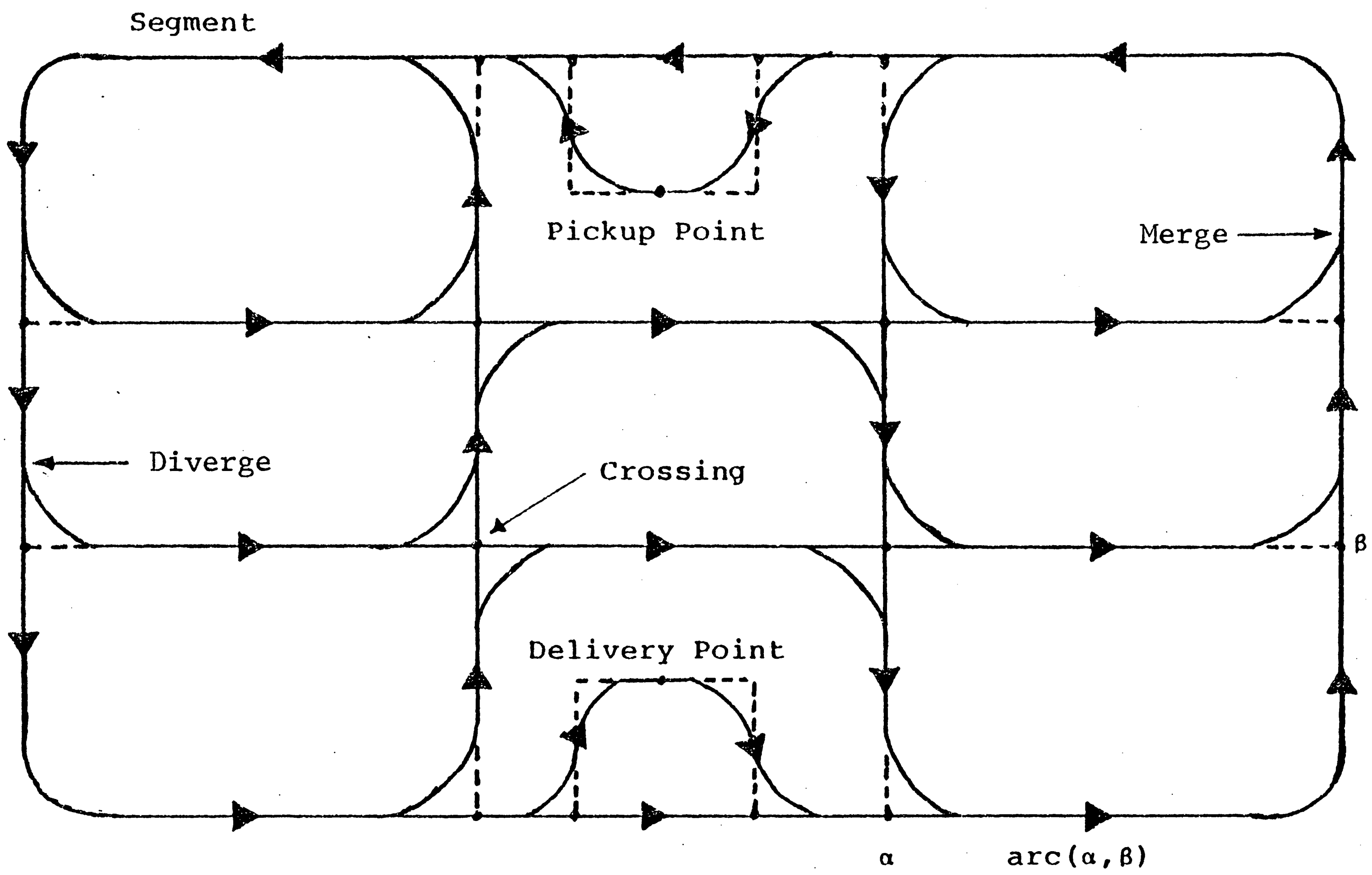


Figure 5.2 A Guide Path System

For convenience of traffic control, nodes are classified into (i) conflict nodes and (ii) non-conflict nodes. Conflict nodes includes all nodes that serve as terminal points to two or more arcs. That is, they are directly reachable from two or more nodes, making it possible for two or more vehicles to arrive at the node almost simultaneously. Simultaneous or near simultaneous arrivals at a node by multiple vehicles result in conflicts between the arriving vehicles as to which has the right-of-way for crossing the node; thus the name conflict nodes. Conflict nodes include all guide path crossings and merges. On the other hand, all nodes that can only be reached from one node constitute the non-conflict nodes and they are so named because conflict from right-of-way is not possible. Non-conflict nodes include entries to pickup and delivery nodes and diverges.

A third class of information that is required at a node for traffic control reasons is the direction an arc departs from a node. An arc can leave and enter a node in one of two directions, namely, along an x-axis or along a y-axis. Depending on the directions of departure and entry to its adjacent nodes, an arc can be classified into one of two families. In the first family, the arc orientation at the source and terminal nodes is the same. In the second family, the orientation at the source node is different from the orientation at the terminal node as shown in Figure 5.3. The second family of arcs also include those arcs obtainable by rotating the ones in Figure 5.3 through 180 degrees.

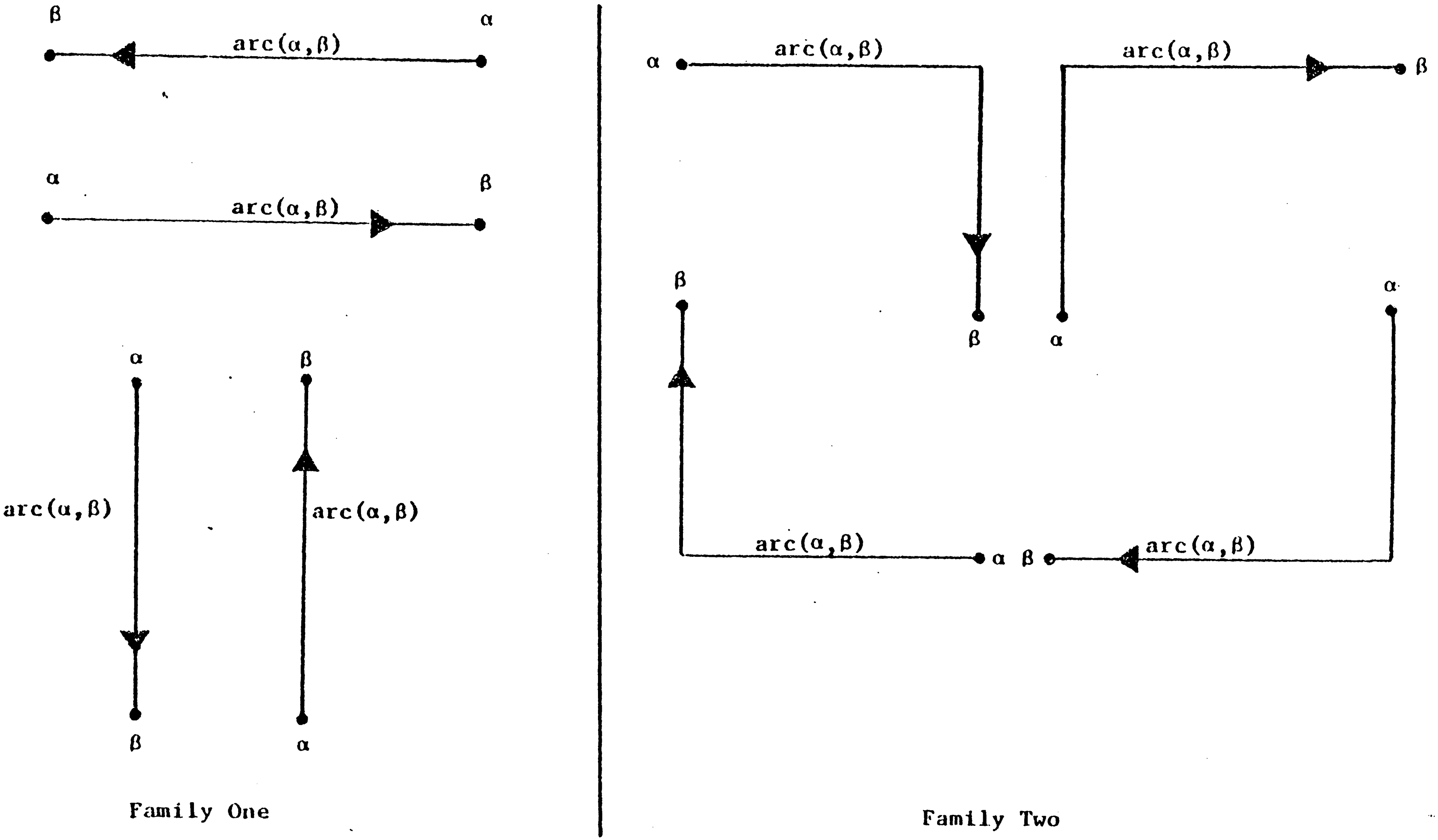


Figure 5.3 Characterization of Arc According to Orientation

5.4 SYSTEM OPERATIONAL DESIGN

5.4.1 The Job Arrival Process To the Shop

A dynamic batch production system with capability to handle different classes of jobs is assumed. The batch arrival process is described by specifying an appropriate probability distribution representing the arrival process of batches into the system. The rate of arrivals is driven by the parameters of the specified distribution.

The arrival of one batch initiates the arrival of the subsequent batch. On arrival, the batch job class is identified according to a probability distribution that describes the distribution of job classes that enter the system. Given that the job class is known, the unit load assignment process is initiated and the batch production route generated according to a prescribed job route sheet.

5.4.2 The Unit Load Assignment Process

Jobs arrive into the shop in batches that belong to job classes. A batch consists of an order of a particular quantity for a particular part. Parts are transported in containers of various sizes. The dimension and weight of parts determine the number that fit in a container. The number of containers obtainable from a batch depends on the size of the order and the number of parts that can be placed per container. Thus, the containers, rather than batches, move through the shop as entities. These entities are called unit loads. The machining requirements of a batch is completed when its last unit load leaves the shop.

The modeling of the assignment process is facilitated by the definition of the following variables.

i = job class i, $i = 1,2,\ldots N$.

j = container type j, $j = 1,2,\ldots J$.

l_j, w_j, h_j = length, width and height of container j.

w_j^c = weight of container j (dead weight)

W_j^{max} = maximum live load container j can support.

$w_i^{(p)}$ = weight of part p in job class i. In general

$w_i^{(1)} \neq w_i^{(2)} \ldots \neq w_i^{(z)}$ for non-homogeneous parts and

$w_i^{(1)} = w_i^{(2)} = \ldots \neq w_i^{(z)}$ for homogeneous parts. The index z signifies the maximum number of part types in job class i.

$v_i^{(p)}$ = volume of part p in job class i

Q = batch order quantity.

$q_{ij}^{(p)}$ = unit load size for part p in job class i using container j.

$\gamma_{ij}^{(p)}$ = constant container fill-ratio or packing factor for part p in job class i using container j. $0 < \gamma_{ij}^{(p)} < 1$.

Therefore, the maximum number of part p of job class i that can be packed in container j by volume is given by

$$[A]^{-} = \left[\frac{l_j w_j h_j \gamma_{ij}^{(p)}}{v_i^{(p)}}\right]^{-}$$

where [A]- is the greatest integer less than or equal to A and [A]+ is the lowest integer greater than or equal A is used later. The maximum number of parts that can be packed by weight is

$$\left[\frac{W_j^{max} - w_j^{c}}{w_i^{(p)}}\right]^{-}$$

Therefore

$$\max q_{ij}^{(p)} = \left\{\left[\frac{l_j w_j h_j \gamma_{ij}^{(p)}}{v_i^{(p)}}\right] \quad , \quad \left[\frac{W_j^{max} - w_j^{c}}{w_i^{(p)}}\right]\right\}$$

If $n_{ij}^{(p)}$ is the number of container type j required for job class i, then

$$n_{ij}^{(p)} = \left[\frac{Q}{\max q_{ij}^{(p)}}\right]^{+}$$

To ensure equal number of parts per container,

$$q_{ij}^{(p)} = \left[\frac{Q}{n_{ij}^{(p)}}\right]^{+}$$

A gain of a few number of parts is possible from the last equation for any batch. In this study, parts in a job class are considered homogeneous.

5.4.3 The Machining Center and Machining Process

The modeling of the machining centers and machining operations are macroscopic in nature. Detailed activities of a machining operation such as machine loading and unloading, movement of unit loads within the center, selection of machining parameters (i.e. feed, speed, and depth of cut) are aggregated as part of the machining requirements.

The system represents a machining center as a multiple server queueing system as in Figure 5.4. Unit loads are delivered into the incoming unit load queue of a center by automatic guided vehicles. The queue is driven by a selected job dispatching rule. Machining time required by unit loads are estimated based on job type and number of parts in the unit load. On completion of machining, the unit load machined is placed in the outgoing queue, bound for the next workcenter. Automatic guided vehicles pick outbound unit loads, again according to some rule.

For the modeling of the machining center activities, the following variables are defined.

M = number of machining centers in the system.

m = machining center m, $m = 1, 2, \ldots M$.

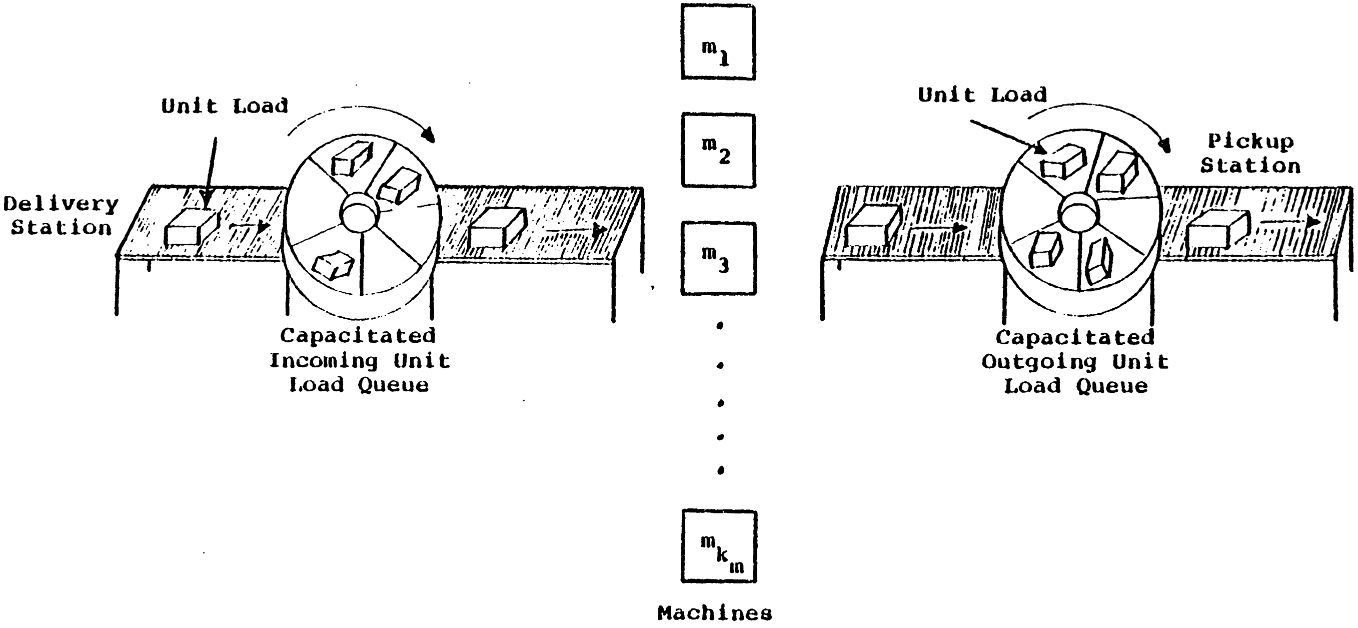


Figure 5.4 Schematic Diagram of a Machining Center

K_m = number of machines in machining center m.

μ_{mk} = machining rate for the kth machine in center m.

k = 1, 2, ... K_m. For homogeneous machine centers μ_{m_1} = μ_{m_2} .... = μ_{mk_m} .

C_m^D = capacity of incoming queue in station m, C_m^D is expressed in unit loads.

C_m^P = capacity of outgoing queue in station m, C_m^P is expressed in unit loads.

τ_{ijkm} = time required to process job class i (in container j) using the kth machine in machining center m.

S_{ikm} = setup time required to machine job class i on the kth machine in center m. S_{ikm} = 0 if the preceeding job processed by the kth machine in center m also belong to the ith job class.

Machines at a particular workcenter are assumed to be homogeneous. τ_{ijkm} is specified either as a constant or according to a probability distribution. No restriction is placed on setup time.

5.5 THE VEHICLE - UNIT LOAD TRANSPORT SYSTEM

Unit loads and vehicles are the only entities that flow in the system. Part of the time, both entities flow as a single entity. This happens when a unit load is being transported by a vehicle. At other times, the entities flow separately. This is equivalent to a vehicle traveling empty or a unit load in a machining center, as the entity flow diagram in Figure 5.5 illustrates. Since the maneuvers required of an empty vehicle are encompassed by those of a loaded vehicle, the more general case of vehicle traveling with a load for delivery to a workcenter is modeled. Loaded vehicular activities can be segregated into

a) pickup a unit load,
b) travel along a segment or arc,
c) cross an intersection, and
d) deliver a unit load.

Each of these four vehicular functions is further described in detail below.

5.5.1 Unit Load Pickup Activity

Vehicles entering delivery and pickup stations, located off a main track, do so only for the purpose of material delivery or pickup. Simultaneous pickups by two or more vehicles from the same station is not permitted. Pickup operations are undertaken sequentially by waiting vehicles on a First Come-First Serve basis. To undertake the pickup operation, a pickup time is estimated. For machining center m, the pickup time is denoted by t_m^p. If T denotes the current time, the pickup operation will be completed at time $T + t_m^p$.

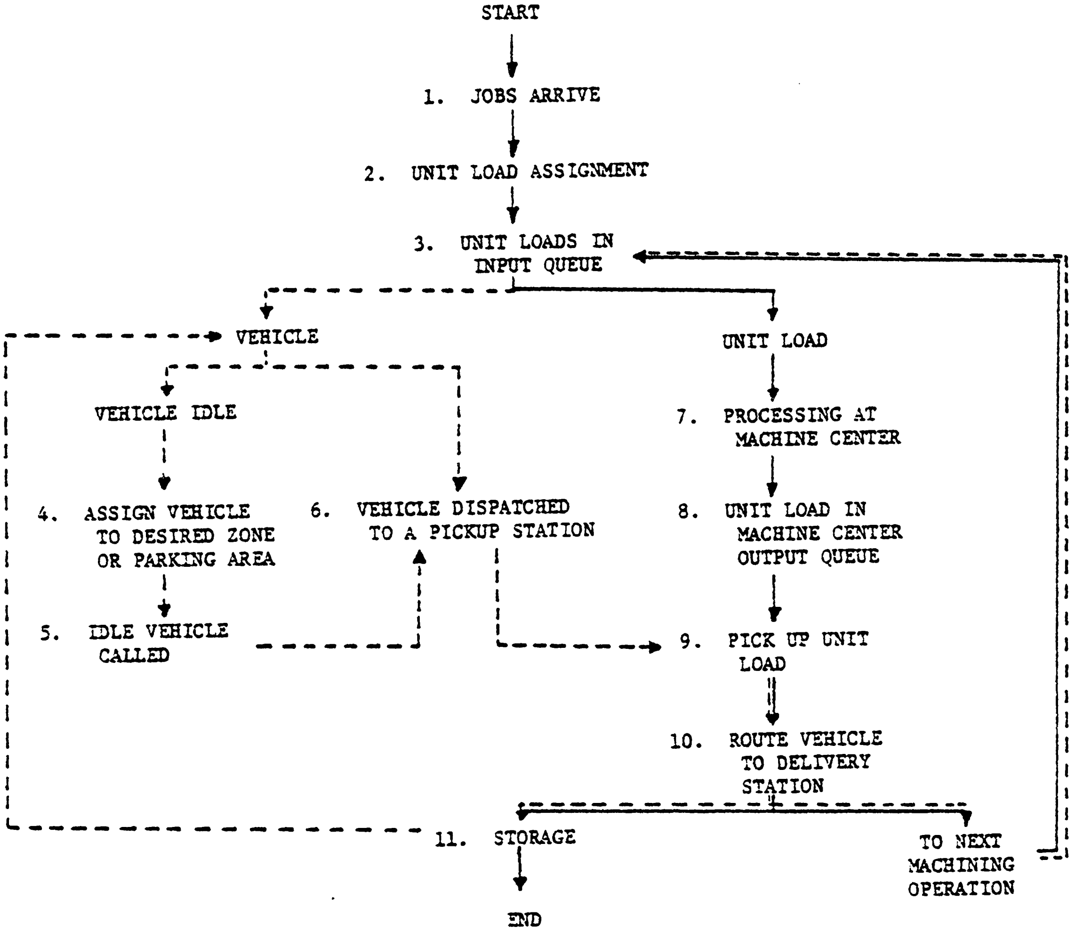


Figure 5.5: Macro Flow Chart for the Operation of an Automated Guided Vehicle System (AGVS).

--- Guided Vehicle
—— Unit Load (Jobs)

To initiate the pickup, the model first looks ahead in time space to determine if any other vehicle(s) is currently scheduled to arrive at that pickup station. If the result of the lookahead proves negative (i.e. no other vehicle(s) is scheduled to arrive) the end of the pickup activity is scheduled. Otherwise, the arrival time of the immediate arriving vehicle is determined. Let the arrival time be denoted by T'. A check is made if $T' > T + t_m^p + t_\varepsilon$ where t_ε denotes the time interval required to clear the minimum headway distance between adjacent vehicles. If the condition $T' > T + t_m^p + t_\varepsilon$ holds the end of pickup operation is scheduled as usual. If $T' < T + t_m^p + t_\varepsilon$, the value of T' is adjusted by equating $T' = T + t_m^p + t_\varepsilon$. The adjustment of T' is equivalent to delaying the arrival time of the arriving vehicle at the pickup station until the current pickup operation is completed.

The adjustment of T' may affect the order of arrivals of other vehicle(s) following the vehicle whose arrival time is adjusted. To maintain the same sequence of arrivals, the time adjustment is recursively propagated to all other vehicles approaching the station whose order of arrival may change unless their arrival time is adjusted. Such propagated arrival time adjustment is not required if the sequence of arrivals remains the same after T' is adjusted.

On completion of the pickup activity, the loaded vehicle departs the pickup point if the exit aisle is not congested. Otherwise, the vehicle is held in place until the aisle is cleared. Should such holding affect the arrival times at the pickup station of other vehicles(s) queueing for service at the station, their arrival times are adjusted in the same manner that was previously described in the paragraphs above.

5.5.2 Traveling Along A Segment

A vehicle traveling in the network performs one of four maneuvers: a) traveling straight, b) slowing down or holding at a point, c) making a turn, and d) accelerating. Holding can take place at an intersection or a pickup and delivery station. Turns occur at intersections for arc interchanges or within an arc. Surrounding every node is a check zone as shown in Figure 5.6. The point where the check zone intersects with an arc entering a node is a check point. The points represented by b_1 and b_2 are examples of check points in Figure 5.6. The distance between a check point and the center of the node it serves is denoted by e. The check points are essentially decision points in the network while check zones are safety zones designed to ensure safe crossing of vehicles. No two vehicles can occupy the same check zone simultaneously. When a vehicle arrives at a check point, a decision is made to either proceed straight through the node or make a turn. A decision is also made whether it is safe to cross the node (i.e. enter the check zone) and if so, is there sufficient space in the subsequent arc beyond the check zone for the vehicle to occupy. A vehicle may fail to enter a subsequent arc due to traffic congestion on that arc. Details on node crossing and transfer to a subsequent arc are discussed in the next section.

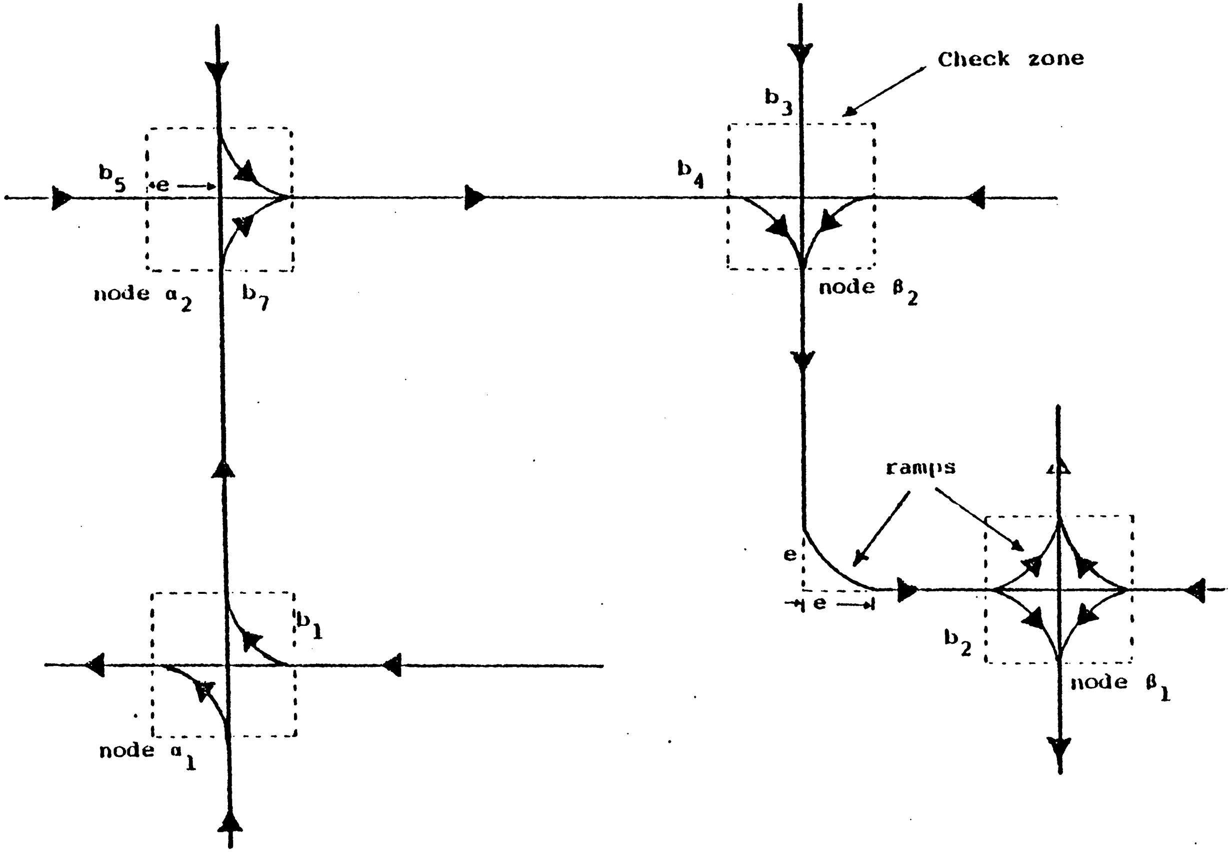


Figure 5.6 A Section of a Guide Path Network

Vehicles travel from check point to check point instead of traveling from node center to node center. The time required to travel from one check point to another depends on the distance between the check points, the vehicle travel speed and the occurence of any delay or traffic congestion. Delay occurs when a slower moving vehicle travels ahead of a faster moving vehicle. To calculate the distance between adjacent check points, the following variables are defined.

α = current node where vehicle is located.

β = next node vehicle is due.

(x_α, y_α) = co-ordinate of node α

(x_β, y_β) = co-ordinate of node β

$S(\omega)$ = speed of vehicle as a function of the weight of the load it carries.

In calculating the distance between adjacent nodes, the following assumptions are made.

1) No sharp vehicle turns are allowed. All turns are accomplished through interchange ramps as in Figure 5.6.

2) The points where a ramp diverges from one arc and merges with another are equidistant points to the center of the node. The distance measure is denoted by e.

3) Second family arcs (i.e. L-shaped arcs) change directions gradually through smoothed ramps. The points where the ramps take off and re-enter the arcs are located a distance of e from the points where the arcs make right angle turns as in Figure 5.6.

The distance between the check point of node α and the check point of node β, where α and β are adjacent nodes, depends on the four cases outlined below.

Case 1: A turn is required in node α to transfer to arc(α,β) and the distance measure from α to β is Euclidean. Case 1 distance is illustrated by the distance measure from check point b_1 of node α_1 (Figure 5.6) to check point b_7 of node α_2 . The distance is

$$d_{\alpha_1\alpha_2} = \{(x_{\alpha_1} - x_{\alpha_2})^2 + (y_{\alpha_1} - y_{\alpha_2})^2\}^{1/2} - 2e + f$$

where f is the length of the ramp and $d_{\alpha_1\alpha_2}$ is the distance from b_1 to b_7.

The value of f can be predefined or approximated by $\pi e/2$.

Case 2: A turn is required at node α to transfer to arc(α, β) and the distance measure from α to β is rectilinear. This is illustrated by a distance measure from check point b_4 of node β_2 to check point b_2 of node β_1 (Figure 5.6). The distance calculation is given by

$$d_{\beta_2\beta_1} = |x_{\beta_2} - x_{\beta_1}| + |y_{\beta_2} - y_{\beta_1}| - 4e + 2f$$

Case 3: No turn is required at node α to transfer to arc(α,β) and the distance measure from α to β is Euclidean. The distance from check point b_5 of node α_2 to b_4 of node β_2 illustrates this case.

$$\begin{aligned} d_{\alpha_2\beta_2} &= \{(x_{\alpha_2} - x_{\beta_2})^2 + (y_{\alpha_2} - y_{\beta_2})^2\}^{1/2} - e + e \\ &= \{(x_{\alpha_2} - x_{\beta_2})^2 + (y_{\alpha_2} - y_{\beta_2})^2\}^{1/2} \end{aligned}$$

Case 4: No turn is required at node α to transfer to arc(α, β) and the distance measure from α to β is rectilinear. In Figure 5.6, this distance measure is represented by moving from point b_5 of node α_2 to b_4 of node β_2. The distance is

$$d_{\beta_2\beta_1} = |x_{\beta_1} - x_{\beta_2}| + |y_{\beta_1} - y_{\beta_2}| - 2e + f$$

In general, for any successive nodes α and β, the distance from the check point of node α to that of node β is

$$d_{\alpha\beta} = \begin{cases} \{(x_\alpha - x_\beta)^2 + (y_\alpha - y_\beta)^2\}^{1/2} + (f - 2e)\,\phi, \text{ if distance} \\ \qquad \text{from } \alpha \text{ to } \beta \text{ is Euclidean.} \\ |x_\alpha - x_\beta| + |y_\alpha - y_\beta| + (f - 2e)(\phi + 1), \text{ if the} \\ \qquad \text{distance from } \alpha \text{ to } \beta \text{ is rectilinear.} \end{cases}$$

where

$$\phi = \begin{cases} 1, & \text{if a turn is required at } \alpha \text{ to reach } \beta \\ 0, & \text{otherwise.} \end{cases}$$

To calculate the time of arrival at the check point of node β by a vehicle currently at a check point of node α, define

$\Delta(\alpha)$ = a vehicle currently at a check point of node α but to travel next in arc(α, β).

$R(\alpha, \beta)$ = the set of all vehicles currently in arc(α,β) traveling to node β. $\Delta(\alpha)$ is not in $R(\alpha,\beta)$.

T_ℓ = the time the last vehicle in $R(\alpha,\beta)$ to enter arc(α,β) is scheduled to arrive at the check point of node β.

t_ε = the time required to travel the minimum headway separation between adjacent vehicles.

T = current time.

The time of arrival at the check point of node B by the vehicle $\Delta(\alpha)$ is

$$T' = \max \{T + d_{\alpha\beta}/S(\omega),\ T_\ell + t_\varepsilon\}$$

If $R(\alpha,\beta)$ is empty, then $T' = T + d_{\alpha\beta}/s(\omega)$.

5.5.3 Crossing An Intersection

The nodes in the network diagram denote intersections within the guide path system. On arrival at a check point of a node, a vehicle seeks information on three questions prior to entering the check zone. The questions, in the order of query, are 1) Is the node a conflict node?, 2) Is the subsequent arc congested?, and 3) Is a turn required? The first question determines if a safety check is required to enter the check zone. Non-conflict nodes are not checked for safe crossing. The purpose of the safety check is to ensure that no collision occurs when the vehicle crosses an intersection. Safe crossing is guaranteed at non-conflict nodes. The second question ensures that a vehicle does not enter or cross a check zone unless it can proceed ahead in the subsequent arc. The response to the first and second questions must be positive for a vehicle to clear a node. If either responses is negative, the affected vehicle is considered blocked. When a vehicle is blocked, it is held at the check point of the node in question for some length of time until the traffic condition around the node improves to permit crossing.

Several rules can be implemented for resolving traffic conflicts at a node. To simplify the discussions that follow, graphical and notational representations will be employed where the author realizes that their applications will help to clarify the points raised. Suppose node α is a conflict node as shown in Figure 5.7. Nodes β_1 and β_2 are directly reachable from node α and β_3 and β_4 are two nodes with arcs leading directly to α. Two strings of vehicles are approaching α from

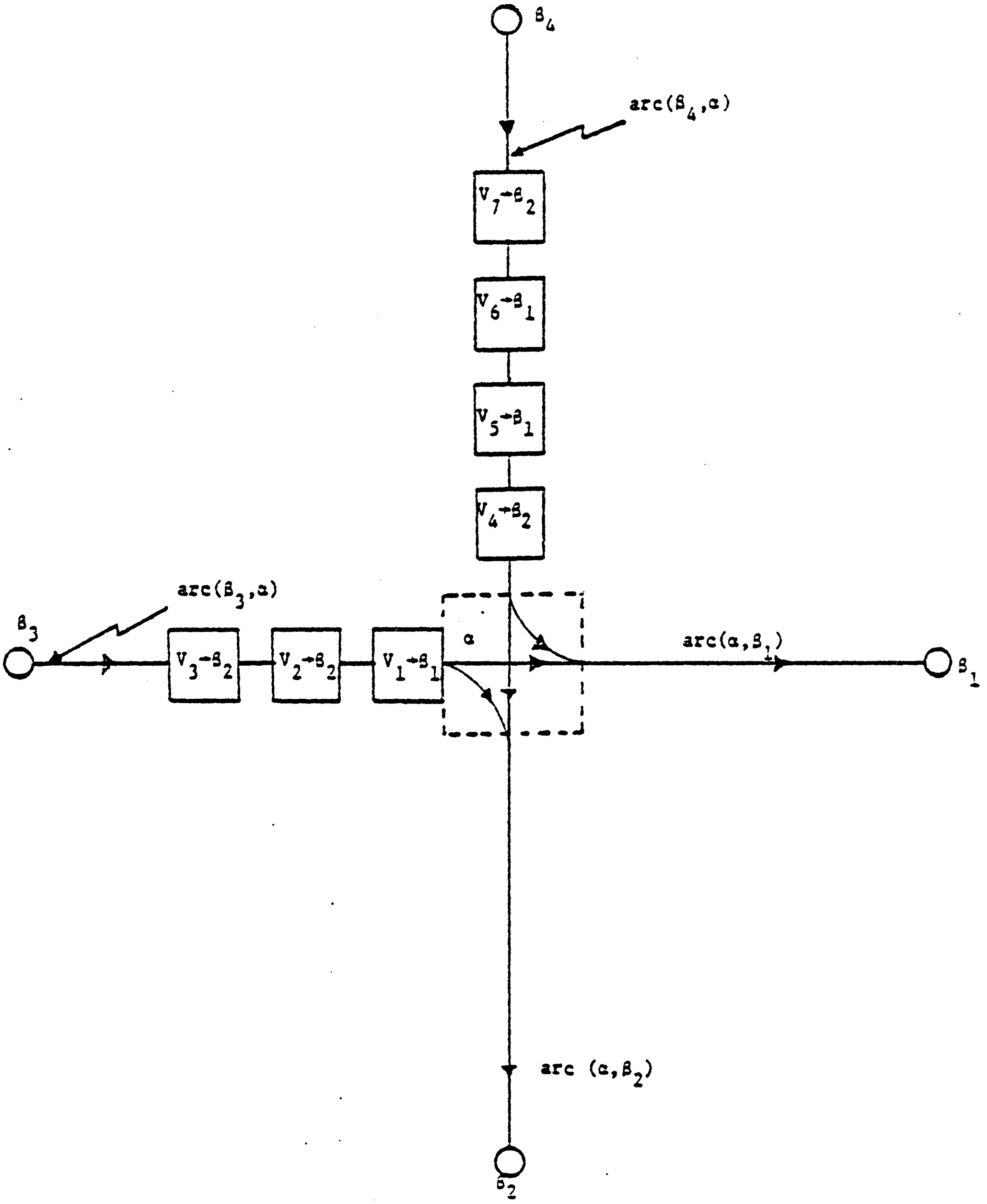


Figure 5.7 Node α

arc(β_3,α) and arc(β_4,α). In arc(β_3,α) are vehicles numbered V_1, V_2, and V_3. Vehicles V_4, V_5, V_6 and V_7 make up the string in arc(β_4, α). Next to each vehicle is a node number, β_1 or β_2, indicating the node the associated vehicle will travel to on arrival at node α. To illustrate the various control measures that can be implemented when blocking occurs at a node, the following example is used. Suppose vehicle V_1 (Figure 5.7) has just arrived at the check point of node α. On arrival, the three questions relating to the condition of the check zone are asked. It is found that V_1 is blocked. Let t_h denote the length of time V_1 is to be held at node α before the traffic status around α is rechecked. When t_h time units elapse, the traffic condition at node α is again queried and the decision is made either to continue holding V_1 for more time units or to route it to the next arc. In our example, the next arc for V_1 is arc(α,β_1). The process of querying the node traffic status and making routing decision is repeated periodically until traffic clearance at node α is achieved. Figure 5.8 represents the scenario just described. The response to the third question only affects distance calculation as demonstrated in the previous section. When V_1 is held for t_h units of time, acceleration control measures are signaled from node α to other neighborhood vehicles approaching it from arc(β_3,α) and arc(β_4,α). For ease of analysis, the acceleration control measures applied to vehicles in arc(β_3, α) are first presented.

When V_1 is held for t_h amount of time, acceleration control signals are sent to stop or decelerate the string of vehicles traveling

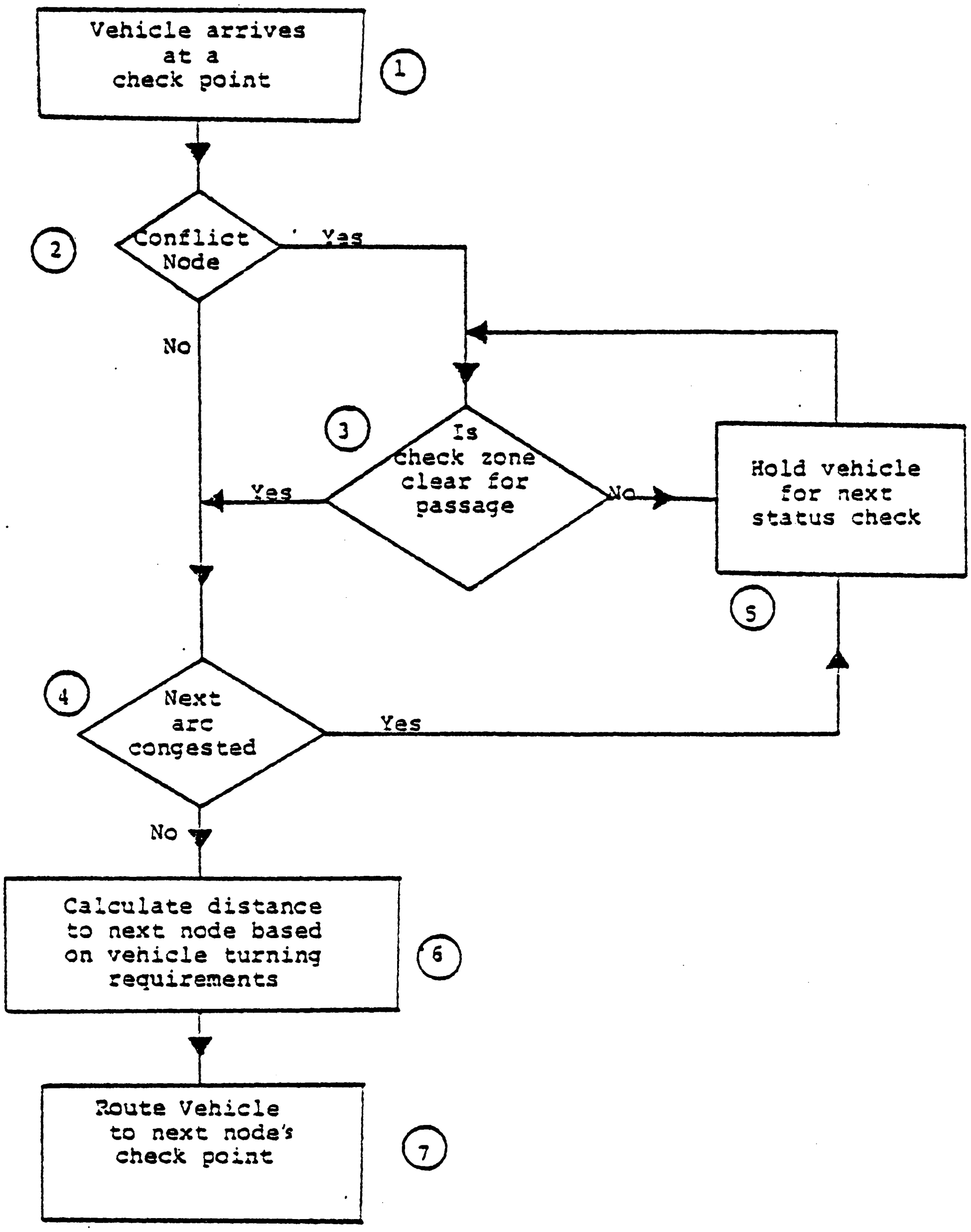


Figure 5.8 Node Clearance Status Check

behind V_1 in arc(β_3, α) as shown in Figure 5.7. The actual number of vehicles stopped or decelerated depend on the separation distances between adjacent vehicles in the string. If the separation distance between V_1 and the vehicle immediately behind it (i.e. V_2 in Figure 5.7) is sufficiently long, no deceleration or stop signal is sent to any vehicle in the string. However, if the signals(s) is activated, the stopping or deceleration process is recursively propagated through the string in arc(β_3, α) until an adequate separation distance exists between adjacent vehicles. When sufficient separation distance is obtained, the propagation of the deceleration control signal to other vehicles further upstream the string is discontinued. The control of vehicles in arc(β_3,α) is completed.

With respect to control measures applied to the string of vehicles in arc(β_4, α) when V_1 is held at node α (Figure 5.7), several heuristic node control rules can be implemented. The rules implemented may differ from one facility to another. Some of the possible rules are presented below.

Rule One: <u>First</u> <u>Come-First</u> <u>Serve</u> (<u>FCFS</u>). Allow departures from a node on a First Come-First Serve basis. Restated differently, the first vehicle to arrive at a node is also the first vehicle to leave that node. In this rule, no other vehicles approaching node α from arc(β_4 , α) can cross the node as long as vehicle V_1 is waiting to cross. For example, if V_4 arrives at node α while V_1 is waiting, V_4 is stopped until V_1 departs. When V_4 stops, deceleration or stop signals are sent to the vehicles traveling behind it. Depending on where sufficient separation distance is obtained between adjacent vehicles, appropriate number of vehicles in arc(β_4, α) are decelerated or stopped in the manner described previously. When the holding time of V_1 elapses, the node clearance questions are repeated. When the condition to cross the check zone is obtained, V_1 departs. Thereafter, V_4 follows.

Rule Two: Restricted First Come-First Serve (RFCFS). Restrict FCFS rule to vehicles transferring to the same arc on arrival at node α. For example, if the blocking of V_1 is due to congestion in arc(α, β_1) and V_4 arrives at node α while V_1 is waiting, V_4 is allowed to cross the node without interruption since V_4 is traveling to node β_2 (Figure 5.7). However, if V_5 also arrives at α while V_1 is still waiting, V_5 is not allowed into arc(α, β_1) before V_1 since both (i.e. V_1 and V_5) are heading to β_1 and V_1 is the first to arrive at the node α. In this case, V_5 is stopped and all other vehicles traveling behind it are decelerated or stopped depending on the separation distance between adjacent vehicles. If this rule is implemented and the described scenario holds, at the time V_1 is signaled to cross the node, the traffic distribution in the network of Figure 5.7 will shift to that of Figure 5.9.

Rule Three: Relaxed Traffic Control (RTC). Eliminate the FCFS restriction completely around node α and allow the flow of traffic from arc(β_4, α) to continue uninterrupted as long as the traffic status around the node α permits. In this rule, if while V_1 is waiting, V_4 arrives at α and is not blocked, it proceeds to arc(α, β_2). Furthermore, as V_5

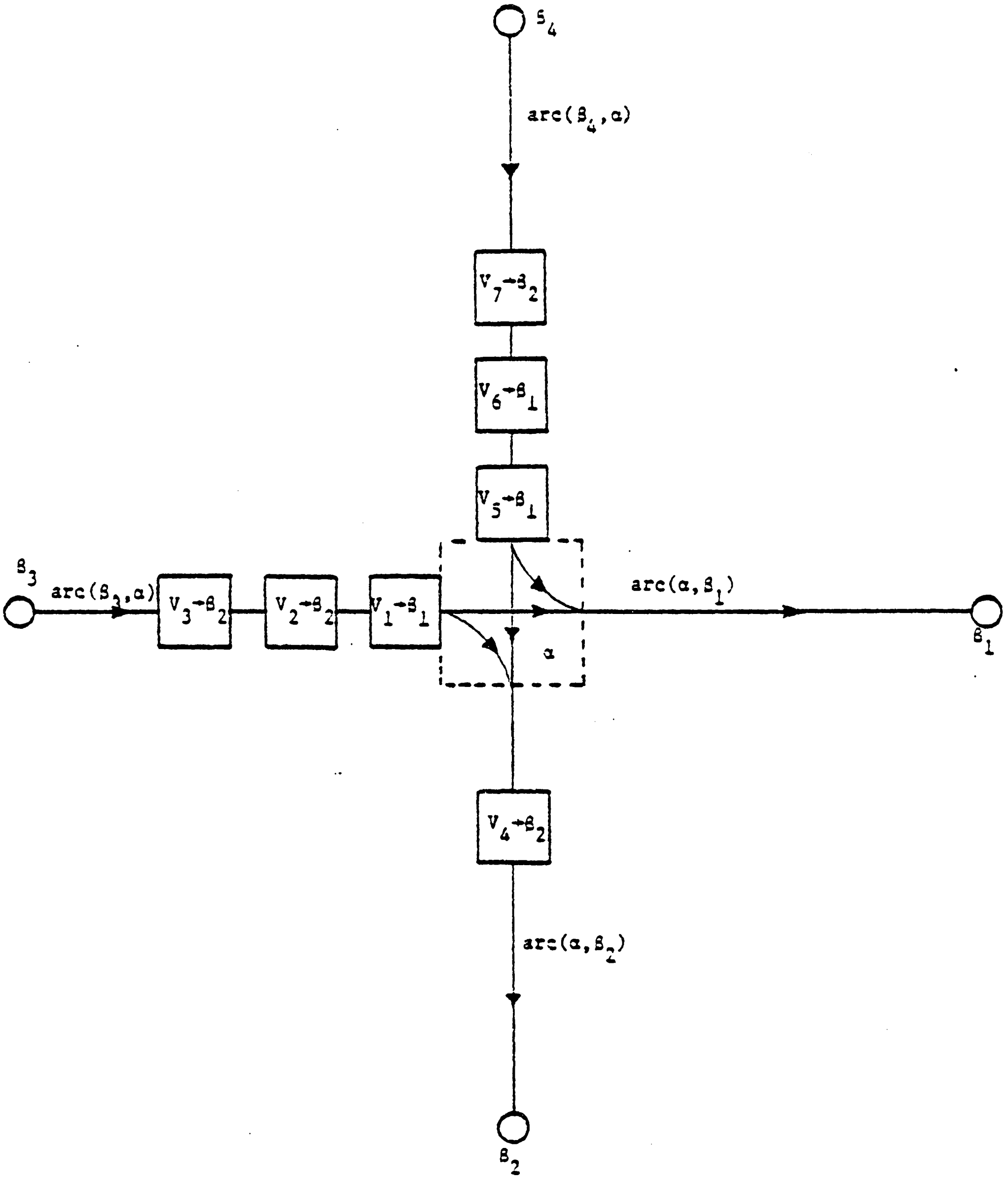


Figure 5.9 The Resulting Distribution of Vehicles from Applying Rule Two at Node α.

arrives and the traffic condition around the node is clear, it too is routed to arc(α, β_1). As many vehicles as possible are routed from arc(β_4, α) to their subsequent arcs from node α during the holding time of V_1. If this rule is used, the vehicles V_5, V_6, and V_7 are allowed to cross node α while V_1 waits. Figures 5.10a, 5.10b, and 5.10c show the vehicle conditions as V_5, V_6, and V_7 crosses node α.

Rule Four: Train Routing (TR). The fourth rule is a function of the characteristics of the string of vehicles in arc(β_4, α). If the distance of separation between adjacent vehicles in the string is short, it may be necessary to continue to hold V_1 until the entire string or part of the string crosses node α. This rule has the potential to reduce the number of vehicle accelerations, decelerations, stops and starts possible in the system. If this rule is used, the resulting distribution of vehicles at the end of the holding time of V_1 could take any one of the forms shown in Figures 5.9 through 5.10c. The redistribution depends on the number of vehicles that actually crossed the node while V_1 was being held. This number could be less than the actual length of the string of vehicles shown in arc(β_4, α) of Figure 5.7.

From the analysis thus presented, the node crossing activity can be completely represented graphically as shown in Figure 5.8 with a slight modification in box number 6. If the box bears an instruction stating that acceleration control measures be applied to other approaching vehicles, then the node crossing representation is complete.

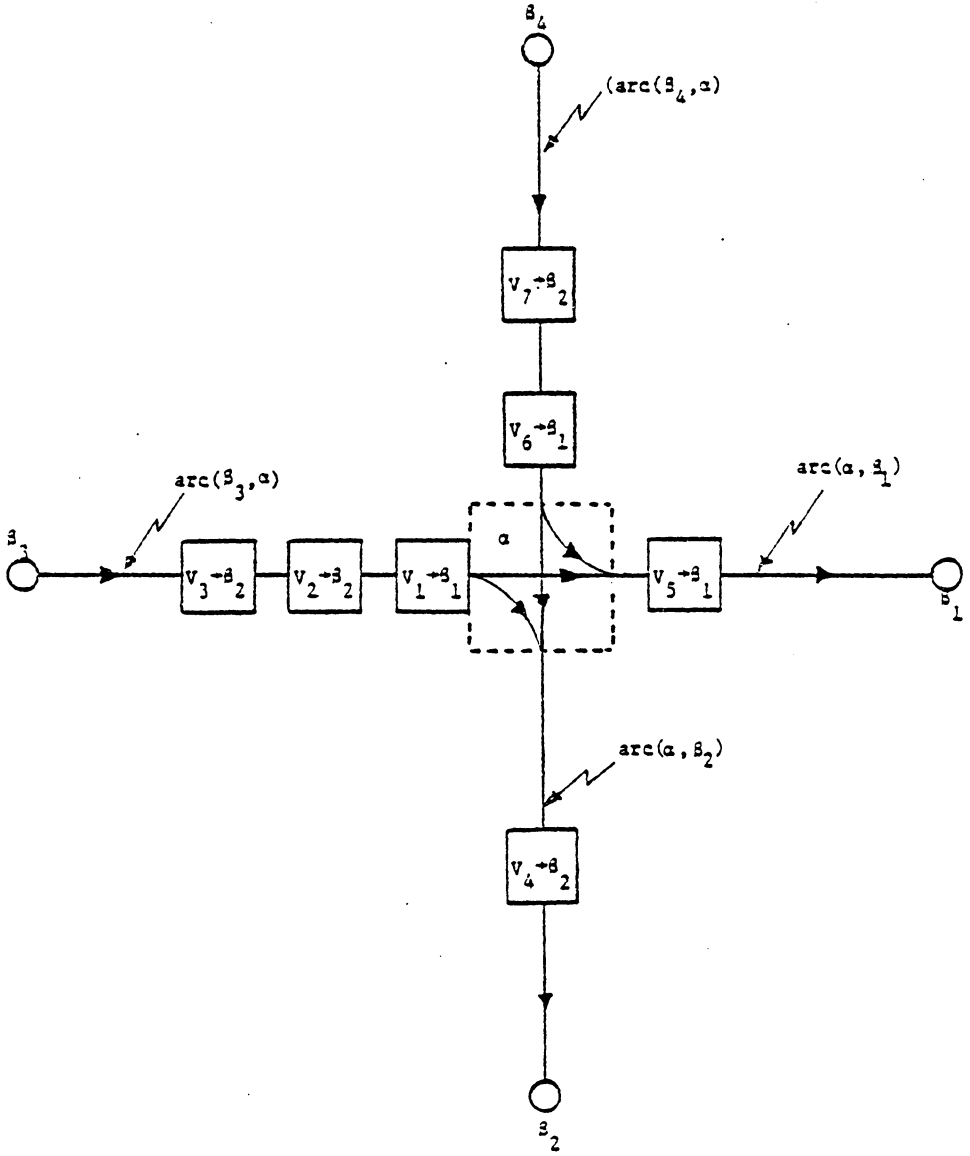


Figure 5.10a Node condition as vehicles V_5 clears the intersection

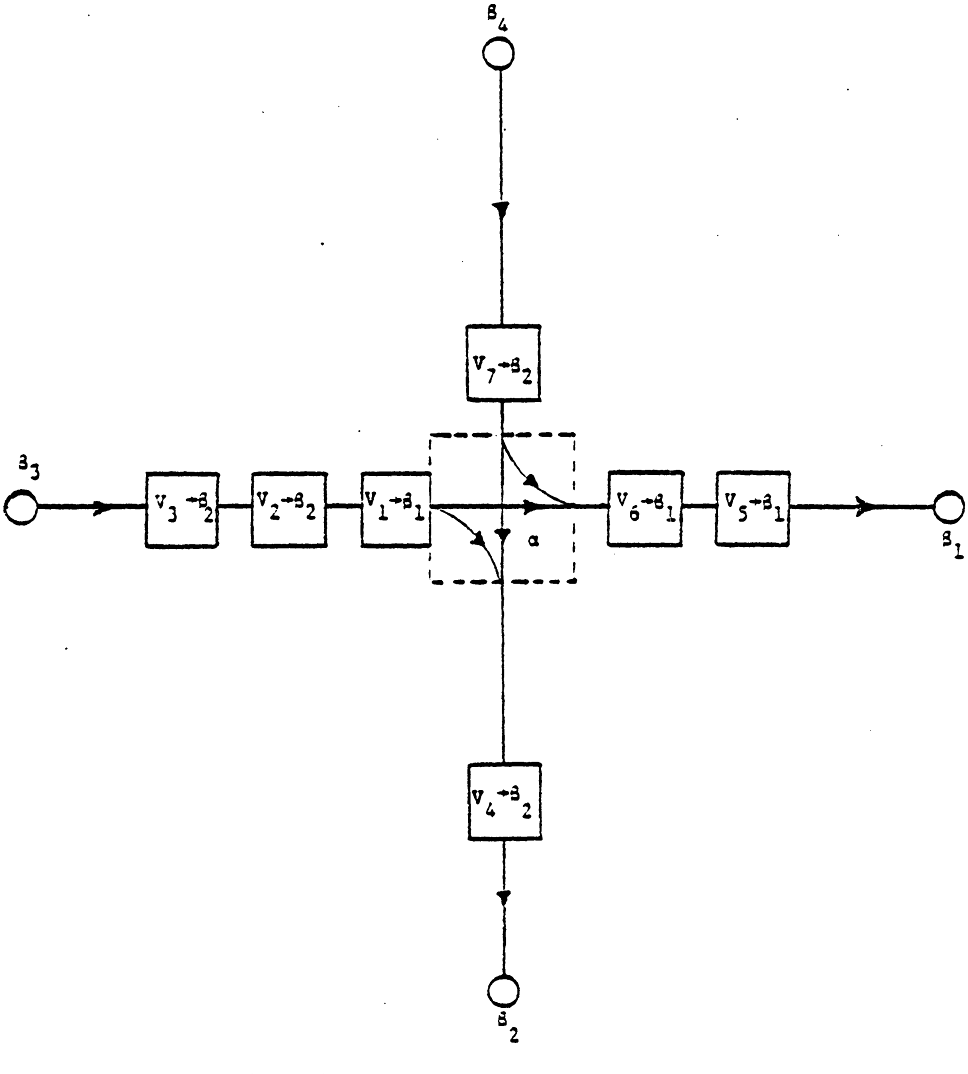


Figure 5.10b Node condition after vehicle V_6 clears the intersection

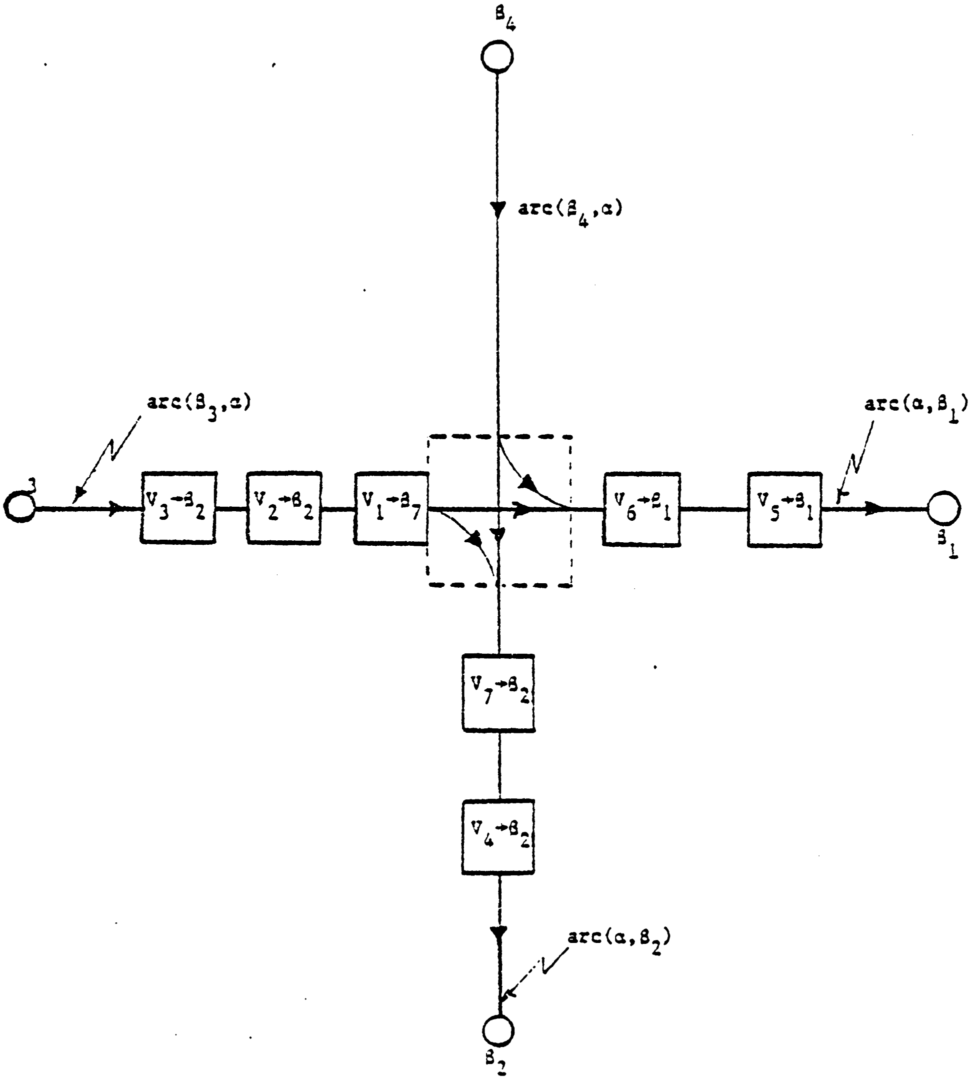


Figure 5.10c Node condition after vehicle V_7 clears the intersection

Other node crossing rules can be implemented on vehicle characteristics. Examples of two such rules can be based on

1) vehicle traveling loaded or empty,

2) vehicle on a high priority mission or not.

5.5.4 Unit Load Delivery Process

The unit load delivery process is identical to the unit load pickup process. The only difference is in the direction of load transfer. In the delivery process, the load flows away from the vehicle while the reverse holds for the pickup process. Therefore, if the pickup time, t_m^P, in machining center m is substituted for the delivery time, t_m^D, in center m, the rest of the analysis remains the same for both cases.

5.6 THE SIMULATION MODEL

The discrete worldview of simulation is used in the study [64]. The time of occurrence of all activities that require the passage of time will be modeled as status disturbing events. The occurence of an event causes the creation of mechanisms to execute status changes within the simulation model, logically linking each event to one another, updating time and model statistics at each status disturbing event and collecting statistics of interest.

The activities modeled as events in the simulation are

1. Job arrival time
2. End of machining

3. End of a load pickup
4. End of a load delivery
5. Vehicle arrival time at a check point.

The end of a vehicle holding time at a check point is not considered a separate event from vehicle arrival time event at a check point. Post simulation analysis is performed to generate management reports on the performance of the simulated systems. A macro flow chart of the simulation model was given previously in Figure 5.5.

CHAPTER 6

A TASK ASSIGNMENT MODEL FOR AUTOMATIC GUIDED VEHICLE BASED MATERIAL HANDLING SYSTEMS

6.1 INTRODUCTION

Hardware failures notwithstanding, the ability of an automated system operating according to promised potential is dependent on operational control measures in force. In this chapter, task assignment (dispatching) rules for Automatic Guided Vehicle based material handling systems are presented. The rules are useful for arbitrating between workstations competing for idle vehicles or between vehicles that can be assigned a mission.

Automated material handling systems, though more flexible and capable than their counterpart non-computer control systems, do, pose more serious and challenging operational control problems. This control problem increases with level of system automation. The manner by which these problems are resolved determine the operating effectiveness of the total system.

Several heuristic rules for assigning priorities to idle vehicles for load pickup and for assigning priorities to workstations requesting idle vehicles are presented in this chapter. In addition to the development and presentation of the rules, the postulated effects of these rules on the performance of the shop are also presented.

In a manufacturing environment consisting of several machine centers performing different machining functions, a typical part or unit load visits several centers before its machining requirements are satisfied. A unit load continues to circulate in the shop between workcenters until it receives its last service. It is this transition of unit loads that generate the vehicle dispatching (task assignment) problem. On the completion of a delivery task, a vehicle is re-assigned another mission immediately if there is any unattended handling task in the facility. Otherwise, the vehicle is set idle and continues to remain idle until a handling task appears, at which time it may be re-assigned. If at the time a vehicle is released (i.e. when it completes a task) from a task, there is only one outstanding (unattended) mission in the facility, the vehicle task assignment problem is trivial. On the other hand, if multiple outstanding missions exist simultaneously, the vehicle task assignment presents a serious operational control problem that involves matching vehicle to task. This problem also appears in another form. When multiple vehicles are idle (unassigned) simultaneously and a pickup task arises, appropriate criteria must be established for selecting an idle vehicle to assign the task (i.e. matching task to vehicle). In a job shop environment where there is no recognized flow pattern of unit loads, vehicles in an AGV system can be dispersed throughout the network or concentrated in a region at any particular time. The distribution of vehicles in the network is an operational control problem that results from measures by which vehicles are assigned tasks. The selected control measures can affect material flow, buffer storage requirements in the departments, machine utilization, and vehicle effectiveness.

The decisions involved in vehicle dispatching problems fall into two categories. The first category is a decision involving the selection of a vehicle from a set of idle vehicles to assign to a unit load pickup task generated at some part of the facility. This class of problem involves a single workcenter and one or more vehicles. It is generally the result of a request from a workcenter for vehicle service. The decision to be made is to determine the vehicle to assign the mission (task). The second category of decisions involves the selection of a workcenter from a set of workcenters simultaneously requesting the service of any vehicle. The decision usually involve a single vehicle and multiple workcenters. The vehicle involved has just completed a delivery task (i.e. released from a delivery task) and is to be re-assigned another task immediately. At the time the vehicle is released, several tasks exist in the facility at various departments. The decision then is to determine a priority assignment procedure to the candidate departments and dispatching (assigning) the released vehicle to the department with the highest priority.

In this study, the first class of problems will be known as 'Workcenter Initiated Task Assignment (Dispatching) problems' while the resulting rules to resolve them will be addressed as 'Workcenter Initiated Task Assignment (Dispatching) rules.' The second class of problems will be addressed as 'Vehicle Initiated Task Assignment (Dispatching) problems.' The corresponding methods for problem resolution will be identified as 'Vehicle Initiated Task Assignment (Dispatching) rules.' Both categories of rules constitute the vehicle task assignment (dispatching) rules as further presented in the subsequent sections.

6.2 WORKCENTER INITIATED TASK ASSIGNMENT PROBLEMS

In a typical manufacturing environment employing AGVs, a workcenter can be represented as in Figure 6.1. It consists of one or more machines, an incoming unit load queue, and an outgoing unit load queue. These queues are generally capacitated. In front of the incoming and outgoing queues are load stands that facilitate the transfer (delivery and pickup) of unit loads from or to the vehicles. Depending on the part processing rate of a department, unit loads are drawn from the incoming queue, processed, and deposited in the outgoing queue at some rate. The deposition of a unit load in the outgoing queue also corresponds to the initiation of a request for an unassigned vehicle for the immediate removal of the load just deposited. Several heuristic rules as outlined below and presented subsequently are available for selecting an unassigned vehicle from a set of candidate vehicles.

a) Random Vehicle (RV) Rule
b) Nearest Vehicle (NV) Rule
c) Farthest Vehicle (FV) Rule (antithetical rule)
d) Longest Idle Vehicle (LIV) Rule.
e) Least Utilized Vehicle (LUV) Rule.

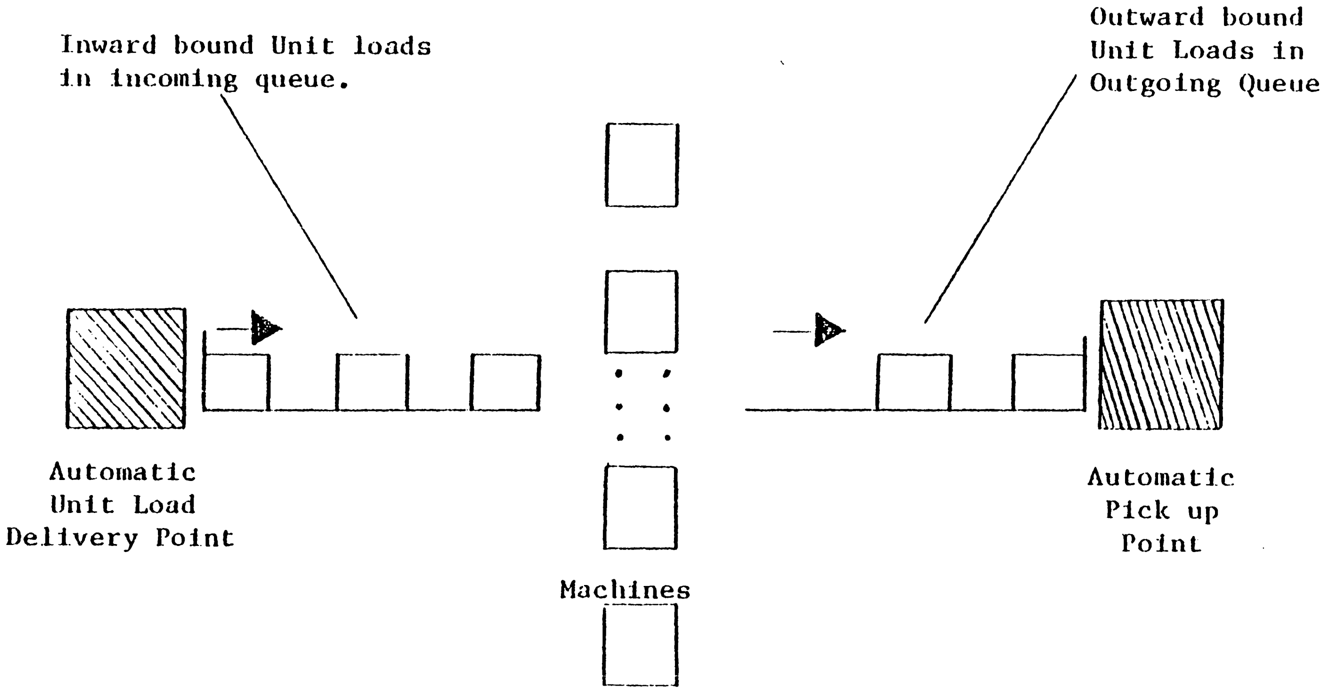


Figure 6.1 Schematic Representation of a Workcenter

6.2.1 Random Vehicle (RV) Rule

The random vehicle assignment rule is essentially based on the assumption that every unassigned vehicle is equally desirable to be assigned any mission irrespective of the physical distance between the vehicle and the point where the vehicle is needed and also without regard to the history of the activities of the vehicle. Therefore, if n idle vehicles exist at the time an assignment decision is to be made, the

$$\Pr(\text{of dispatching vehicle } i) = P_i = 1/n$$

where vehicle i is currently idle, and Pr = nomenclature for probability. The advantage of this rule is its simplicity for implementation. It requires very minimal computational effort, and perhaps, a mere table lookup. On the other hand, the rule could result in ineffective utilization of vehicles in the sense that the proportion of time vehicles may be traveling unloaded (empty) could be very high since no consideration is given to vehicle location at the time of assignment. If the percentage of the time vehicles travel empty is high, actual conveying time is affected. Thus, the rate of transitions between workstations by unit loads is reduced.

6.2.2 Nearest Vehicle (NV) Rule

This rule requires that at the time of request for a vehicle by a workcenter, the physical location of every unassigned vehicle be determined. Given the location of the workcenter from which the request is initiated, the distance of every unassigned vehicle from the workcenter along the shortest path is computed. Mathematically, this is equivalent to computing

$$d_i = d_{\alpha_i}\phi + \sum_{k=1}^{J-1} d(n_k, n_{k+1})$$

where

d_i =distance of vehicle i from workcenter along the shortest path.

$$\phi = \begin{cases} 1, & \text{if vehicle i is between two nodes} \\ 0, & \text{otherwise.} \end{cases}$$

d_{α_i} =distance of vehicle to the next immediate node along its path.

$d_{\alpha_1} = 0$ if $\phi = 0$.

J = number of nodes along the shortest path from current vehicle location to the point where vehicle is needed.

$d(n_k, n_{k+1})$= distance between the adjacent nodes n_k and n_{k+1} such that n_k precedes n_{k+1}.

Dispatch vehicle i to the calling workstation such that

$$d_i/s_i = d^*/s^* = \min_{\forall k}\{d_k/s_k\}$$

where s_i =traveling speed of idle vehicle i.

The ratio d_k/s_k is an estimate of the expected traveling time for vehicle k to arrive at the calling workstation if it (vehicle) is dispatched. The assumption underlying this rule is that the shortest travel distance also results in the shortest travel time. This is not generally true in traffic congested networks.

The implication of this rule is that the elapsed time between the time a request is placed for a vehicle and the time a vehicle actually arrives at the calling station is reduced. Improved vehicle response time can be translated to prompt removal and delivery of unit loads from one workcenter to another. This suggests that the average outgoing queue length at workcenters will be lowered and unit load transition rate improved. The disadvantage of the rule, however, is that it requires a tremendous amount of computation. The computational task is increased as the vehicle fleet size increases.

6.2.3 Farthest Vehicle (FV) Rule (antithetical rule)

This rule operates quite opposite to the NV rule. Instead of dispatching the vehicle i that has the minimum travel time as computed in section 6.2.2, it dispatches the vehicle j with the maximum travel time. This is equivalent to dispatching vehicle j such that

$$d_j/s_j = d^*/s^* = \max_{\forall k} \{d_k/s_k\}$$

where the previous definitions for d_k , s_k and k hold.

In terms of implementation of an AGV system, this rule may not offer any usefulness. It has all the drawbacks associated with NV rule. In addition, it maximizes the percentage of time vehicles travel unloaded in responding to requests and in so doing reduces the rate of unit load transition between workcenters. The only advantage to this rule is that it provides the system designer the information on how badly travel distance does affect the performance of a shop with respect to unit load transitions and completions. Consequently, job flow times will increase.

6.2.4 Longest Idle Vehicle (LIV) Rule

This rule is based on the time a vehicle currently unassigned was last released from an assignment. The basis of this rule is the sequential assignment of tasks to idle vehicles in the order by which they were released from their previously recorded missions. The rule operates as follows: For each vehicle k not immediately re-assigned after completing a task, the time the task was completed was marked. Let this time be denoted as T_k for idle vehicle k.

Let T_c = time when a vehicle request is placed by a workcenter.

$T_c \geq T_k$ for all k. For each vehicle not yet assigned, compute the length of idle time t_k where

$$t_k = T_c - T_k$$

The decision rule is to dispatch vehicle i to the requesting workstation such that

$$t_i = t^* = \max_{\forall k}\{t_k\}$$

The advantage of this rule is its simplicity for implementation and its load balancing effect among the vehicles. Its weakness, however, like some of the other rules already discussed, is that it does not take vehicle travel distance into consideration.

6.2.5 Least Utilized Vehicle (LUV) Rule.

Like the Longest Idle Vehicle rule, LUV acts as a workload balancer among the vehicles. Unlike the other rules, LUV requires that a proper account be kept on the utilization of each vehicle in the shop. The rule functions as follows. At the time a vehicle assignment decision is to be made, the mean utilization, U_k, of every unassigned or idle vehicle k is determined. U_k is a time persistent variable that is continuously being updated as the status of the vehicle changes from busy to idle and vice versa. The dispatching decision is to dispatch vehicle i such that

$$U_i = U^* = \min_{\forall k} \{U_k\}$$

The advantage of this rule is its ease of implementation since statistics on vehicle utilization is readily available in most systems as part of the regular periodic reporting procedure. The weaknesses are similar to those of Longest Idle Time rule presented in the last section.

6.3 VEHICLE INITIATED TASK ASSIGNMENT PROBLEMS

A typical batch manufacturing facility consists of several workcenters, each generating unit loads into the outgoing queue of the center as illustrated in Figure 6.1. From the operational point of view, the most desirable level of handling effectiveness is that which ensures that unit loads which are completed at a workcenter are removed promptly and transported to their subsequent destinations with minimum amount of delay times in the queue. Actual operating conditions do, however, deviate from this scenario in varying degrees. The degree of deviation is a function of the number of vehicles in the system, shop loading, size of the shop and the layout of the guidance network. Operating conditions do arise when requests for vehicle(s) from workcenters cannot be immediately satisfied (i.e. request is uneventful). This is the case when all vehicles are engaged in missions. Such uneventful calls are therefore logged and considered for satisfaction when any of the unavailable vehicles is released. The procedures by which the workcenters are dynamically prioritized for service by the released vehicle(s) is the item of presentation in this subsection.

Like the workcenter initiated task assignment problem, several heuristic rules are available for ranking workcenters requesting for unassigned vehicle(s). Common rules are as follows:

a) Random Workcenter (RW) rule.

b) Shortest Travel Time/Distance (STT/D) rule.

c) Longest Travel Time/Distance (LTT/D) rule (antithetical rule)

d) Maximum Outgoing Queue Size (MOQS) rule

e) Minimum Remaining Outgoing Queue Space (MROQS) rule

f) Modified First Come-First Serve (MFCFS) rule

g) Unit Load Shop Arrival Time (ULSAT) rule.

6.3.1 Random Workcenter (RW) Rule

The random workcenter rule is simple to implement as it requires very minimal amount of information about the shop condition in making any vehicle assignment decision. All that is required at the time of assignment is a list of all workcenters having at least one unit load in the outgoing queue that is not yet assigned to a vehicle. From this list, a workcenter is randomly selected.

The implications of this rule are obvious. It does not recognize workcenters running out of queue space for the deposition of newly processed unit loads, nor does it take into consideration the length of time a particular unit load has been waiting in the queue. Also not considered is the traveling distance required by the vehicle in getting to the selected workcenter. With respect to the workcenters themselves, the rule is only fair if the volume of unit load flow through each department is well balanced with respect to the other departments.

6.3.2 Shortest Travel Time/Distance (STT/D) Rule

This rule is based on the minimization of time that vehicles travel empty (unloaded). Vehicles completing missions are generally released at unit load delivery locations or at incoming unit load queue areas. On the release of a vehicle, all workcenters with unit load(s) in the outgoing queue are identified. The workcenter whose unit load pickup point is the nearest to the released vehicle along the direction of traffic flow is assigned the vehicle.

Alternatively, instead of using the shortest distance criterion above, an equivalent criterion is the shortest travel time. The shortest travel route in terms of distance measure is not necessarily the shortest travel time route. Interferences between vehicles along the shortest distance route may cause actual vehicle travel time to deviate significantly from the expected time. It is an approximation to equate the shortest distance route to the shortest travel time route because of the inability to predict future events with certainty. The approximation methodology is implemented in this study.

While this might improve the times released vehicles get to their points of assignments, it is biased against those workcenters whose unit load pickup points will only rarely qualify as the nearest to any vehicle released point when compared to the pickup point of other competing workcenters. The effect of this is that the rate of unit load removal from some workcenters will be low; thus, congesting the workcenters and perhaps blocking machines because of limited outgoing queue capacity. The unit load pickup point of a workcenter may not necessarily be the nearest to the unit load delivery (vehicle release) point of that workcenter. The determination of the optimal location of unit load delivery and pickup points with respect to the direction of traffic flow in the guidance network is a facility layout problem. Another weakness of this rule is the amount of computational effort that is involved.

6.3.3 Longest Travel Time/Distance (LTT/D) Rule

This is an antithetical rule to the STT/D rule. The workcenter whose pickup point is the most remote with respect to the location of the released vehicle along the direction of traffic flow is assigned the higest priority. There is no foreseable benefit in applying this rule other than for experimentation purposes. It has all the weaknesses associated with the STT/D rule and without any offsetting advantages.

6.3.4 Maximum Outgoing Queue Size (MOQS) Rule

At the time of a vehicle release, all workcenters requiring vehicle assignments are identified and the number of unit loads awaiting vehicle pickup assignments in their respective queues are noted. The workcenter whose outbound queue has the largest number of unit loads not yet matched to a vehicle is assigned the released vehicle. Notationally, this can be represented as follows.

Let q_k = number of unassigned unit loads residing in outgoing queue at workcenter k, $q_k \geq 1$.

The decision rule is to dispatch the released vehicle to workcenter i such that the following condition holds.

$$q_i = q^* = \max \{q_k\} \text{ for all } k \text{ whose } q_k \geq 1$$

Note that if $q_k = 0$ for all k, there is no outstanding pickup mission in the facility that is not yet matched to a vehicle. This is the case when a vehicle is set idle after completing an assignment.

The only recognizable advantage to this rule is its ease for implementation. Also, if the capacities of all outgoing queues in the facility are equal and the load levels among the various workcenters are well balanced, this rule could be a fair one. No workcenter can dominate any other workcenters and the rate at which vehicles are assigned to the departments will be determined mostly by the unit load processing rates of the individual departments. On the other hand, if queue capacities are not all identical and workload levels are also not balanced among the departments, decisions based on queue size alone has the potential to create serious bottleneck problem. Queue sizes in the highly constrained queues are inhibited to grow; thus reducing (inhibiting) their ability to compete with the less capacitated queues that can can grow over a wider range of lengths. Another disadvantage of this rule is its lack of consideration for the distance an empty vehicle has to travel in getting to its destination.

6.3.5 Minimum Remaining Outgoing Queue Space (MROQS) Rule

The essence of this rule is to assign higher priorities to those workcenters whose remaining (unfilled) outgoing queue positions are approaching faster to zero (i.e. queue size is approaching queue capacity). The rule operates as follows.

Each time a vehicle is released, all workcenters having unassigned unit loads for pickup from the outgoing queue are identified and their criticality index computed acording to the form below.

Let Q_k = capacity of outgoing queue at workcenter k.
S_k = current length of the outgoing queue at center k.
R_k = number of unit loads in outgoing queue of center k not yet assigned any vehicle.

For each center k ($R \geq 1$), compute the criticality index, C_k, such that

$$C_k = Q_k - S_k$$

The decision rule is to dispatch vehicle to center i such that the equation below holds.

$$C_i = C^* = \min_{\forall k,\ R_k \geq 1} \{C_k\}$$

The advantages of this rule are obvious. It reduces the possibility of any workcenter being blocked. Even if blocking does occur, the length of time the blocking persists at any affected workcenter will be small. Furthermore, the rule recognizes the dynamic behavior of the queues. On the other hand, the weakness of the rule is that the effect of empty vehicle travel distance on the utilization of vehicles is not considered. Thus, the percentage of actual vehicle conveying time is bound to be low. In essence, the rule provides a tradeoff between improved utilization of machines at workcenters because of reduced chances of blocking and reduced vehicle utilization because of excessive empty vehicle travel distance.

6.3.6 Modified First Come-First Serve (MFCFS) Rule

This rule is essentially a modification of the traditional First Come-First Serve rule. The underlying basic principle is the assignment of vehicles to departments sequentially in chronological order of time that requests for vehicles are received from departments. When a department places a call (request) for an idle vehicle and the call cannot be immediatele satisfied, the time the call was generated is saved for the department. The saved call and time are used for future vehicle assignment decisions. If subsequent calls emanate from a department before an earlier saved call is satisfied, the times of occurences of the subsequent calls are not saved. In other words, no department can have two or more outstanding unsatisfied saved calls simultaneously. When a vehicle becomes available, it is assigned to the department that has the earliest outstanding saved call and time. At the moment a saved call from a department is satisfied (i.e. a vehicle is dispatched to the department), the vehicle needs of such department is updated in one of two ways:

a) a zero outstanding call is recorded for the affected department if it needs exactly one vehicle. The number of vehicles a department needs at any time is equal to the number of unit loads awaiting vehicle assignment for pickup from the department.

b) if more than one vehicle is required at the department, a new call is saved immediately against the department and the corresponding time associated with the new call is set equal to the time the old saved call was satisfied.

Although this rule does not consider any impending blockages of departments due to imminent exhaustion of queue space, it does, however, ensure that the interval between the time a request is placed by a department and the satisfaction of that request is reduced. The number of vehicle aasignments made to a department is related to the unit load traffic intensity in that department. The rule regulates the flow of unit loads out of a department. Of course, the rule is weak with regard to the minimization of empty vehicle travel time as pointed out for earlier rules.

6.3.7 Unit Load Shop Arrival Time (ULSAT) Rule

This rule recognizes the time each unit load within the system enters the shop. At the time of release of a vehicle from an assignment, the number of unit loads, R_k, in the outgoing queue of department k that is not yet assigned to a vehicle is determined. For each department whose $R_k \geq 1$, the time of arrival into the shop of the unit load at the head of the queue among the R_k yet unassigned unit loads is determined. Let this time be denoted as T_k for department k. Also, let T_c be the current time or the decision time when vehicle assignment decision is to be made. Dispatch vehicle to department i such that

$$t_i = t^* = \max\{T_c - T_k\} \text{ for all } k,\ R_k \geq 1$$

Alternatively, the dispatching decision can be made mainly on the basis of T_k. In that case, vehicle is dispatched to workcenter i where

$$T_i = T^* = \min_{\forall k,\ R_k \geq 1} \{T_k\}$$

The disadvantages of this rule are similar to those of the other rules discussed earlier. It does not recognize critical queue conditions, distances, and unit load traffic intensity in the departments.

6.4 CONCLUSION

Several policies for managing the assignment of released (unassigned) vehicles in an Automatic Guided Vehicle System as well as the implications of each policy have been presented. The material provides a basis for selecting the appropriate combination of vehicle assignment policies, each from the two categories of rules discussed. Automated material handling systems require skillful management control strategies that provide the environment for the realization of the potentials of automation. The problem of vehicle assignment as presented here is not unique to automated manufacturing systems, it also appears in several sectors of production such as mining and physical distribution [14,37,79].

CHAPTER 7

THE SIMULATOR

7.1 INTRODUCTION

The submodels presented in chapters 5 and 6 were integrated and implemented via a computer simulation program. Although not all aspects of an AGV based system were captured and explicitly addressed in these models, several of these factors were, however, incorporated into the simulator. These factors include the following:

a) periodic battery recharge of run down vehicles in the shop.

b) blocking of machines at workcenters when the capacity of the outgoing unit load queue is exhausted.

c) the possibility of parking unused (idle) vehicles at some points in the guidance network or circulation in some circulatory loop.

d) the possibility of vehicles bypassing their destinations when traffic or production conditions make it necessary to do so.

The FORTRAN based simulation program is composed of several subroutines which were modularly developed to reflect the multi-component nature of the system modeled. The simulator provided the laboratory environment under which the experiments presented in the subsequent chapters of this manuscript were conducted. Detailed description of the simulator, including the requirements for user applications are provided in Appendices A, B, and C of this manuscript and in [32]. Appendices A and B contain the program flowchart and the User's guide to the simulator. Appendix C describes the structure of the simulator and how Users can construct their own functions to interface with the main body of the simulator. The referenced Technical Report [32] also contains the program listing of the simulator. A brief description of the functions of the various computer subroutines that compose the simulator follow. In Appendix B, the simulator is simply addressed as Routine B to distinquish it from Routine A which is a data preparation program for the simulator. Figures 7.1 and 7.2 give an overview on how the subroutines of the simulator are linked. A more detailed representation is as given in Appendix A.

ROUTINE NAME	FUNCTION OF ROUTINE
1. MAIN	Reads all input data to the simulator describing the shop environment, invokes appropriate routines for system initialization and sets the drive mechanism that allow the system to function as a unit.
2 INTLC	Sets up initial conditions for the simulator.

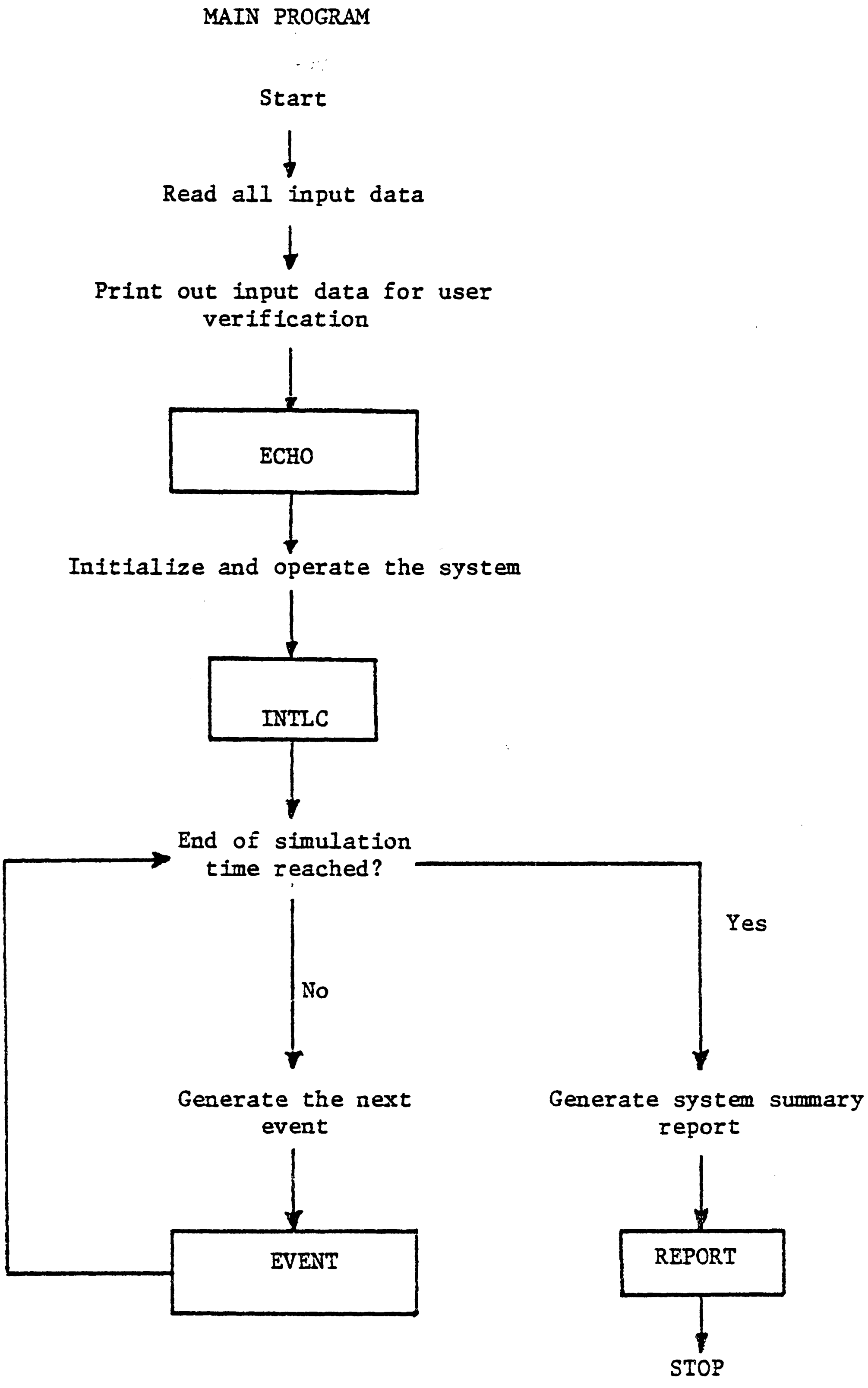


Figure 7.1: Simulator Architecture: Main Program

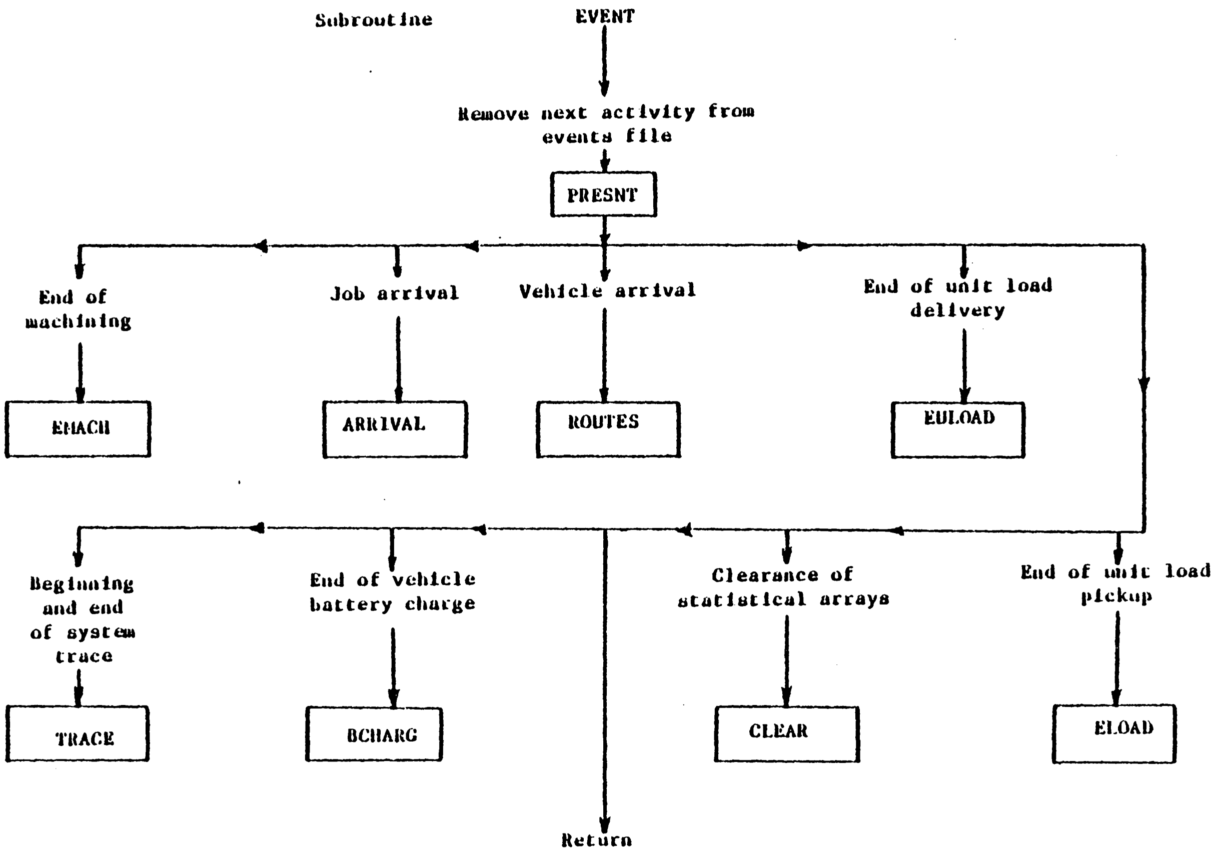


Figure 7.2: Simulator Architecture: The Event Routine

3.	EVENT	Brain of the simulator. It transfers controls to appropriate sections of the simulator, setting up the linkage mechanism that integrate the whole system as a functioning unit.
4.	ARIVAL	Receives all arriving jobs into the shop. The arrival of one job triggers the arrival of the next subsequent job.
5.	ASSIGN	Models the unit load assignment process.
6.	DCKQUE	Models activities at the shop entry dock.
7.	BLOAD	Performs activities marking the beginning of a unit load pickup operation.
8.	ELOAD	Performs activities marking the end of a unit load pickup operation.
9.	BMACH	Initiates activities marking the start of a unit load machining operation.
10.	EMACH	Performs transactions marking the end of a unit load machining operation.
11.	UNLOAD	Models the initiation of activities marking the beginning of a unit load delivery function.

12. EULOAD	Models activities marking the end of a unit load delivery operation.
13. UPDATE	A supporting routine for subroutine EULOAD.
14. BPARK	Selects a parking area or circulatory loop to route a released vehicle not immediately re-assigned.
15. EPARK	Regenerates the circulatory loops for vehicles circulating in loops. It also performs end of vehicle parking duties for vehicles routed to a parking area.
16. ROUTES	Master controller for vehicles traveling in the network. It directs vehicles to perform required maneuvers at appropriate places and time.
17. AHEAD	A supporting routine for subroutine ROUTES. It activates the portion of the simulator responsible for intersection control algorithms. It also transfers control to the portion of the system that models the energizing of the guide path.
18. RESOLV	Provides information about traffic condition around intersections. The information is passed on to the intersection control measure in force to make vehicle routing decisions at intersections.

19. CROSS1	Models intersection control rule type one.
20. CROSS2	Models intersection control rule type two.
21. CROSS3	Models intersection control rule type three.
22. REFILE	Supporting routine for CROSS1, CROSS2, and CROSS3.
23. CROSS4	Models intersection control rule type four.
24. ADVANS	Models the actual energizing of the guide wire system and the advancement of vehicles along the guide path.
25. CALLED	Models the workcenter initiated task assignment (dispatching) rules.
26. DSPACH	A supporting routine for subroutine CALLED. Here the appropriate task assignment rule in force is invoked each time a vehicle dispatching decision is to be made.
27. SORT	A sorting routine that provides support for the subroutine DSPACH.
28. STORAG	Models unit load completion/departure from the shop. It represents the final storage area of the shop. Necessary processes marking the completion of a unit load or batch are performed.

29. SELECT	Models the vehicle initiated task assignment (dispatching) rules.
30. SEEK	Seeks the shortest path between any pair of points in the network. This path is then communicated to the vehicle involved.
31. GIVE	A supporting routine for the subroutine UPDATE. It is used for updating vehicle status as their assignments change.
32. SLOW	Decelerates or puts on hold other vehicle approaching to occupy a pickup/delivery point when the said point is being occupied by another vehicle at the very instance.
33. BLOCK DATA	Initializes storage arrays and other systems variables at program compile time
34. QTITY	Generates number of parts (batch size) in batch job that arrive into the shop.
35. FILEM	One of two major subroutines that form the core of the filing system. It places entities in files and in proper sequence.
36. RMOVE	Also one of the two subroutines that form the core of the filing system. It removes the entities placed in file by subroutine FILEM.

37. SETTER	A support routine for RMOVE and FILEM. It is an integral part of the filing system and it is responsible for initially setting pointers to the storage locations in array AKEEP where all file entities reside.
38. COPY	A service routine for the filing system. It makes available to the system attributes of entities in files and it does so without pulling them from the file.
39. NNQ	It returns the number of entities in any file to the system whenever such information is needed.
40. SCHDL	Schedules future events in the events file through subroutine FILEM. Events are then ordered in their proper sequence of time to occur.
41. PRESNT	Invokes events in the events file to occur at their proper sequence of time. It uses RMOVE as an intermediary in the process.
42. COLCT	Collects statistics for variables based on observations e.g. flow time, waiting time.
43. TIMST	Collects statistics for time persistent variables e.g. queue length, equipment utilization.

44. BYPASS	A support routine for routing vehicles through the network. It allows vehicles to bypass their destinations if the entrance to the point is blocked.
45. TRACE	Initiates and terminates system trace activities.
46. CLEAR	Clears and re-initializes system statistical arrays if statistics collection is to resume at any other time other than time zero.
47. HOLD	Places blocked machines on hold when the outgoing unit load queue is full and there is no more room to release completed unit loads.
48. FREE	Releases blocked machines from hold when a queue space is created in the outgoing unit load queue.
49. BCHARG	Sets up conditions marking the beginning of a vehicle battery recharge operation.
50. ECHARG	Performs activities marking the end of a vehicle battery recharging function.
51. REPAIR	Updates the attributes of vehicles due for battery recharg.

52. ECHO	Prints out some of the data read in the main (i.e. MAIN) program. This is solely for the purpose of data verification by system users.
53. REPORT	Generates system reports at the end simulation It is an end of simulation processor.
54. SERVIC	Generator of service time for unit loads.
55. NORMAL	Generates normally distributed deviates.
56. UNFRM	Generates uniformly distributed deviates.
57. EXPON	Generates exponentially distributed deviate.
58. DRAND	Generates uniformly distributed random numbers between zero and one (0,1) via the IMSL routine GGUBS. GGUBS is the only external routine to the simulator.
59. ERROR1	An error routine generally invoked by the system whenever a fatal abnormal condition is observed or encountered anywhere in the system.
60. WCTASK	A dummy routine. In the event that a user runs the simulator without the user supplied subprogram in the name 'WCTASK' (see Appendix C), the dummy routine WCTASK automatically fills the gap.

61. VCTASK	VCTASK is also a dummy routine defined in the same manner as WCTASK (also see Appendix C).
62. XEROX	XEROX copies the attributes of entities that reside in files. Its function is identically similar to that of the subroutine COPY. The only exception is that XEROX is never invoked internally by the simulator. It is merely a service routine intended to provide users the tool to copy the attributes of files entities with minimum difficulty as presented in Appendix C.
63. UTIL	Like XEROX, unless invoked by users through the user supplied subprograms WCTASK and VCTASK, UTIL is never invoked internally by the simulator. UTIL provides the user the tool to retrieve statistics on equipment utilization should such information be required for vehicle dispatching decisions as discussed in Appendix C.

CHAPTER 8

ILLUSTRATION OF PROCEDURES FOR EVALUATING AGV SYSTEM CONTROL STRATEGIES

8.1 INTRODUCTION

An integral part of any design problem is the evaluation of the effectiveness of alternative control strategies for operating the system. In the realm of AGV system design, the control strategies include all the system operational rules.

Four cases of AGV system operations, namely, a) vehicle task assignment (dispatching) rules, b) unit load selection rules, c) unit load sequencing rules at workcenters, and d) network control rules are the primary focus of the discussion to follow. The materials presented in this chapter through 11 are intended to accomplish two objectives.

a) To demonstrate how the effectiveness of an AGV based material handling system can be affected by both the choice of operating policies and by the technological and resource constraints in the shop.

b) To illustrate the application of systematic statistical procedures for ranking and selecting operating rules that are alternatives to accomplishing similar tasks. The inferences drawn from these statistical analyses are generally based on small data sample size. As a result, the conclusions drawn should be considered as suggestive only.

Building on these objectives, the framework for the rest of the materials presented in this and subsequent chapters are both evaluational and statistical in nature.

8.2 CHARACTERIZATION OF A SHOP UNDER VEHICLE DISPATCHING RULES

The modeling and importance of vehicle dispatching rules in an AGV-based material handling system was presented in chapter 6 under two subclasses, namely, a) Vehicle Initiated Task Assignment (Dispatching) rules and b) Workcenter Initiated Task Assignment (Dispatching) rules. To operate a flexible AGV system, rule combinations from these subclases is required to assign vehicles to workcenters and vice versa for unit load pickup activities. Thirty simulation experiments were conducted on fifteen rule combinations to evaluate their effects on shop performance. The following rules categorized by rule subclass, were included in the experiments.

a) Vehicle Initiated Task Assignment Rules

i) maximum outgoing queue size (MOQS)
ii) shortest travel time/distance (STT/D)
iii) longest travel time/distance (LTT/D)
iv) minimum remaining outgoing queue space (MROQS)
v) modified first come-first serve (MFCFS)

b) Workcenter Initiated Task Assignment Rules

i) nearest vehicle (NV)
ii) farthest vehicle (FV)
iii) longest idle vehicle (LIV)

The shop environment where these rules were applied has the following characteristics:

i) a job shop with thirteen departments. Ten different job classes are processed in the shop.
ii) multiple identical machines per department.
iii) six automatic guided vehicles.
iv) capacitated input and output queues in each department with the exception of the input queue of the first (receiving)

department and both queues of the last (finished goods) departments.

Figure 8.1 shows the layout of the facility described.

With respect to the choice of a performance measure to evaluate the effectiveness of a shop for any dispatching rule combinations, several criteria could be employed. Possible measures include:

a) Mean Outgoing Unit Load Queue Size. Long waiting queues imply unit loads were not removed as promptly as they should. This is a measure of how well a dispatching rule responds to departmental needs.

b) Mean Job Flow Time. Total times jobs spend in the shop can be segregated into four components, namely, waiting time in incoming unit load queues, processing time, waiting time in outgoing unit load queues, and transit time. The larger the third component, the less desirable the rule becomes.

c) Mean Number of Jobs in the Shop. The lower this value becomes, the more attractive the rule is. A good rule should accelerate the flow of jobs through the shop.

d) Total Unit Load Throughput. This is a derivative of criterion (c) above. The higher this value is, the better the system.

e) Equipment Utilization. Higher utilization of machining center would be desirable.

f) Vehicle Interference Level. A rule that results in frequent conflicts between vehicles will obviously be considered undesirable.

These measures can be integrated into a single performance indicator by assigning appropriate weight to each criterion. Alternatively, they can be employed singly to characterize a system. In this study, total unit load throughput is chosen as the primary measure of system performance. This criterion represents the main objective of a production sys-

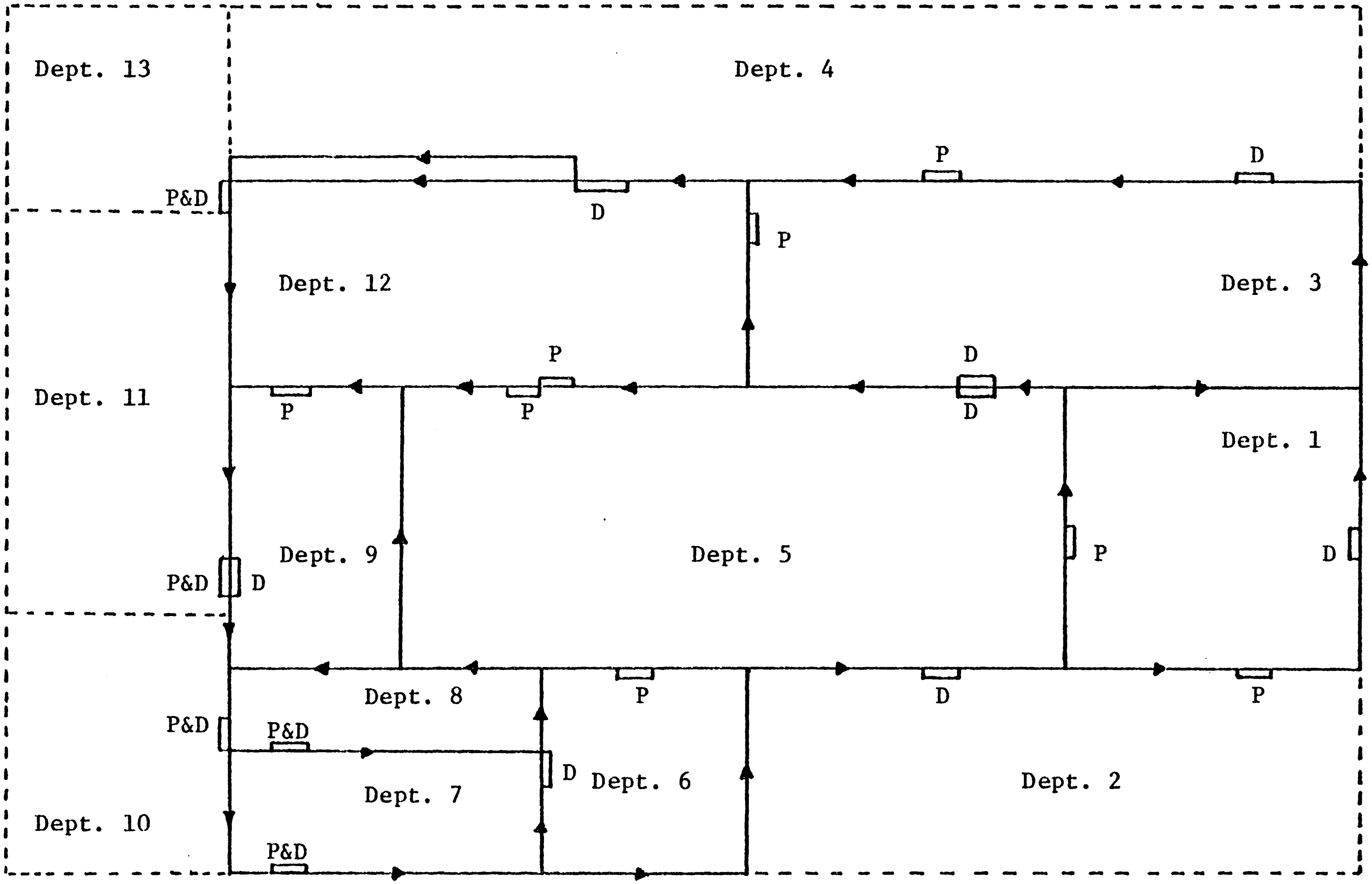


Figure 8.1: Network Layout of Demonstrative Facility.

D = delivery station; P = pickup station.

——▶—— AGVS Guide Path and Dept. Boundaries.

- - - - - - Dept. Boundaries Only.

tem. The optimization of any of the other measures mentioned above is considered local since they are themselves not the end objective of a shop but a means to the end. However, references will be made to the responses of some of these measures with respect to vehicle dispatching rules where appropriate. The use of these measures as secondary criteria is attractive to better characterize the shop behavior to changing operating rules.

Table 8.1 summarizes the results obtained under the thirty simulation runs cited earlier. The number of astericks in a cell indicates the number of times that rule combination resulted in a locking of the shop under two simulation trials. A shop is considered 'locked' if the following conditions hold:

a) the input and output queues are simultaneously full at some or all the departments and the machines in the affected departments are blocked,

b) all vehicles transporting unit loads cannot make their deliveries because the input queues are full and there are no available vehicles to remove loads from the output queues, and

c) all empty vehicles dispatched for load pickup cannot get to their destinations due to interference from other vehicles.

When a shop locks, the entire system remains at a stalemate; thus causing all seizures of material flow and parts completions.

As Table 8.1 shows, all the first nine rule combinations resulted in locking. From the actual throughput statistics, there is a strong reason to believe that locking took place at fairly early stages of the simu-

Table 8.1: Shop Throughput Measured in Unit Loads (* locking encountered by the shop).

Nomenclature:

MOQS = maximum outgoing queue size
STT/D = shortest travel time/distance
LTT/D = longest travel time/distance
MROQS = minimum remaining outgoing queue space

MFCFS = modified first come - first serve
NV = nearest vehicle
FV = farthest vehicle
LIV = longest idle vehicle

		VEHICLE INITIATED TASK ASSIGNMENT RULES				
		MOQS	STT/D	LTT/D	MROQS	MFCFS
WORKCENTER INITIATED TASK ASSIGNMENT RULES	NV	*	*	*	766	775
		*	*	*	763	770
	FV	*	*	*	765	767
		*	*	*	770	777
	LIV	*	*	*	766	775
		*	*	*	763	770

lation. The actual throughput for the locked cases ranged from one to 108 unit loads as compared to over 700 for all rule combinations that involved MROQS and MFCFS rules.

8.2.1 Explanation of The Shop Locking Phenomenon

A fair statement with respect to those rule combinations that involve MOQS, STT/D, and LTT/D is that they are very prone to producing machine blockings at various departments. This blocking effect eventually propagates to the vehicles to produce a total system deadlock.

Generally, vehicles on assigned missions are released at unit load delivery points the moment a delivery task is completed. Thereafter, a Vehicle Initiated Task Assignment rule is invoked and another workcenter is selected to be served by the vehicle. If no workcenter is selected due to lack of unit loads in outgoing queues, the released vehicle is set idle and can be re-assigned only by invoking a Workcenter Initiated Task Assignment rule. The fact that Vehicle Initiated Task Assignment rules can be invoked only at specific locations in the facility suggests that those rules that are derivative of distance measures will be very sensitive to the layout of the facility and the location of pickup and delivery points. In particular, these rules are STT/D, LTT/D, NV, and FV. Unless the pickup/delivery points of all departments are well located with respect to one another, the effectiveness of these rules will always be impaired. If this layout condition is not met, some workcenter(s) will fail to receive vehicle assignments if based on STT/D or LTT/D even though they may continue to receive new deliveries of parts from other departments. Parts accumulate, eventually blocking machines at these workcenters and blocking any vehicles from making new deliveries. The performances of those rule combinations that involve MOQS, MROQS, and MFCFS are attributable to the postulates put forward in chapter 6 under them.

In practice, when a shop locks, some form of intervention is required to unlock it. The intervention can be manual or automatic. Common industrial practice is to dispatch a lift truck operator to dislodge the system. Depending on how vulnerable the system is to locking, the frequency of intervention required depends on the operating rules in force.

8.2.2 Operating An AGV System With Automatic Intervention

In a shop characterized by frequent locking, a procedure to reactivate the system when it fails has to be developed. Several methodologies can be devised to do so. The efficiency of each technique may be shop dependent. In this study, an automatic antilocking technique was developed and its contribution to improving the performance of the fifteen rule combinations evaluated. The methodology can be interpreted to be a lock preventive rather than a lock release mechanism.

The technique operates as follows. Each time a unit load delivery is to be made at a department, the input and the output queues of that department are interrogated. If both queues are full and there is no known vehicle enroute to remove a load from the output queue of that department, it is assumed that the department is blocked or at least approaching so. If this condition holds, the vehicle attempting to make the delivery is instead rerouted to a buffer queue area to make its delivery. Thereafter, it is dispatched empty to the blocked department for load removal to a second department. From the second department, the vehicle returns to the buffer queue, picks up its temporarily buffered item and subsequently delivers it to the department just unlocked; thus reactivating the department and completing the delivery cycle.

Applying the antilock mechanism to the fifteen rule combinations resulted in a significant improvement on system throughput for those rule combinations that involve MOQS, STT/D, and LTT/D. Rule combinations that involved MROQS and MFCFS showed no improvement. In fact, for the case demonstrated, intervention was not required by these two rules. Despite the large improvement shown by the rule combinations under MOQS, STT/D, and LTT/D, in actual throughput count, they still ranked lower than the outputs obtained under the rule combinations that involved MROQS and MFCFS. Whereas the system throughput ranged from 290 to 596 unit loads for rules involving MOQS, STT/D, and LTT/D, these values are lower compared to the throughput of 763 and above obtainable under the MROQS and MFCFS rules.

Table 8.2 shows the behavior of the buffer queue under the rule combinations. Table elements are maximum and average buffer queue length. Information of this type is useful for determining additional buffer space that may be required at different rule combinations if adopted as part of a shop operating policy.

8.2.3 System Performance Based On Infinite Queues

Operating rules notwithstanding, the blocking of machining centers are the direct results of capacitated queues. By relaxing the queue capacity constraints, the effect of locking will be removed and the potential of every rule combination can be realized. To explore this postulate, the shop was simulated under unconstrained (infinite) queue capacity. The shop throughput under the different rule combinations is shown in Table 8.3.

Looking at the table rowwise, the differences among the rules is not as pronounced as it appeared among the rules columnwise. All rule combinations that have elements of queue characteristics (i.e. MOQS and MROQS) performed poorer than all other rule combinations. Also all combinations that invove LTT/D performed poorly. STT/D and MFCFS outperformed all rules, with MFCFS exceling. The weakness of STT/D compared to MFCFS is that it is biased against certain departments due to the physical location of their pickup stations. Loads were never picked up from these departments. In essence, they (the departments) were transformed to sink nodes. No parts ever left these departments

Table 8.2: Maximum^{+} and Average* Buffer Queue Length Using System Antilock Mechanism.

Nomenclature:

MOQS = maximum outgoing queue size
STT/D = shortest travel time/distance
LTT/D = longest travel time/distance
MROQS = minimum remaining outgoing queue space
MFCFS = modified first come - first serve
NV = nearest vehicle
FV = farthest vehicle
LIV = longest idle vehicle

		VEHICLE INITIATED TASK ASSIGNMENT RULES				
		MOQS	STT/D	LTT/D	MROQS	MFCFS
WORKCENTER INITIATED TASK ASSIGNMENT RULES	NV	17^{+} 6.22*	5 1.06	9 1.31	0 0	0 0
	FV	15 5.80	6 1.04	8 1.26	0 0	0 0
	LIV	17 6.22	5 1.06	9 1.31	0 0	0 0

Table 8.3: Shop Unit Load Throughput at Infinite Queue Condition.

<u>Nomenclature:</u>

MOQS = maximum outgoing queue space
STT/D = shortest travel time/distance
LTT/D = longest travel time/distance
MROQS = minimum remaining outgoing queue space
MFCFS = modified first come - first serve
NV = nearest vehicle
FV = farthest vehicle
LIV = longest idle vehicle

		VEHICLE INITIATED TASK ASSIGNMENT RULES				
		MOQS	STT/D	LTT/D	MROQS	MFCFS
WORKCENTER INITIATED TASK ASSIGNMENT RULES	NV	348	669	431	346	764
	FV	334	664	434	350	758
	LIV	348	669	431	346	764

for subsequent departments. Excluding the queues in the receiving department, output queues under STT/D grew as high as 231 unit loads in some departments as against a maximum of 13 for MFCFS. This implies that enormously large buffer spaces may be required at some departments if STT/D is to become a viable rule. In essence, given the scarce manufacturing space that characterize most facilities, STT/D is an inoperable rule. For the shop tested, MFCFS regulated the number of parts that were removed from the receiving area to the shop floor. STT/D on the other hand was emptying the receiving area and dumping its elements on the shop floor.

8.2.4 Sequential Vehicle Dispatching Rule

A commonly applied vehicle dispatching strategy that has gained wide industrial acceptance is to service workcenters sequentially. The system operates as follows. Unassigned vehicles are pre-programmed to stop at every department in some sequence for load pickup. If at a department a unit load needs to be removed, the load is picked up by the stopping vehicle and conveyed to its (unit load) destination. On the delivery of the load, the released vehicle immediately resumes its sequential departmental visitation by calling at the pickup station of the department it just served (i.e. delivered a load). Thereafter, visit to the next department following the department just served may be made. If no load to be removed exists at a department visited, the vehicle immediately proceeds to the next department in the sequence and the process regenerates itself. Since the sequence forms a loop, vehicles continue to operate in the loop until interrupted by some external requirements such as calls for battery charge or maintenance.

Generally, attempts are made to locate all delivery and pickup points along a unidirectional traffic flow loop so as to minimize the distance between adjacent workcenters in the sequence. This is usually done during the system design phase. However, in complex systems or facilities with existing layouts, the sequence specification decision is a contrained optimization problem that resembles the classical traveling salesman problem. In practice, effort is made to select a good sequence without actually embarking on a rigorous optimization exercise.

The sequential vehicle assignment principle was tested in this study and the resulting shop performance compared to that obtained under the rule combinations LIV-MROQS and LIV-MFCFS. Given the facility layout of Figure 8.1, the departmental sequence below was tried.

1→4→13→11→10→8→6→2→12→5→9→7→3→1

Figure 8.2 shows the resulting loop from this sequence. It requires multiple passes in some aisles to complete the loop.

Two simulation runs were made to test this control strategy. The shop throughput in unit loads along with those obtained under LIV-MROQS and LIV-MFCFS rules are shown in Table 8.4. In both runs, the shop completed fewer number of unit loads under the sequen-

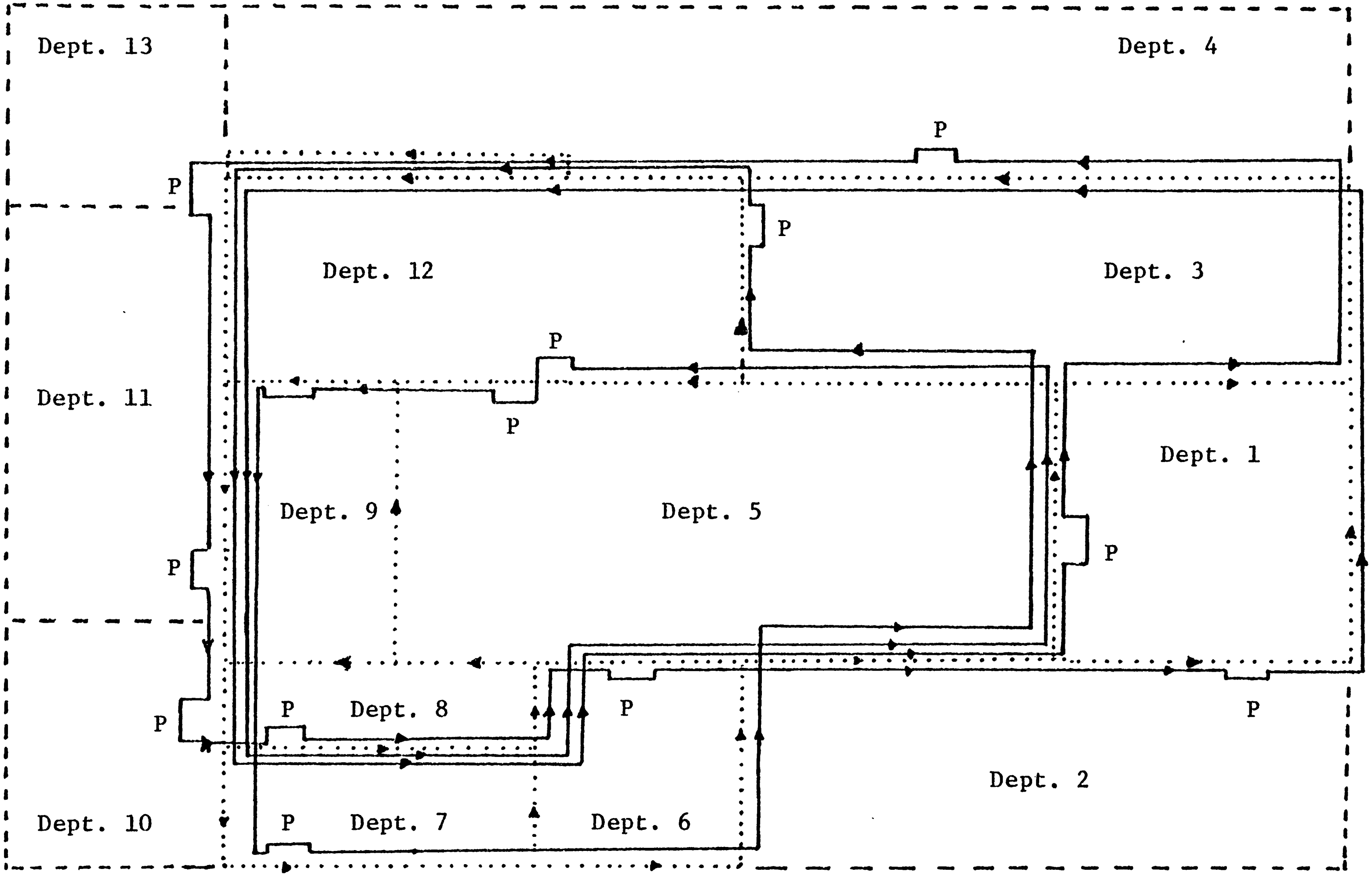


Figure 8.2: A Single Loop Vehicle Assignment System Based on Demonstrative Facility.

P = pickup; ——▶—— Assignment Loop.
· · · · ·▶· · · · · AGVS Guide Path and Dept. Boundaries
– – – – – – Dept. Boundaries Only.

Table 8.4: Unit Load Throughput Under Sequential and Nonsequential Dispatching Rules.

Nomenclature:

LIV = longest idle vehicle
MROQS = minimum remaining outgoing queue space
MFCFS = modified first come - first serve

RULE COMBINATIONS		SEQUENTIAL DISPATCHING
LIV-MROQS	LIV-MFCFS	
740	770	406
754	783	499

tial assignment rule than it did under the LIV-MROQS and LIV-MFCFS rule combinations.

Although the sequence tested is just one of many possible sequences, the weakness of the technique in this facility is apparent. Unnecessary visits are made to departments at times when some of them had no need for a vehicle. The time wasted on these visits could have been better spent to do productive work at other departments where there are definite needs for vehicles. Furthermore, the approach lacks the flexibility and versatility that proves AGVs to be viable handling equipment in job shop and warehousing environments. The rule does not recognize the special needs of some departments. For example, the receiving department with much higher unit load traffic deserves more vehicle visits than any other departments. Therefore, the actual number of unit loads admitted onto the shop floor is automatically constrained by the approximate number of round trip visits made by the vehicles. Finally, unproductive travel distances are involved unless remedied by adequate facility layout condition.

Sequential dispatching rule is, however, not without advantages. Vehicles are much easier to control. The system has built-in capacity to prevent machine blocking at departments. In fact, one of the major preoccupation of the strategy is to reduce the growth of outgoing queues in all departments as it can be operationally feasible.

8.3 DETERMINATION OF OPERATING LEVELS VIA STATISTICAL PROCEDURE

Steps for the design of an effective production system include:

a) Identification of those decision variables whose contributions significantly affect shop performance.

b) Determination of optimum control level of each variable to effectively operate the shop.

In system design through simulation, the solution to the above problem is achieved through systematic statistical analysis on the simulated output. The discussion thus far presented merely characterized the behavior of the shop under alternative operating conditions. Such characterization does not identify what may constitute a good operating rule for a shop, although from common sense, certain rules may be more favored.

Through an adoption of an experimental design, analysis of variance (ANOVA) procedure can be employed to identify significant operating factors. Thereafter, Duncan's Multiple Range test is applied to rank the levels within a factor. If there is no interaction between the factors, an operating level can be specified to correspond to the combination of the highest ranked level of each factor. If interaction is present, the application of response surface methodology is advised. Alternatively, each rule combination can be considered a factor of its own and the resulting design analyzed as a one-way analysis of variance procedure followed by Duncan's Multiple Range test or via one of the several statistical selection and ranking procedures. Statistical methods generally require large volumes of data before any sound and valid inferences on the factors can be made.

In this section, ANOVA procedure to determine the significance of vehicle dispatching rules on shop performance is demonstrated. Due to the high vulnerability of STT/D, LTT/D, and MOQS rules to system locking, only the MFCFS and MROQS rules from the subclass Vehicle Initiated rules will be included in the experiments to follow. The following hypotheses were tested in the analysis

a) vehicle initiated task assignment rules have no significant effect on the performance of a shop.

b) workcenter initiated task assignment rules have no significant effect on the performance of a shop.

c) if there is any interaction between vehicle initiated task assignment rules and workcenter initiated task assignment rules, the interaction effect is not significant.

A two-way 3X2 factorial experiment was implemented for the investigation.

8.4 ANALYSIS OF EXPERIMENTAL RESULT ON VEHICLE DISPATCHING RULES

Three replications per rule combination were made. Table 8.5a contains the simulation output in unit loads for 120 hours of simulation time. Other system secondary performance measures are shown in Tables 8.5b, 8.6a, and 8.6b. Elements of the Tables are 1) mean job (not unit loads) flow times, 2) mean outgoing queue length, and 3) mean number of jobs in the shop.

Table 8.5a: Unit Load Throughput for 3 x 2 Factorial Experiment.

<u>Nomenclature</u>:

MROQS = minimum remaining outgoing queue space
MFCFS = modified first come - first serve
NV = nearest vehicle
FV = farthest vehicle
LIV = longest idle vehicle

		VEHICLE INITIATED TASK ASSIGNMENT RULES	
		MROQS	MFCFS
WORKCENTER INITIATED TASK ASSIGNMENT RULES	NV	766	775
		763	770
		740	770
	FV	765	767
		770	777
		740	770
	LIV	766	775
		763	770
		740	770

Table 8.5b: Job Flow Times for 3 x 2 Factorial Experiment.

		VEHICLE INITIATED TASK ASSIGNMENT RULES	
		MROQS	MFCFS
WORKCENTER INITIATED TASK ASSIGNMENT RULES	NV	2317.57	2139.83
		2023.09	1788.01
		1900.83	1684.67
	FV	2334.45	2155.92
		2009.97	1803.36
		1900.83	1684.67
	LIV	2317.57	2139.83
		2023.09	1788.01
		1900.83	1684.67

Table 8.6a: Mean Outgoing Queue Length.

<u>Nomenclature</u>:

MROQS = minimum remaining outgoing queue space
MFCFS = modified first come - first serve
NV = nearest vehicle
FV = farthest vehicle
LIV = longest idle vehicle

		VEHICLE INITIATED TASK ASSIGNMENT RULES	
		MROQS	MFCFS
WORKCENTER INITIATED TASK ASSIGNMENT RULES	NV	12.42	8.54
		11.93	8.28
		11.89	8.09
	FV	12.44	8.53
		11.82	8.27
		11.89	8.09
	LIV	12.43	8.54
		11.93	8.28
		11.89	8.09

Table 8.6b: Mean Number of Jobs in the Shop.

		VEHICLE INITIATED TASK ASSIGNMENT RULES	
		MROQS	MFCFS
WORKCENTER INITIATED TASK ASSIGNMENT RULES	NV	73.69	69.18
		57.23	52.19
		56.37	51.07
	FV	73.77	69.91
		56.30	52.00
		56.37	51.07
	LIV	73.69	69.18
		57.23	52.19
		56.37	51.07

With an F-statistics of 3.16, 3 and 14 degrees of freedom, the ANOVA model was not significant at the 95% confidence level. Also not significant is the main effect due to Workcenter Initiated Task Assignment rules and the interaction effect. With an F-statistics of 9.42 , 1 and 14 degrees of freedom, the Vehicle Initiated Task Assignment rules were significant.

The Duncan's Multiple Range test showed that the two levels of Vehicle Initiated Task Assignment rules (i.e. MROQS and MFCFS) were significantly different at the 95% level of confidence.

The limitation of the above analysis should be well understood. It involves small data size. As a result, the inferences drawn should be viewed as suggestive rather than conclusive.

The result of the test can be explained as follows. In a busy shop under steady state condition, vehicles are rarely idle. As a result, most of the calls for vehicles generated by workcenters for load pickup are uneventful. Therefore, Workcenter Initiated Task Asignment rules are ineffective tools for dispatching idle vehicles. These rules (i.e. Workcenter Initiated) are generally employed during the early stages of the shop opening time to make the initial sets of task assignments to the vehicles. Thereafter, vehicles are re-assigned according to Vehicle Initiated Task Assignment rules. This explanation is supported by the fact that rules NV and LIV produced identical results despite the fact that they are based on completely different principles. They do, however, show different results when applied to situations where the handling task is light compared to available handling capacity. Under such conditions, the presence of idle vehicles become common; thus necessitating the frequent use of Workcenter Initiated rules to prioritize vehicles for assignment.

8.4.1 Secondary Measures of System Performance

A shop can be evaluated based on mean job flow time (shown in Table 8.5b), mean outgoing queue length (shown in Table 8.6a), and mean number of jobs in the shop shown in Table 8.6b. A cursory look at the data values in these tables indicate that the values are consistently better under MFCFS than it is under MROQS. These data can be analyzed statistically and inferences on system performance made based on them. However, it can be easily shown that the rule that results maximum mean system throughput will also excel if mean job criterion is used.

8.5 SENSITIVITY ANALYSIS

Analysis was also undertaken to investigate any behavioral changes that may result among the rules by varying one of several control parameters. Three nonsimultaneous parameter variations were introduced. The parameters of interest were vehicle speed, vehicle fleet size, and shop loading. Since the Workcenter Initiated rules were not significantly different from one another, the current analysis is focused mainly on MROQS and MFCFS rules.

8.5.1 Variation In Vehicle Speed

Keeping all other control variables unchanged, the effect of increased vehicle speed on system performance was investigated. Vehicle speed was increased from 120.0 feet per minute (fpm) to 180.00 fpm. Table 8.7a shows the unit load throughput under the six rule combinations. In Table 8.7b are the mean job (not unit loads) flow times for the jobs completed. Under both criteria, the shop performed better under MFCFS than it did under MROQS, although the mean performance difference may not be statistically significant. The higher vehicle speed resulted in higher system throughput.

8.5.2 Variation In Vehicle Fleet Size

Increasing the fleet size of vehicles in a shop has the potential of increasing both unit load throughput and the degree of interference between vehicles. Because of the differences on the principles underlying the rules, it is tempting to suggest that some rules will be more prone to vehicle interferences than others, thereby inhibiting their ability to perform effectively, especially at higher traffic densities.

To gain some insight on the response of the system at higher traffic density, the simulation was again run by increasing the number of vehicles in the shop from six to twelve. The resulting simulation output is shown in Table 8.8a (unit load throughput) and Table 8.8b (mean job flow time). For MFCFS, the mean throughput was 1409.67 as against 1408.33 for MROQS rule. There was barely no difference bet-

Table 8.7a: Unit Load Throughput at Increased Speed.

Table 8.7b: Job Flow Times at Increased Speed.

Key: * value before increased speed.

Nomenclature:

MROQS = minimum remaining outgoing queue space
MFCFS = modified first come - first serve

NV = nearest vehicle
FV = farthest vehicle
LIV = longest idle vehicle

Table 8.7a

WORKCENTER INITIATED TASK ASSIGNMENT RULES		VEHICLE INITIATED TASK ASSIGNMENT RULES	
		MROQS	MFCFS
	NV	1077	1091
		766*	775*
	FV	1070	1098
		765*	767*
	LIV	1077	1091
		766*	775*

Table 8.7b

WORKCENTER INITIATED TASK ASSIGNMENT RULES		VEHICLE INITIATED TASK ASSIGNMENT RULES	
		MROQS	MFCFS
	NV	1449.05	1292.35
		2317.57*	2139.83*
	FV	1472.97	1267.76
		2334.45*	2155.92*
	LIV	1449.05	1292.35
		2317.57*	2139.83*

ween the rules. Actually, nearly all the unit loads that entered the shop were completed by the end of the simulation. On the other hand, if mean job flow time criterion is used, the mean value for MFCFS was 270.17 minutes and for MROQS, it was 302.88 minutes.

8.5.3 Variation In Shop Loading

The effect of shop loading on rule performance and ranking was also investigated. Shop loading as used in this analysis is defined as the ratio of mean number of hours required to process all jobs in the shop to the mean number of machine hours available in the shop, both computed over the same length of time. Alternatively, it can be defined as the ratio of work content in the shop to shop capacity; both expressed in the same unit of time for a fixed time span. For a fixed shop capacity, shop loading depends on the rate jobs arrive at the shop.

After increasing job arrival rate from two to four jobs per hour, simulation runs were made for the six rule combinations in Tables 8.9a and 8.9b. Elements of the tables are unit load throughput and mean job flow times respectively. There is no change in ranking between MFCFS and MROQS due to increase in shop loading. Increase in shop loading lowered the overall throughput but not significantly.

Table 8.8a: Unit Load Throughput at Increased Vehicle Fleet Size.

Nomenclature:

MROQS = minimum remaining outgoing queue space
MFCFS = modified first come - first serve
NV = nearvest vehicle
FV = farthest vehicle
LIV = longest idle vehicle

		VEHICLE INITIATED TASK ASSIGNMENT RULES	
		MROQS	MFCFS
WORKCENTER INITIATED TASK ASSIGNMENT RULES	NV	1409	1408
	FV	1407	1408
	LIV	1409	1413

Table 8.8b: Mean Job Flow Time at Increased Vehicle Fleet Size.

		VEHICLE INITIATED TASK ASSIGNMENT RULES	
		MROQS	MFCFS
WORKCENTER INITIATED TASK ASSIGNMENT RULES	NV	291.89	264.72
	FV	302.42	283.17
	LIV	314.33	262.63

Table 8.9a: Unit Load Throughput at Increased Shop Loading.

Key: * value before increased shop loading.

Nomenclature:

MROQS = minimum remaining outgoing queue space
MFCFS = modified first come - first serve

WORKCENTER INITIATED TASK ASSIGNMENT RULES	VEHICLE INITIATED TASK ASSIGNMENT RULES: MROQS	MFCFS
NV	741	751
	766*	775*
FV	734	763
	765*	767*
LIV	741	751
	766*	775*

Table 8.9b: Job Flow Times at Increased Shop Loading.

NV = nearest vehicle
FV = farthest vehicle
LIV = longest idle vehicle

WORKCENTER INITIATED TASK ASSIGNMENT RULES	VEHICLE INITIATED TASK ASSIGNMENT RULES: MROQS	MFCFS
NV	3078.55	2940.26
	2317.57*	2139.83*
FV	3132.64	2946.30
	2334.45*	2155.92*
LIV	3078.55	2940.26
	2317.57*	2139.83

8.6 CONCLUSION

The inferences drawn here are preliminary or may be considered a starting basis for more analysis since different results may be obtained for different shop layout, job routes, and perhaps product mix. Work involving sufficient data is required before any firm conclusions can be drawn about the characteristics of the rules.

CHAPTER 9

THE EFFECT OF UNIT LOAD SIZE ON SHOP PERFORMANCE

9.1 INTRODUCTION AND DESIGN OF EXPERIMENT

As mentioned in the earlier chapters, the class of manufacturing shops being modeled in this study are those in which parts are transported in unit loads. A unit load consists of several parts. The parts contained in a unit load are constrained to be identical (homogeneous) in this study. Depending on the quantity of parts within a job (batch), a certain number of unit loads are generated from the batch. The number of unit loads generated also depends on the physical characteristics of the parts and the container that provides the supporting structure for the load. In chapter 3, the effect of unit load size on system performance was postulated. In this chapter, an experiment is designed to investigate the effect of unit load sizes on shop throughput over a defined period of time. System throughput in this analysis measures the number of jobs or batches (not unit loads) completed over the specified period of time. Throughput measured in terms of unit loads completions was discounted as a poor system performance measure because of the difference in work content between two unit loads that are inherently different in size.

The experimental design opted for in the analysis is a one-way design. All control parameters of the shop were kept at a fixed level throughout the experimentation with the exception of the applicable unit load type being investigated. The control parameters at constant level included vehicle dispatching rules, unit load sequencing rules at workcenters, network control rules, and shop loading. Vehicle dispatching rule was fixed at the combination of the Nearest Vehicle (NV) rule under workcenter task assignment and Modified First Come-First Serve (MFCFS) rule.

Three different sizes of containers were considered in the experiment (see Table 9.1). Uniform base but variable height containers were assumed because of the imposed constraints on queue capacities in the shop. This assumption, though not necessary for the experiment, does provide the convenience of not requiring that queue capacities be defined as a function of the container type in use. If the uniform base assumption is superimposed over the assumption that stacking of unit loads at the queue area for the purpose of increasing the capacities of the queues is not permitted, then a single definition of queue capacities that is independent of the container size in use is sufficient. Table 9.2 is a layout of the one-factor experimental design. The elements x_{ij} represent the jth replicate under the ith container type. The containers, and hence the unit loads, were applied under identical production environment.

Table 9.1: Description of Containers Used in Experiment.

CHARACTERISTICS CONTAINER NO.	LENGTH	WIDTH	HEIGHT	MAX. WT.	FILL RATIO
1	24"	24"	12"	1400 lb	0.7
2	24"	24"	15"	1800 lb	0.7
3	24"	24"	20"	2200 lb	0.7

Table 9.2: One-Factor Experiment to Investigate the Effect of Unit Load Sizes on Shop Performance.

	CONTAINER NUMBER		
REPL. NO.	1	2	3
1	x_{11}	x_{21}	x_{31}
2	x_{12}	x_{22}	x_{32}
3	x_{13}	x_{23}	x_{33}
4	x_{14}	x_{24}	x_{34}
5	x_{15}	x_{25}	x_{35}
6	x_{16}	x_{26}	x_{36}

9.2 ANALYSIS OF EXPERIMENTAL RESULTS

For each container type, the simulation was replicated six times. In addition to system throughput as the primary measure of system performance, mean job flow time was taken as a secondary performance measure; thus broadening the strength of any inferences drawn on the response of the shop with respect to various sizes of containers. Tables 9.3 and 9.4 are the data obtained from the simulation runs which were conducted by employing six automatic guided vehicles. Figures 9.1 and 9.2 are the plots of the data of Tables 9.3 and 9.4.

The hypothesis tested in the experiment was:

Ho: $U_1 = U_2 = U_3$

where U = population mean for the number of jobs completed when using container type i

as against

H : at least $U_i \neq U_j$ for some i and j, $i \neq j$

The above test was conducted using SAS (Statistical Analysis System) package [8]. The results of the analysis of variance performed on the sample data is in Table 9.5. At the five percent significance level, the F-statistic is significant. This implies that for some i and j ($i \neq j$), $U_i \neq U_j$.

At the five percent level of significance, a Duncan's Multiple Range test conducted on the mean shop throughput resulting from employing the three sizes of the containers led to the following inferences.

Table 9.3: Number of Jobs Completed by Container Type.

REPL. NO.	CONTAINER NO.		
	1	2	3
1	97	119	159
2	94	117	153
3	96	117	155
4	97	119	155
5	97	118	152
6	91	116	149

Table 9.4: Mean Job Flow Time by Container Type.

REP. NO.	CONTAINER NO. 1	2	3
1	2788.05	1778.41	1178.82
2	2366.65	2177.41	1796.09
3	2013.45	1651.53	1096.95
4	2405.52	2130.49	1614.48
5	2028.76	1648.36	1134.14
6	2317.55	1876.57	1238.43

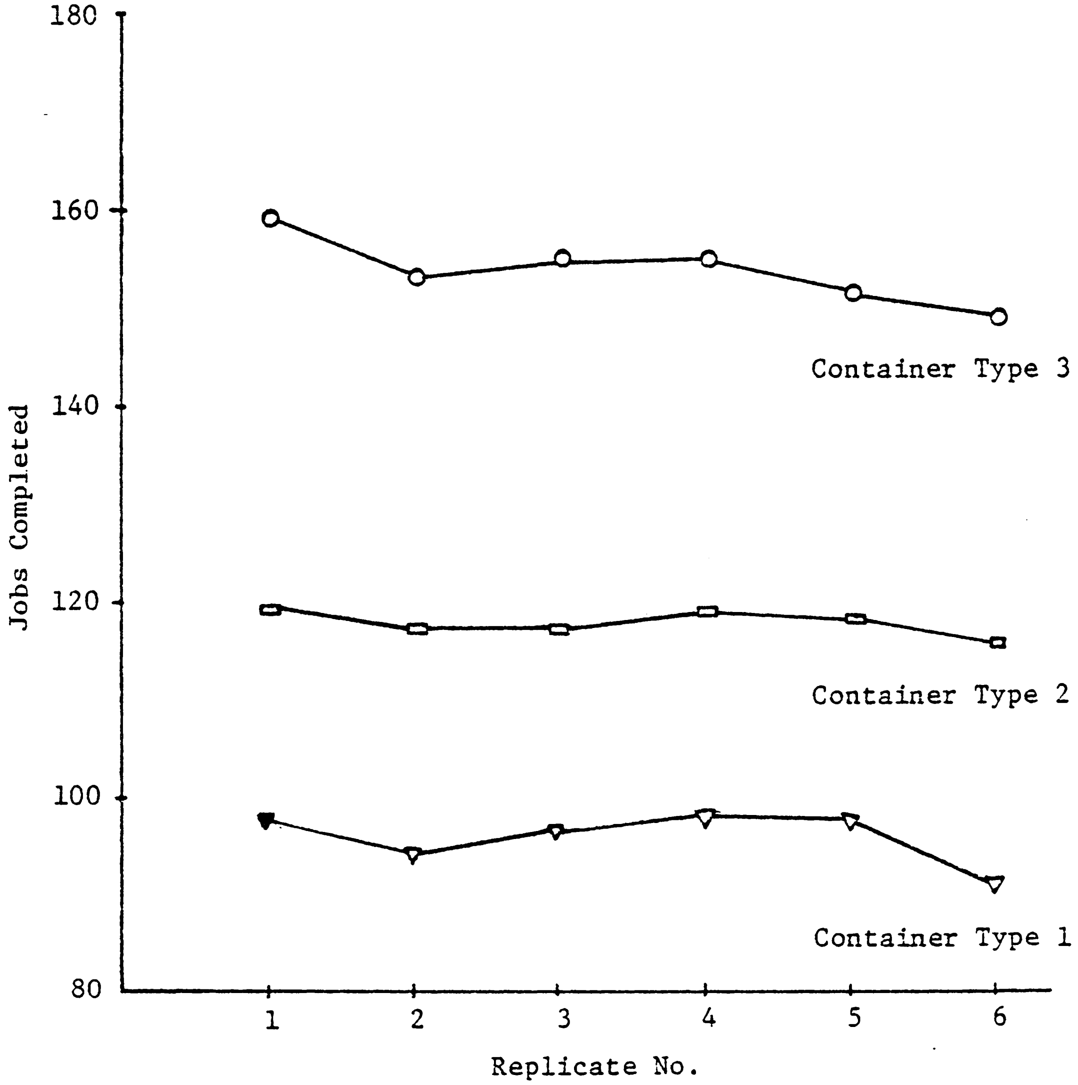


Figure 9.1: Number of Jobs Completed by Container Type.

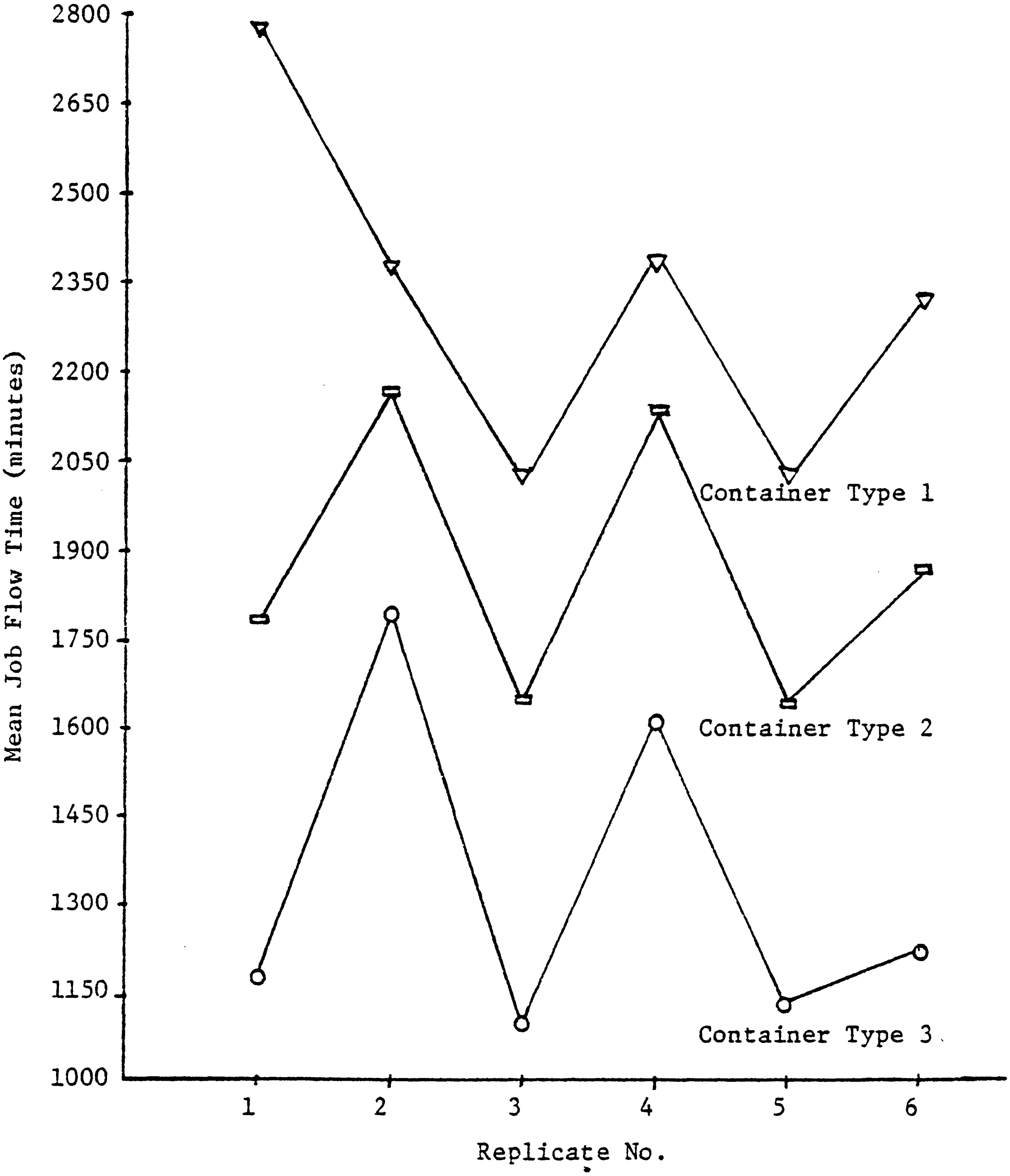


Figure 9.2: Mean Job Flow Times.

Table 9.5: One-way Analysis of Variance on the Effect of Unit Loads on Shop Performance.

SOURCES	DF	SS	MS	F-VALUE	R-SQUARE
CONTAINER	2	10458.11	5229.06	838.89	0.99
ERROR	15	93.50	6.23		
TOTAL	17				

a) No two pairs of the containers tested have similar effect on system throughput rate when measured in terms of whole jobs completed.

b) System throughput rate increases with increasing size of container employed for the conveyance of parts.

The result above is not unexpected, seeing the data of Table 9.2. For any level of replication, the third (i.e. the largest) container outperformed the first and the second containers. Also the second container or unit load size yielded better result than the first (i.e smallest) unit load size. The lesson here is that transporting large number of parts per move is preferable to transporting few number of parts per move. Two effects that were postulated from the selection of unit load size for transporting parts were the following:

a) moving fewer parts per trip (i.e smaller unit loads) results in better machine utilization since parts belonging to the same job can be distributed to many workstations simultaneously (lap phasing). This makes the job more likely to be processed by several workstations at the same time. Each workstation operates on a different processing stage of the job.

b) moving larger number of parts (i.e. larger unit loads) results in inefficient use of machine resources because parts are held up at upstream workcenters while downstream centers may be waiting idle.

c) in adopting smaller unit loads, there is a loss in efficiency resulting from the use of material handling devices (AGVs) because more moves are required to transport the same number of items. Furthermore, there is also a loss in efficiency due to interferences between vehicles. The degree of interferences increases as the number of moves required increases.

d) the conditions in (c) is reversed with larger unit loads.

While the result of the experiment does not prove or disprove any of the four postulates, it does, however, suggest that overall, it is better to move more parts per trip. The loss in overall system efficiency is lower for larger unit loads than it is for smaller unit loads.

Although a larger number of experimental replications may be required to draw stronger conclusions on unit load effect on shop performances, the inferences above tend to reconfirm the general belief that most delays experienced by parts in a manufacturing shop are the result of handling rather than machining. A note of caution is adequate at this conclusion. There is likely to be an upper bound on the maximum size container that can be used in any application beyond which the performance of the system deteroriates. This is the classical law of diminishing return. The rated handling capacity of the AGVs may also be a limiting factor.

9.3 MEAN JOB FLOW TIME AS A PERFORMANCE CRITERION

Mean job flow time as a measure of the performance of a shop is not uncommon in the theory of job scheduling [14,21,25]. Also not uncommon in the evaluation of the performance of a system is the use of multiple criteria [14]. Appropriate weights are assigned to each of the criterion and by using these weights, a single decision criterion is obtained through a linear combination of the criteria. Alternatively, the criteria are ranked and decision is made to conform to this ranking.

In this analysis, none of the two techniques is used. The adopted approach is simply to characterize the behavior of the shop with respect to mean job flow time when different unit load sizes are employed.

9.3.1 Statistical Analysis

The mean job flow time plot of Figure 9.2 displays a large amount of variability for each container type. This large variation threatens the violation of the homogeineity of variance assumption rquired by the analysis of variance (ANOVA) procedure [17,34]. To stabilize the variance for the application of ANOVA test, statistical analysis was performed on the natural logarithmic transformation of the raw data instead of the raw data such that

$$X'_{ij} = \ln(X_{ij})$$

where X_{ij} = original data on mean job flow time.

X'_{ij} = transformed version of X_{ij}.

The application of ANOVA procedure on the transformed data yielded an F-statistic of 20.10. At ninety five percent confidence level and 2 and 15 degrees of freedom, the statistic is significant. This implies that the mean flow times of jobs are significantly different for each unit load type.

A Duncan's Multiple Range test comparison on the mean job flow time under each type of unit load duplicates the earlier result obtained under the criterion of job throughput. The result of the analysis is summarized below.

a) every pair of unit loads yielded significantly different mean job flow time.

b) larger unit loads yielded better mean job flow times than smaller unit loads.

The above inferences should be interpreted only within the framework and limitations discussed on the interpretation of the inferences drawn under the unit load throughput criterion presented in section 9.2.

9.4 MULTIPLE SHOP - MULTIPLE UNIT LOAD ASSIGNMENT

To this point, the study of unit load effect has been confined to one particular shop. The unanswered question, however, is whether the results so far established can be repeated or reproduced in other shops that have characteristics that are different from the model shop in this study. This problem was approached by repeating a modified version of the earlier experiment. Six different shops were included in the experiment. The basic differences in the shops came in three sources, namely, a) number of Automatic Guided Vehicles in use, b) vehicle traveling speed, and c) the rate at which jobs arrive into the shop (i.e. shop loading).

The number of vehicles ranged from six to fifteen, vehicle speed ranged from 120 feet per minute (fpm) to 200 fpm while job arrival rates ranged from 2 jobs per hour to 4.5 jobs per hour. The same set of containers (unit load sizes) as defined in section 9.1 were used in the experiment. The characteristics of the six shops are as tabulated below:

Shop Number	Applicable No. of Vehicles	Vehicle Speed	Job Arrival Rate
1	6	120fpm	2.00/hour
2	9	150	2.40
3	5	180	2.70
4	7	200	4.00
5	15	175	4.50
6	8	190	2.56

Tables 9.6 and 9.7 contain the sample data obtained by running the simulation model for each shop under each container type. The entries in the table are respectively the number of jobs ccompleted and the mean job flow times.

9.4.1 Statistical Analysis of Number of Jobs Completed

Rather than using the ANOVA procedure to analyze tha data so obtained, a nonparametric (distribution free) test was employed. The variability displayed by the data (Table 9.6) makes it very unlikely that two of the assumptions required by the ANOVA procedure [17,34] will be satisfied. These are the normality and the equality of variance assumption for the observations Xij, where Xij represents the response from the ith shop using the jth container. The Friedman Rank Sums test [46] was the selected test procedure. The following hypothesis was tested.

$$Ho: U_1 = U_2 = U_3$$

against

Table 9.6: Number of Jobs Completed by Shop and Container.

		CONTAINER NO.		
		1	2	3
SHOP NO.	1	97	119	159
	2	173	128	273
	3	113	140	186
	4	175	219	284
	5	119	376	402
	6	189	231	291

Table 9.7: Mean Job Flow Time by Shop and Container.

SHOP NO.	CONTAINER NO. 1	CONTAINER NO. 2	CONTAINER NO. 3
1	2178.05	1778.41	1178.82
2	1450.58	515.91	309.44
3	2439.48	2112.43	1699.06
4	2298.29	1966.63	1407.88
5	792.18	1393.77	747.25
6	1232.00	736.00	198.46

H : not all the Ui's are equal.

where Ui (measured in number of jobs
completed) is the mean effect
due to using container type i.

For the data of Table 9.6, let the following definitions be made.

K = number of treatments (i.e. container types)

n = number of blocks (i.e shops)

Xij = observation resulting from using the jth treatment in the ith block.

Rij = rank of observation Xij among the K observations generated in the ith block, $1 \leq Rij \leq k$.

$R_j = \sum_{i=1}^{n} Rij$ for j=1,2,3

R.j = Rj/n for j=1,2,3

R.. = (k+1)/2

Using the above definitions, Table 9.8 and the following test parameters were calculated.

$R_1 = 7$; $R_2 = 11$; $R_3 = 18$

$R._1 = 7/6$; $R._2 = 11/6$; $R._3 = 18/6$; and R.. =(3+1)/2 = 2.

At an α level of five percent, the statistics

$$S = \frac{12n}{k(k+1)} \sum_{j=1}^{k} (R.j - R..)^2$$

Table 9.8: Ranked Data of Number of Jobs Completed According to Friedman Rank Sums Test.

		CONTAINER NUMBER		
		1	2	3
SHOP NUMBER	1	1	2	3
	2	2	1	3
	3	1	2	3
	4	1	2	3
	5	1	2	3
	6	1	2	3

$$S = \frac{12(6)}{3(4)} [7/6 - 2.0)^2 + (11/6 - 2.0)^2 + (18/6 - 2.0)^2]$$

$$= 10.333 > S(\alpha,k,n) \simeq 6.33 \text{ is significant}$$

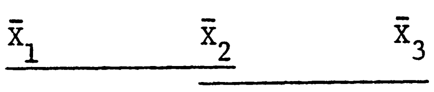
This implies the rejection of the null hypothesis and the conclusion that at least some of the Uj's are unequal. Using distribution-free multiple comparison test based on Friedman Ranked Sums, the following K(K-1)/2 = 3 absolute differences were computed and compared to the critical test values at an level of 0.029 for a one-tail test.

$|R_1 - R_3| = 11 > r(0.029,3,6) = 9$ (significant)

$|R_1 - R_2| = 4 < r(0.029,3,6)$ (insignificant)

$|R_2 - R_3| = 7 < r(0.029,3,6)$ (insignificant)

The result of the statistical analysis indicated that there is significant difference in the number of jobs completed between the third (largest) and the first (smallest) size containers but no such difference was detected between the second (medium) container and any other containers. The schema shown below summarizes the result.



The variable Xi represent the estimate of the mean number of jobs completed by the treatment (container) i over all blocks (shops).

9.4.2 Characteristics of Mean Job Flow Time Under The Multiple Shop Case

The Friedman Rank Sums nonparametric test was also applied to the simulated data on mean job flow times of Table 9.4. The equivalent table of ranked observations is as shown in Table 9.9. Using the test procedure as described in section 9.4.1, the following inferences were drawn:

i) The three container (unit load) sizes produced mean job flow times that were significantly unidentical at the five percent level of significance.

ii) At the test significant level of 2.9 percent, the Friedman Ranked Sums multiple comparisons test showed that the mean job flow times under the largest unit load (i.e. container three) and the smallest unit load (i.e. container one) were significantly unequal. However, the mean job flow time that resulted from using the medium unit load (i.e. container two) was not significantly different from that attained under the largest or the smallest size containers.

This result is summarized schematically as shown below.

$$\begin{array}{ccc} y_3 & y_2 & y_1 \\ \cline{1-2} \\[-2ex] \cline{2-3} \end{array}$$

where y_i = mean job flow time across all shops that resulted from using container type i.

By comparing the inferences drawn on the behavior of the shop with respect to using different container sizes, the following point is apparent. Not only does the smaller unit load reduce the total number of jobs completed over a period of time but also increased the mean time jobs spent in the shop. This result suggests that the use of smaller unit load sizes for parts handling is an undesirable tactic for improving overall shop performance.

Table 9.9: Ranked Data of Mean Job Flow Times According to Friedman Rank Sums Test.

		CONTAINER NUMBER		
		1	2	3
SHOP NUMBER	1	3	2	1
	2	3	2	1
	3	3	2	1
	4	3	2	1
	5	2	3	1
	6	3	2	1

CHAPTER 10

THE JOINT EFFECT OF JOB SEQUENCING RULES, VEHICLE DISPATCHING RULES AND SHOP LOADING ON SYSTEM PERFORMANCE

10.1 INTRODUCTION

Unit load sequencing rules, or simply job sequencing rules are queue ordering procedures for prioritizing entities waiting for service in incoming job queues. Depending on the sequencing rule in force, processors (machines) draw entities from the queue for processing at some rate, assuming the distribution times to process the entities remain the same. Just as the vehicle dispatching rules are responsible for providing the driving potential (pushing effect) for unit loads in outgoing queues, the unit load sequencing rules generate the flow potential (flow effect) for entities residing in incoming unit load queues. Studies have shown that different sequencing rules accelerate jobs differently through the shop [25]. This can be translated to differences in system throughput over the same length of time. Similar result was established in chapter 8 for vehicle dispatching rules. These two sets of results suggest that certain combinations of vehicle dispatching rules and unit load sequencing rules are likely to result in higher number of job completions while other rule combinations may not perform equally well. Some combinations could accelerate the machine/vehicle blocking phenomenom cited in chapters 6 and 8.

In view of the above postulates, the material presented and discused in this chapter is focused on the investigation of the joint effects of unit load sequencing rules and vehicle dispatching (task assignment) rules on the performance of an AGV based material handling systems. Furthermore, the investigation is undertaken at more than one level of shop loading. In an earlier experiment reported in chapter 8, there was an indication that shop loading has relatively no effect on the performance rankings of the vehicle dispatching rules. However, the study did not show the effect of shop loading in the presence of vehicle dispatching and unit load sequencing rules. It is this unanswered question that motivates the inclusion of shop loading in this investigation.

10.2 THE DESIGN OF EXPERIMENT

The design of the current experiment builds on the results of earlier experiments on vehicle dispatching rules. This includes the finding that some combinations of vehicle dispatching rules perform very poorly relative to others. With this information known, only a few combinations of vehicle dispatching rules that have been found to perform competively are considered in the current experiment. With regard to the sequencing of unit loads at workstations, only First Come-First Serve, Shortest Operation Time (SOT), and Last In-First Out (LIFO) rules are considered.

Unit load (job) sequencing rules have enjoyed long research attention in the academic community and this has led to the development of several sequencing rules. Depending on the applicable system performance measure in use, some rules are known to outperform others [21,25]. Also, some have enjoyed wider applications than others [21,25]. All these factors considered led to the retriction of the number of rules included in this experiment to three.

The design analysis opted for in this investigation is a 3x2x3 factorial experiment. The three factors are

a) unit load sequencing rules,
b) vehicle dispatching rules, and
c) shop loading.

Various levels of shop loading are obtained simply by varying the rate at which jobs arrive into the shop, keeping the shop capacity fixed. Higher rates of arrivals translate to higher shop loading. The levels of the factors as used in the experiment are as given below.

Factor 1: Unit load Sequencing Rules

level 1: First Come-First Serve (FCFS)
level 2: Shortest Operation Time (SOT)
level 3: Last In-First Out (LIFO)

Factor 2: Vehicle Dispatching Rules

level 1: The combination of the Nearest Vehicle (NV) rule and Minimum Remaining Outgoing Queue Space (MROQS) rule (NV-MROQS).

level 2: The combination of the Longest Idle Vehicle (LIV) and the Modified First Come - First Serve (MFCFS) rule (LIV-MFCFS)

Factor 3: Shop loading

level 1: λ = 2.5 jobs per hour.

level 2: λ = 3.5 jobs per hour.

level 3 λ = 4.5 jobs per hour.

The layout of the design is as shown in Table 10.1. The matrix elements xijk are the values of the response variable at the ith level of unit load sequencing rules, jth level of vehicle dispatching rules, and the kth level of shop loading. The primary response variable is the number of unit loads completed within the experimental period. References will be made to mean job flow times and mean number of jobs in the shop whenever appropriate.

10.3 ANALYSIS OF EXPERIMENTAL RESULT

The experiment described was replicated two times as shown in Tables 10.2, 10.3, and 10.4. The elements of the Table 10.2 (i.e. the response variable or performance measure) are the number of unit loads completed over the simulation time. Table 10.4 shows the mean flow time of the jobs (not unit loads) that were completed. Since the shop was not flushed empty at the end of the simulation time, only the flow times

Table 10.1: Layout of Experiment in Three Factors.

		$\lambda = 2.5$		$\lambda = 3.5$		$\lambda = 4.5$	
		VEH. DISPATCH. RULES		VEH. DISPATCH. RULES		VEH. DISPATCH. RULES	
		1	2	1	2	1	2
UNIT LOAD SEQUENCING RULES	FCFS	x_{111}	x_{121}	x_{112}	x_{122}	x_{113}	x_{123}
	SOT	x_{211}	x_{221}	x_{212}	x_{222}	x_{213}	x_{223}
	LIFO	x_{311}	x_{321}	x_{312}	x_{322}	x_{313}	x_{323}

Table 10.2: Number of Unit Loads Completed--Three Factor Experiment.

Nomenclature:

A = NV - MROQS
B = LIV - MFCFS
NV = nearest vehicle
LIV = longest idle vehicle

MROQS = minimum remaining outgoing queue space
MFCFS = modified first come - first serve

		λ = 2.5		λ = 3.5		λ = 4.5	
		VEH. DISPATCH. RULES		VEH. DISPATCH. RULES		VEH. DISPATCH. RULES	
		A	B	A	B	A	B
UNIT LOAD SEQUENCING RULES	FCFS	1334	200	418	165	684	169
		1384	617	591	623	586	628
	SOT	1385	859	441	200	422	152
		1411	620	590	632	566	631
	LIFO	1432	1443	607	684	992	568
		1430	612	460	506	565	437

Table 10.3: Mean Number of Jobs in the Shop--Three Factor Experiment.

<u>Nomenclature</u>:

A = NV - MROQS
B = LIV - MFCFS
NV = nearest vehicle
LIV = longest idle vehicle

MROQS = minimum remaining outgoing queue space
MFCFS = modified first come - first serve

		$\lambda = 2.5$		$\lambda = 3.5$		$\lambda = 4.5$	
		VEH. DISPATCH. RULES		VEH. DISPATCH. RULES		VEH. DISPATCH. RULES	
		A	B	A	B	A	B
UNIT LOAD SEQUENCING RULES	FCFS	16.36	112.54	140.38	181.09	174.15	245.12
		13.39	53.44	117.52	109.61	179.20	170.12
	SOT	14.32	31.45	139.60	174.47	207.89	247.75
		12.67	52.85	119.86	109.59	184.33	169.12
	LIFO	14.55	13.67	142.02	127.92	192.12	218.17
		13.91	55.06	153.43	138.92	209.16	217.29

Table 10.4: Mean Job Flow Times--Three Factor Experiment.

Nomenclature:

A = NV - MROQS
B = LIV - MFCFS
NV = nearest vehicle
LIV = longest idle vehicle

MROQS = minimum remaining outgoing queue space
MFCFS = modified first come - first serve

		λ = 2.5		λ = 3.5		λ = 4.5	
		VEH. DISPATCH. RULES		VEH. DISPATCH. RULES		VEH. DISPATCH. RULES	
		A	B	A	B	A	B
UNIT LOAD SEQUENCING RULES	FCFS	392.60	254.18	411.12	267.86	920.38	317.24
		321.26	196.77	453.87	414.55	746.76	691.75
	SOT	349.62	267.13	394.91	320.42	577.25	305.27
		295.92	193.38	419.14	413.22	677.86	635.65
	LIFO	327.44	327.91	319.82	316.55	594.25	273.13
		321.65	228.49	277.46	269.34	391.09	257.29

of those jobs that were completed were included in the statistics collected. The entries of Table 10.3 are the mean number of jobs in the shop.

A close observation of the elements of Table 10.2 shows that the responses under the lowest level of shop loading (i.e. 2.5 jobs per hour) are generally higher than those at loads of 3.5 and 4.5 jobs per hour respectively. Application of standard statistical analysis procedure, the ANOVA, on the data and employing a five percent level of significance resulted in the following inferences.

i) The number of unit loads completed over a period of time is affected by the levels of the factors included in the experiment.

ii) Unit load sequencing rules do not produce any significant effect on the number of unit loads, and hence jobs completed over a period of time.

iii) Vehicle dispatching rules and shop loading each has a significant effect on the number of unit loads completed over an interval of time.

iv) Vehicle dispatching rules and levels of shop loading interact. The interaction effect is significant. Thus, it affects the number of unit loads completed over a period of time.

The above inferences which are based on a sample size of 36 (i.e. two replications per cell) are summarized by the Analysis of Variance in Table 10.5.

10.3.1 Differences Between Levels of Experimental Factor

The relative performances of the various vehicle dispatching rules were analyzed in chapter 8. The result of this experiment indicates that differences among the three levels of job sequencing rules investigated were insignificant. This implies that all levels of job sequencing rules have equal effect on the number of unit loads completed. With regard to the characterization of the three levels of shop loading employed in the experiment, a Duncan's Multiple Range test was applied to the means of the unit loads completed under each level. The result of the test at the five percent level of significance is summarized below.

i) The number of unit loads completed at the lowest level of shop loading (i.e. load rate of 2.5 jobs per hour) was significantly different from those at higher shop loadings. Higher number of unit load completions were generally obtained at lower level of shop loading than those at higher levels.

ii) The mean number of unit loads completed at $\lambda = 3.5$ and 4.5 levels of shop loading were statistically equal.

Further analysis of the effects of the experimental factors are presented in the following subsections.

Table 10.5: Analysis of Variance on Three Factor Experiment.

Nomenclature:

SQ = job sequencing rules
VD = vehicle dispatching rules
SL = shop loading

SOURCES	DF	F-VALUE	R-SQUARE
Model	7	12.44	0.7557
Error	28		
SQ	2	2.65	
VD	1	18.01	
SL	2	25.31	
VD*SL	2	6.60	

10.3.2 Unit Load Sequencing Effect

The application of sequencing rules in a job shop has meaning only if there are two or more candidate jobs (unit loads) competing simultaneously for machining resource at a center. When such competition exists, a queue ordering procedure is required for selecting the appropriate job for processing. However, if jobs seldomly queue up at machining stations, then a formal queue ordering rule is not necessary. Even if one is instituted, it is likely to be ineffective because without it, the same number and sequence of jobs would have been processed by the machining center for a fixed time span. In this experiment, the lack of queue (incoming queues) buildups explain why job sequencing rules were apparently ineffective. Vehicles were not deliverying unit loads fast enough into the incoming job queues to cause queue buildups. Queue buildups necessitate the use of queue ordering rules to prioritize entities in queues. This result implies that in this shop, vehicles were the constraining resource on the flow of jobs rather than machines. This last assertion also imply that if machines rather than vehicles become the constraining resource, then the significance level between job sequencing rules and vehicle dispatching rules is likely to be reversed from the current result. Also if machining resources and handling resources do not dominate one another, both factors could simulataneously become statistically significant. Thus, the conclusions drawn here may be shop dependent.

10.3.3 Vehicle Dispatching Rule Effect

The effect of vehicle dispatching rules formed the basis of the experiments and analysis in chapter 8. However, it should be sufficient to recognize that even at different levels of shop loading and job sequencing rules, vehicle dispatching policies are a major factor in influencing the rate at which jobs are completed and released from the production floor.

10.3.4 Shop Loading Effect

In this experiment, test result showed that higher unit load throughput is achieved at lower shop loading than at higher loading. In this particular shop, the reason underlying the outcome of the test could be explained as follows. At lower shop loading, fewer number of jobs compete for the service of the material handling resource than at higher shop loading. For a fixed number of handling devices, this implies that the rate of transition between workcenters per job in the shop is higher at lower level of shop loading. If material handling equipment are the constraining resource in the flow of materials, the higher transition rate per job easily translates to higher rates of job completions and vice versa. This does not imply that the effectiveness of the vehicles in providing handling services is diminished at higher levels of shop loading. However, it does imply that the same level of service is being distributed over a larger number of jobs such that only a fewer number of jobs actually receive sufficient service to have their technological needs (processing requirements) satisfied.

In addition to the explanation presented above, another point needs to be cleared. If the above explanation holds, then why does the test not detect any differences between the two higher levels of shop loading (i.e. shop load, of 3.5 and 4.5 jobs per hour, respectively). The answer to this question can be provided purely in terms of the shop capacity. The shop capacity is constrained by the number of machines and vehicles in the shop. This capacity determines the actual number of unit loads that can be admitted onto the shop floor for processing for any time interval. Once this capacity is reached, additional jobs arriving into the shop only queue up at the receiving area and cannot actually be permitted to enter or circulate on the shop floor. Once the capacity of the shop is reached, the number of unit loads completed over a period of time stabilizes, making it nonresponsive to increasing levels of shop loading. A graphical relationship between shop loading, shop capacity, expected rate of job completions and the expected rate of growth of the incoming job queue at the receiving area is shown in Figure 10.1a and 10.1b.

10.4 SECONDARY MEASURES OF SHOP PERFORMANCE

The response of the shop was also characterized using mean job flow time and mean number of jobs in the shop. However, caution has to be exercised in drawing any conclusions based on these criteria. For a fixed level of resource, higher levels of shop loading will inevita-

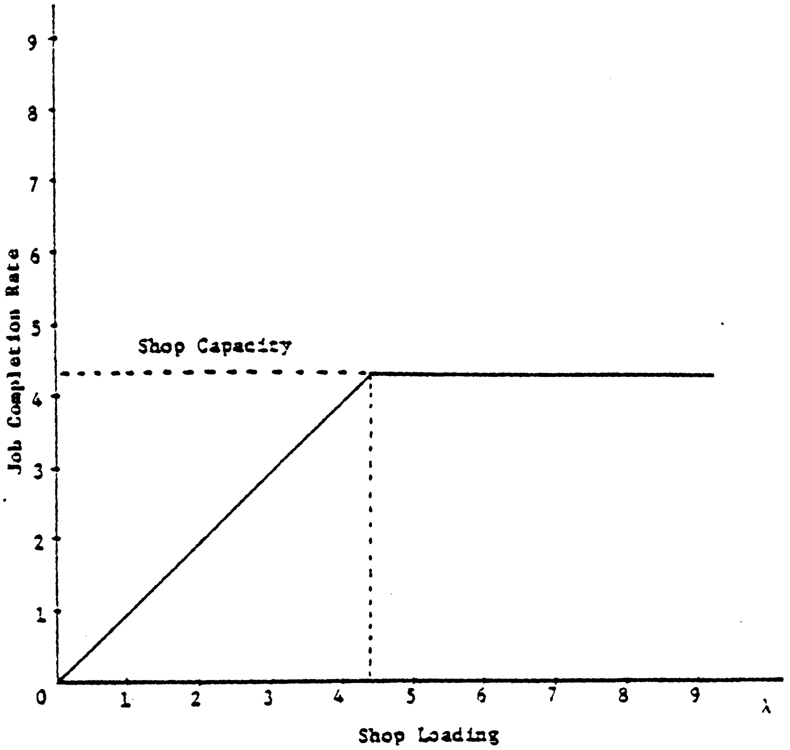


Figure 10.1a: Job Completion Rate, Shop Capacity and Shop Loading.

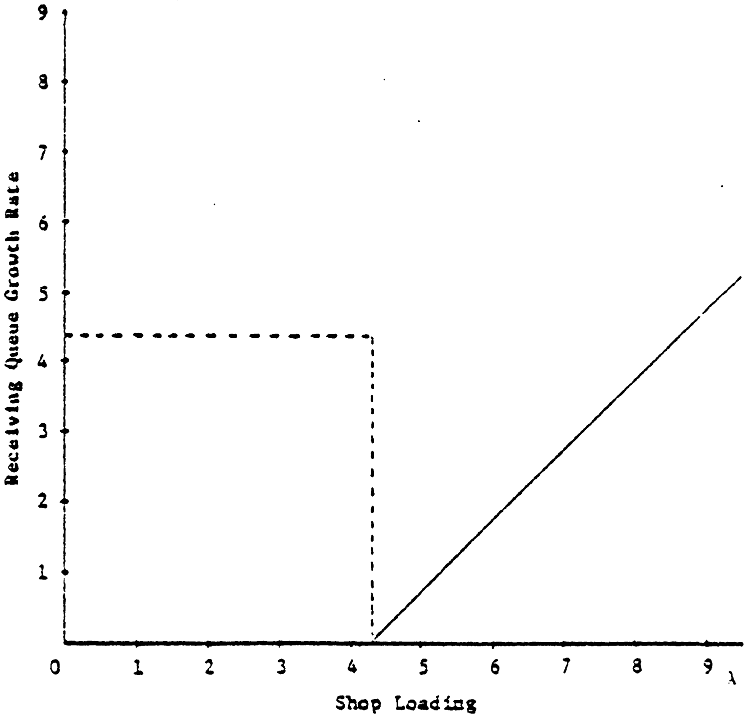


Figure 10.1b: Queue Growth Rate, Shop Capacity and Shop Loading.

bly produce higher mean number of jobs in the shop. Mean job flow times will also be higher at higher shop loading since larger number of jobs are competing for the same amount of resources. This increases the mean waiting time per job. Mean number of jobs or mean job flow times can only be used to compare different levels of job sequencing and vehicle dispatching rules.

Statistical analysis of the data of Tables 10.3 and 10.4, again using the ANOVA procedure, led to the conclusions presented in the following subsections.

10.4.1 Mean Number of Jobs In The Shop

i) Job sequencing rules had no significant effect on the mean number of jobs in the shop. This result is not unexpected since it was detected by the earlier analysis that they (i.e. sequencing rule) do not influence the number of unit loads, and hence, the jobs completed.

ii) The effect of shop loading was highly significant on the mean number of jobs in the shop. This result reconfirms an expected result. Vehicle dispatching rules also affected the number of jobs in the shop. The analysis did not detect any interaction effect due to the factors included in the experiments.

A Duncan's Multiple Range test performed on the mean effect of each level of shop loading detected significant differences between all levels. The mean number of jobs in the shop increases with increasing shop loading. With respect to the two levels of vehicle dispatching rules employed in the experiment, rule number one (i.e. combination of Nearest Vehicle rule and Minimum Remaining Outgoing Queue rule) was found to be superior to rule number two (i.e. combination of Longest Idle Vehicle rule and the Modified First Come-First Serve rule). All test conclusions were based on a sample size of thirty six observations (i.e. two observations per treatment combination) and at the five percent level of significance.

10.4.2 Mean Job Flow Times

With regard to mean job flow time as a decision measure, analysis showed that all main effects, including job sequencing rules were significant. The significance of job sequencing rules is not intuitively clear since it was not found significant using mean jobs in the system and unit load throughput criteria.

Among the three levels of sequencing rules, no difference was found between FCFS and SOT rules. There was also no difference between SOT and LIFO. However, there was a significant difference between FCFS and LIFO rules, with LIFO yielding much lower mean flow time than FCFS rule.

The three levels of shop loading were significantly different from one another. Mean job flow time decreases with with decreasing level of shop loading. The two levels of vehicle dispatching rules were also significantly different. The order of superiority among the levels was reversed from that obtained under 'mean number of jobs' criterion.

10.5 CONCLUSION

The tests performed and presented in this chapter produced a tremendous amount of insight into the behavior of an AGV-based material handling system. Some portions of the results were easily comprehensible, others reconfirmed expected beliefs while others produced results that were not obvious. The fact that sequencing rules had no noticeable effect on the number of unit loads completed and mean number of jobs in the shop is one case that needs further investigation. By embarking on a robust analysis such as increasing the volume of data used, it may be much easier to uncover some of the fuzziness on the test results. Increased sample size will not only help to clarify results but also strengthens any conclusions that may have been reached.

CHAPTER 11

SELECTING A NETWORK CONTROL STRATEGY

11.1 INTRODUCTION

On several occasions in this study, the importance of a properly designed, well co-ordinated vehicle management scheme in the operation of Automatic Guided Vehicle based material handling system has been emphasized. One aspect of this management scheme is the definition of the routing and control algorithms applied to vehicles as they traverse through the guidance network. In chapter 5 where the network control measures were developed and presented, several rules were mentioned for routing vehicles through an intersection. Among these alternatives, four were discussed in detail. Included in the exposition were the following rules:

a) First Come-First Serve (FCFS) rule.

b) Restricted First Come-First Serve (RFCFS) rule. Under this rule, first come-first serve at an intersection applies only to vehicles proceeding to the same arc after the current node. This is to ensure that vehicles arriving at an intersection and proceeding to the same direction are ordered in the subsequent aisle in the order they approached the intersection. Highest priority is given to the first vehicle that arrived at the intersection.

c) Relaxed Traffic Control (RTC) rule. Elimination of any formal intersection control policy around the node and allowing the traffic conditions around the intersection determine the vehicle that has the right of way.

d) Train Routing (TR) rule. In this alternative, routing priority at an intersection is given to the longest approaching string of vehicles from the various arcs that feed into the intersection. However, only strings in the neighborhood of the intersection are considered for priority assignment.

It was postulated that in situations where vehicles are approaching the neighborhood of an intersection from different directions simultaneously, the manner by which these vehicles are prioritized to use the intersection affects time losses due to vehicle interferences. The net effect of these time losses will eventually reflect on the effectiveness of the vehicles to respond to load pickup calls, or their ability to timely complete their missions.

Testing the above postulate is the item of primary interest in this chapter. The test performed should indicate the relative rankings of the network control alternatives to one another. Since any differences among the rules will be in terms of overall time saving potential, this suggests that the use of ssvings in time can be a basis for comparing alternative intersection control rules. However, such direct comparisons of time savings due to reduced vehicle interferences is meaningful only if such savings can be directly translated into increases in the productive ability of the overall shop. If a significant amount in time savings from one rule over another does not necessarily result in a significant increase in the productive power of the shop, then it is logical to assume that the two rules provide essentially the same degree of effectiveness to the shop. Thus, number of jobs completed (or unit loads completed) rather than direct time savings will be used for comparing the effectiveness of the network control rules in this experiment. The rest of the analysis adopts this last view, that is, using number of unit loads completed as a basis for rule comparisons. References will be made to secondary measures of performance such as job flow times and jobs in the shop wherever appropriate.

In addition to arbitrating between vehicles competing for sequential use of an AGV wire guidance intersection, network control rules share a common characteristics with vehicle dispatching rules. Both families of rules assist in distributing vehicles throughout the guidance network. This suggest that there may exist some relationship between the two classes of rules and that such relationship could have some bearing on the overall performance of a shop. Therefore, an experiment in two factors (i.e. network control and vehicle dispatching rules) is adopted for the investigation to follow. The investigation interest is in finding the effect of network control rules and the interaction of network control and vehicle dispatching rules on the performance of an AGV system.

11.2 THE DESIGN OF THE EXPERIMENT

The selected experimental design is a 2x4 factorial experiment. The network control measures appear in four levels, with each level corresponding to each of the rules presented in chapter 5 and listed in section 11.1. Vehicle dispatching rules appear in two levels as defined in section 10.2. Table 11.1 gives the layout of the experiment.

It was well understood during the setup of this experiment that there are several factors that contribute to vehicle interferences. Other

Table 11.1: Layout of Experiment on Network Control and Vehicle Dispatching Rules.

X_{ij} = response due to the combination of the i^{th} vehicle dispatching rule and the j^{th} network control rule.

		NETWORK CONTROL RULES			
		FCFS	RFCFS	RTC	TR
VEHICLE DISPATCH. RULE	NV-MROQR	X_{11}	X_{13}	X_{13}	X_{14}
	LIV-MFCFS	X_{21}	X_{22}	X_{23}	X_{24}

than the network control and vehicle dispatching rules, the form of the network layout could be a major vehicle interference inducing factor. Network intersections where two or more aisles converge (conflict nodes) are more prone to vehicle interferences than non-conflict nodes.

The size of the vehicle fleet is another factor that deserves recognition. For a fixed layout, the larger the fleet size, the higher the frequency of occurence of conflicts between vehicles. Alternatively, for a fixed fleet size, the smaller the area covered by the guidance network, the greater the probability of interference between vehicles. This excludes the one vehicle facility case. Therefore, any findings in terms of the behavior of a shop with respect to the application of a given network (intersection) control measure can only be interpreted in terms of the layout in use and the given size of vehicle fleet.

11.3 ANALYSIS OF EXPERIMENT: NETWORK CONTROL AND VEHICLE DISPATCHING RULE

The results presented here is based on a vehicle fleet size of eleven. With the exception of the network control rule and the vehicle dispatching rule being investigated, all experimentation was performed under fixed shop condition. The experiment was replicated three times as shown by the data of Tables 11.2, 11.3, and 11.4. The responses in Table 11.2 are the number of unit loads completed over the simulation time. Tables 11.3 and 11.4 represent the mean number of jobs in the shop and the mean job flow times, respectively.

Table 11.2: Number of Unit Loads Completed by Network Control Rules.

Nomenclature:

NV = nearest vehicle
MROQS = minimum remaining outgoing queue space
LIV = longest idle vehicle
MFCFS = modified first come - first serve

FCFS = first come - first serve
RFCFS = restricted first come - first serve
RTC = relaxed traffic control
TR = train routing

		NETWORK CONTROL RULES			
		FCFS	RFCFS	RTC	TR
VEHICLE DISPATCH. RULES	NV-MROQS	1416	1416	1416	476
		209	209	209	212
		658	658	658	677
	LIV-MFCFS	39	39	39	32
		715	715	715	714
		24	24	24	15

Table 11.3: Mean Number of Jobs in the Shop by Network Control Rules.

Nomenclature:

NV = nearest vehicle
MROQS = minimum remaining outgoing queue space
LIV = longest idle vehicle
MFCFS = modified first come - first serve

FCFS = first come - first serve
RFCFS = restricted first come - first serve
RTC = relaxed traffic control
TR = train routing

VEHICLE DISPATCH. RULES		NETWORK CONTROL RULES			
		FCFS	RFCFS	RTC	TR
	NV-MROQS	88.35	88.35	88.35	143.90
		161.68	161.68	161.68	161.70
		90.37	90.37	90.37	88.19
	LIV-MFCFS	208.31	208.31	208.31	209.24
		91.22	91.22	91.22	91.26
		183.44	183.44	183.44	185.35

Table 11.4: Mean Job Flow Times by Network Control Rules.

Nomenclature:

NV = nearest vehicle
MROQS = minimum remaining outgoing queue space
LIV = longest idle vehicle
MFCFS = modified first come - first serve

FCFS = first come - first serve
RFCFS = restricted first come - first serve
RTC = relaxed traffic control
TR = train routing

		NETWORK CONTROL RULES			
		FCFS	RFCFS	RTC	TR
VEHICLE DISPATCH. RULES	NV-MROQS	1618.87	1618.87	1618.87	811.81
		241.82	241.82	241.82	247.52
		542.71	542.71	542.71	517.06
	LIV-MFCFS	183.07	183.07	183.07	167.58
		651.08	651.08	651.08	653.30
		161.82	161.82	161.82	127.25

Without performing any formal statistical analysis on the data of Table 11.2, it is reasonable to conclude that there is no difference in performance among the four levels of network control rules tested. In fact, the first three levels of network control rules produced identically the same number of unit load completions in every case. With the exception of two observations, the responses under the fourth rule are generally lower than those of the other three rules, although not significantly. The insignificant differences (if any) in performance between the rules is so apparent that the use of a formal statistical procedure to validate the conclusion drawn above is not justifiable. Even the interaction effect between the control rules and the vehicle dispatching rules as postulated in section 11.1 is apparently nonexistent, seeing the experimental responses. The data of Table 11.3 (i.e. mean jobs in the shop and that of Table 11.4 (i.e. mean job flow times) also reinforce the uniformity effect among the four levels of the rule.

With respect to the vehicle dispatching rules, there is obviously a difference in performance among the two levels. This is merely a reconfirmation of what had been indicated in earlier sections of this study. In view of this, no further analysis on these rules (i.e. vehicle dispatching rules) is presented in this chapter.

11.3.1 Explanation of Experimental Result

Intuitively, it is not obvious why the procedure by which vehicles are routed through an intersection in an AGV system has no significant influence on the effectiveness of the vehicles in the shop. However, a careful evaluation of the function of the four network control rules tested explains the result obtained in the experiment.

When two or more vehicles approach an intersection zone simultaneously from different directions, there will definitely be a loss of time involved by some of the vehicles as they are slowed down or held in place to give other vehicles the right-of-way. Intersection or network control rules determine only the sequence by which vehicles are to be routed through the intersection. They provide virtually no facilities for reducing the probability of two or more vehicles approaching the neighborhood of an intersection simultaneously. If the subsequent aisles the vehicles are due after crossing the intersection are not overcongested and furthermore, assuming that all vehicles travel at a uniform speed (as is the case in this experiment), then it requires exactly the same length of time for each vehicle to cross the intersection zone. Since no two or more vehicles can cross or enter the intersection zone simultaneously, the sum of all delay times experienced by all the vehicles in the neighborhood of the intersection will be the same regardless of the order by which the vehicles are routed through the intersection. While intersection control rules only determine the set of vehicles to be delayed or routed through, in the macroscopic view, the system as a whole loses the same amount of time respective of the control rule (routing sequence) in force. Individual vehicles may gain or lose time at some points in the network, however, with the control rules in their present forms, the system may be no better off or worse off under the application of any rule. If any differences among the rules exists, it may be very marginal and more likely to be felt at higher levels of vehicle fleet sizes.

The sequencing of vehicles through an intersection is analogous to the n/1 machine scheduling problem where all the n jobs require identical processing times. For the case of identical processing time, regardless of the order by which the jobs are sequenced through the machine, the same makespan and mean job flow time is obtained.

However, the possibility exists that the application of more powerful intersection control rules could produce significantly better results compared to the four cases tested here. An example of a more powerful control rule could be one that has a lookahead capability as well as the ability to synchronize routing decisions at all intersections. This technique operates on the principle of an integrated intersection controller rather than on localized controllers. All the four alternatives included in the current investigation belong to the family of local controllers. Under integrated systems, intersection controllers communicate to one another or are themselves governed by a higher hierarchy controller that synchronizes the activities of all local controllers.

Another explanation why the network control rules have no significant (statistical) effect on shop performance can also be provided in terms of the magnitude of the time losses encountered by vehicles at intersection points. For vehicles traveling at about 180 feet per minute, it takes only a few seconds for any vehicle to cross the intersection. Therefore, depending on the number of vehicles queueing up to use an intersection, the sum of all time losses at any intersection by a set of vehicles at a particular instant of conflict resolution process is likely to be well under a minute. These vehicle delay (holdup) times can be translated to mean delay (holding) times for unit loads in transit. However, when these transit delay (holding) times are compared to the long waiting times unit loads undergo in queues at various workcenters, it becomes easily comprehensible why the network control rules and, hence, lost time in transit become statistically insignificant. This explanation, of course, assumes that the network is not overly loaded with vehicles so as to make traffic congestions a common place.

CHAPTER 12

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

12.1 SUMMARY

A methodology for the design of operational control elements for an Automatic Guided Vehicle (AGV) based material handling system was presented. The environment of application of the model is a manufacturing facility consisting of several workstations (machining centers) and each center having one or more identical machines. Several elements of a production facility are identified to affect the performance of an AGV system. These factors include the volume of production, and hence the type of production system, layout and selection of the guide path system, location of facilities (i.e. departments, pickup/delivery areas, etc.) in the shop, management and control of vehicles, job scheduling, vehicle fleet size, quantity of parts (i.e. size of a unit load) transported per vehicle trip, and characteristics of applicable vehicles. These factors provide the foundation or basis for the developed design model.

The general model therefore is composed of several submodels, with each submodel representing parts or combination of parts of the critical design factors listed above. The submodels include the following:

1) the job arrival model,

2) the unit load assignment model,

3) the machining center and machining process model, in 5 4) the AGV system network design model,

5) the vehicle-unit load transport model

    a) unit load pickup process,

    b) network travel,

    c) intersection crossing and control model,

    d) unit load delivery process, and

6) vehicle task assignment (dispatching) model

    a) workcenter initiated task assignment model,

    b) vehicle initiated task assignment model.

It is assumed that several classes of jobs can be processed in the model shop. The job arrival pattern into the job is described by a probability distribution. Each job that arrives consists of several parts, all identical and requiring identical shop resources. Because of the multiplicity of parts in each arriving job, the jobs are better described as batch jobs. The arrival of one job initiates the arrival of the next subsequent job. Parts are transported between workcenters by automatic guided vehicles. Because of the multiple number of parts in a batch, it is not uncommon to find components belonging to the same batch at different stages of production. This condition is made possible by the fact that several vehicle trips may be required to transport all items of a batch between any pair of points in the network. During this transport time, work completion on some of the earlier transported items may have occured, making them a candidate for a second interworkcenter move. A batch is not completed until the last item of that batch leaves the shop.

Since each job consists of several components, parts grouping is necessary for economic handling. The number of parts grouped together and transported as a unit constitutes a unit load. Thus, unit loads of jobs rather than whole jobs move through the shop. The process of specifying the number of parts to constitute a handling unit (unit load) and the selection of a particular container size to house the unit constitutes the unit load assignment model. Factors considered in the specification of an appropriate unit load size for any combination of job class and container type are the physical characteristics (i.e. weight, dimenson, geometry) of the components of the job class involved and the physical limitations (i.e. volume, dead weight, live weight) of the selected container type. Container specification is done via container selection rules. Thus, once grouped as an entity, parts in a unit load traverse through all stages of production as an entity until their shop transactions are completed.

A machining center in the model is represented as a collection of one or more identical machines and exactly two queues. A machining center is considered to occupy a physical location in the shop that is distinct from any other locations housing other departments. Unit loads are processed at the machining centers. The operation time per unit load in any department is a function of the job class, the number of parts in the unit load and the department involved.

Each job class has a predefined job route and all unit loads belonging to the same job class follow an identical path. Operation times at workcenters can be specified as constants or random variable with known probability distribution.

Serving every machining center are two unit load queues, namely, the incoming unit load queue and the outgoing unit load queue. When a unit load arrives at a workcenter, it does so through the incoming unit load queue. Thereafter, it is scheduled for processing if an idle machine is available. Otherwise, the unit load waits in the queue until a machine becomes available. The sequencing of unit loads in the queue for processing is governed by the scheduling rule in force. Completed unit loads at a center are deposited in the outgoing unit load queue and continue to remain in the queue until picked up by an automatic guided vehicle.

Both the incoming and the outgoing queues are modeled as having fixed capacities. When the incoming queue is full, subsequent deliveries into the queue is prohibited. This creates a vehicle blocking problem at a delivery point. Accordingly, a machine blocking problem exists if the outgoing queue is full and subsequent deposition of completed unit loads by machines can no longer be achieved. The blocking will persist until a queue space is released.

The vehicles provide the transport mechanism for all job entities in the shop. The wire guidance system on which the vehicles operate is modeled as a unidirectional network consisting of nodes and arcs. The nodes represent the intersection points while the arcs represent the aisles. The location of every node is uniquely defined by its Cartesian cordinate. Also, the specification of the nodes bounding an arc uniquely identifies it (i.e. the arc). Only 'I' and 'L' shaped arcs are permitted by the model. All other shapes including 'U' shaped arcs are invalid. Parallel arcs between adjacent nodes are also not allowed. The shape of the arcs and the cordinates of the nodes are used in calculating the distance between two points in the network along the direction of traffic flow. The distance calculation model explicitly recognizes any changes in direction of traffic flow as vehicle transfers are made from one arc to another at node points.

The movement of unit loads and vehicles in the guidance network is modeled as the 'Vehicle-Unit Load Transport System.' Here, the various maneuvers required of vehicles in the network are modeled. The maneuvers include a) unit load pickup activity, b) unit load delivery activity, c) network travel along the arcs, and d) intersection crossing.

The unit load pickup and delivery activities are modeled as events that require the passage of time. The elasped time between the beginning and the ending of the pickup/delivery function is equivalent to the pickup/delivery time. A vehicle dwells at the pickup/delivery point until the pickup/delivery task is completed. During the dwell time, other vehicles are prohibited from occupying the same pickup/delivery area.

This implies that simultaneous undertaking of loading/unloading operations by two or more vehicles at any pickup/delivery point is not permitted.

Network travel along the arcs is represented as a series of successive discrete jumps by vehicles between adjacent nodes and in the direction of traffic flow. The jump (travel) time is a function of vehicle traveling speed, distance between the end points of the jump, and the actual traffic density in the arc joining the points. The actual jump time is not known until the vehicle arrives at the other end of the jump. The model has a lookahead (information gathering) capability that allows vehicles to react immediately to changing traffic conditions along their path of travel.

The intersection crossing model involves a system of control logic, decision making processes, and lookahead capabilities. The lookahead function permits a vehicle in the neighborhood of an intersection to receive appropriate information and instructions regarding traffic condition around the intersection. The information is processed according to the control algorithm in force. From this algorithm, a decision is made on whether a vehicle should hold, yield for right of way for other vehicles, or proceed unimpeded through the intersection. The decision making process is repeated at every intersection on the travel path of the vehicle until the final destination is reached.

The vehicle task assignment (dispatching) problem arises in two forms. It arises when a pickup task is generated at some location in the facility and there are multiple vehicles that can be assigned the task. The problem therefore is one of deciding on and selecting a vehicle from the idle set to assign the task. The problem is alternatively generated when a vehicle previously assigned a mission is released and is to be reassigned to another task. If several pickup tasks exist simultaneously at the time the vehicle was released, then the problem is one of deciding on which task to assign the vehicle. Several heuristic rules were presented for resolving these two categories of problems.

All the submodels discussed above were integrated to form a unified model and implemented through a computer simulation. The simulation model provided the tools under which several experiments were performed for the testing of the effects of several design factors. Vehicle dispatching rules, unit load assignment rules, job sequencing rules at workcenter level, network control algorithm, and shop loading were the factors whose effects were investigated.

12.2 CONCLUSIONS

Through a series of simulation experiments, the behavior of an AGV-based material handling system was characterized under several operating conditions. The results from the experiments indicated the following:

a) Unless the pickup/delivery points of the machining centers are well located with respect to one another, some combinations of vehicle dispatching rules, especially those derived from distance measures, are likely to lock up the shop at some point in time. This phenomenon can be expected if some pickup point is neither the nearest nor the farthest away from some delivery point. For less busy shop, locking may not occur.

b) Unless an Automatic Guided Vehicle System has the capability to identify and initiate actions to free a blocked department, regular intervention (manual or automatic) on the system may be necessary to reactivate blocked departments or shops in order to maintain regular flow of materials through the shop. The frequency of intervention depends on the form of vehicle dispatching rules in force, facility layout condition, and volume of material flow.

c) Without a good shop layout, pre-programmed sequential visits to departments by vehicles as a dispatching strategy is counter productive. The system looses its flexibility and versatility to exhibit its full conveying potential.

d) Vehicle task assignment (dispatching) rules affect the overall performance of an AGV system. Performances among different levels of Vehicle Initiated Task Assignment rules were significantly different. More experimental work is required to actually classify and rank the competitive rules (i.e MROQS and MFCFS) in this family. No differences were observed between the levels of Workcenter Initiated Task Assignment rules investigated.

e) Different unit load sizes affect shop performance differently, using system throughput as a measure. Larger unit loads accelerate jobs faster through the shop than smaller unit loads. This result is more pronounced when the volume of material flow is heavy compared to available handling resource. For a fixed shop condition, the performance measure improves with increasing unit load size. Of course, it is only logical to interpret this result with caution. There is likely an upper limit on the applicable size of unit loads beyond which the system performance starts to deteriorate. The rated capacity of the applicable AGVs may also constrain the size of unit loads.

f) For the shop modeled in the experiments, unit load sequencing rules were not found to have any significant effect on shop performance. This may be due to the fact that handling devices rather than machines at the workcenters were the constraining resource in the material flow link. If the incoming unit load queues were allowed to grow or machines rather than vehicles become the constraining resource, a significantly different result may obtain.

g) Shop loading affects system performance measures. As long as there are sufficient number of unit loads to be transported and processed on the shop floor, increasing shop loading decreases the overall performance of the shop if system throughput is the primary measure of performance.

h) The four network control alternatives investigated in the study have significantly the same mean effect on the shop performance.

In all the experiments and the analyses performed, system throughput measured in unit loads or jobs were used as the primary measure of system performance. Other performance measures such as mean job flow time, mean number of jobs in the shop, and mean queue lengths were also provided as secondary criteria in some sections of the analyses.

It should be well understood that the interpretation of the above conclusions should be made within the context of the applicable size of data employed in drawing these conclusions. Actual decision making processes based on the inferences drawn above may require much larger number of experimental replications to reach any firm conclusions.

12.3 RECOMMENDATIONS

While reports of increased corporate research on AGVS hardware is not uncommon, also common is the increasing use of AGV system in both manufacturing and warehousing. However, the increase on corporate research is not being matched by a corresponding increase on research directed to the application of AGV system. The operational system design view taken in this research is a move in the direction to emphasize the importance of operational factors in attaining a functioning system. The study is, however, far from being complete. There are several aspects of AGV system applications that require further investigation.

For example the current model uses a preselected path between two points in the network for routing vehicles. This path selection is static and corresponds to the shortest path between the two points. An improved path selection procedure will be one that responds to changing traffic conditions in the network. Such selection will be dynamic and flexible. Under this alternative, paths are not prespecified at departure time of vehicles but are continuously being updated as the vehicle moves from one intersection to another. At intersection points, vehicles make path selection decisions that consider expected travel distance as well as responding to actual and anticipated traffic conditions along all possible paths between the current vehicle location and its final destination. A path selected at one node may only be used up to the next node where a new path selection decision is made using up-to-date traffic information in the network. Thus, the actual path taken by a vehicle from its point of origin to its final destination may not necessarily be the shortest path but may result in the shortest travel time path if the procedure is to be meaningful.

Another extension that is closely related to the dynamic vehicle rerouting problem suggested above is the concept of a global network control system rather than a series of independently applied local controls whose activities are uncoordinated. Under the global control concept, vehicle intersection crossing decisions at all intersections are coordinated and are made based on the expected effect of such decisions on the entire network at some near future time. Such future effect could be evaluated in terms of degree of vehicle interferences introduced by taking a certain action.

Finally, the value of the experimental results obtained in this study could be greatly enhanced if real factory data were used.

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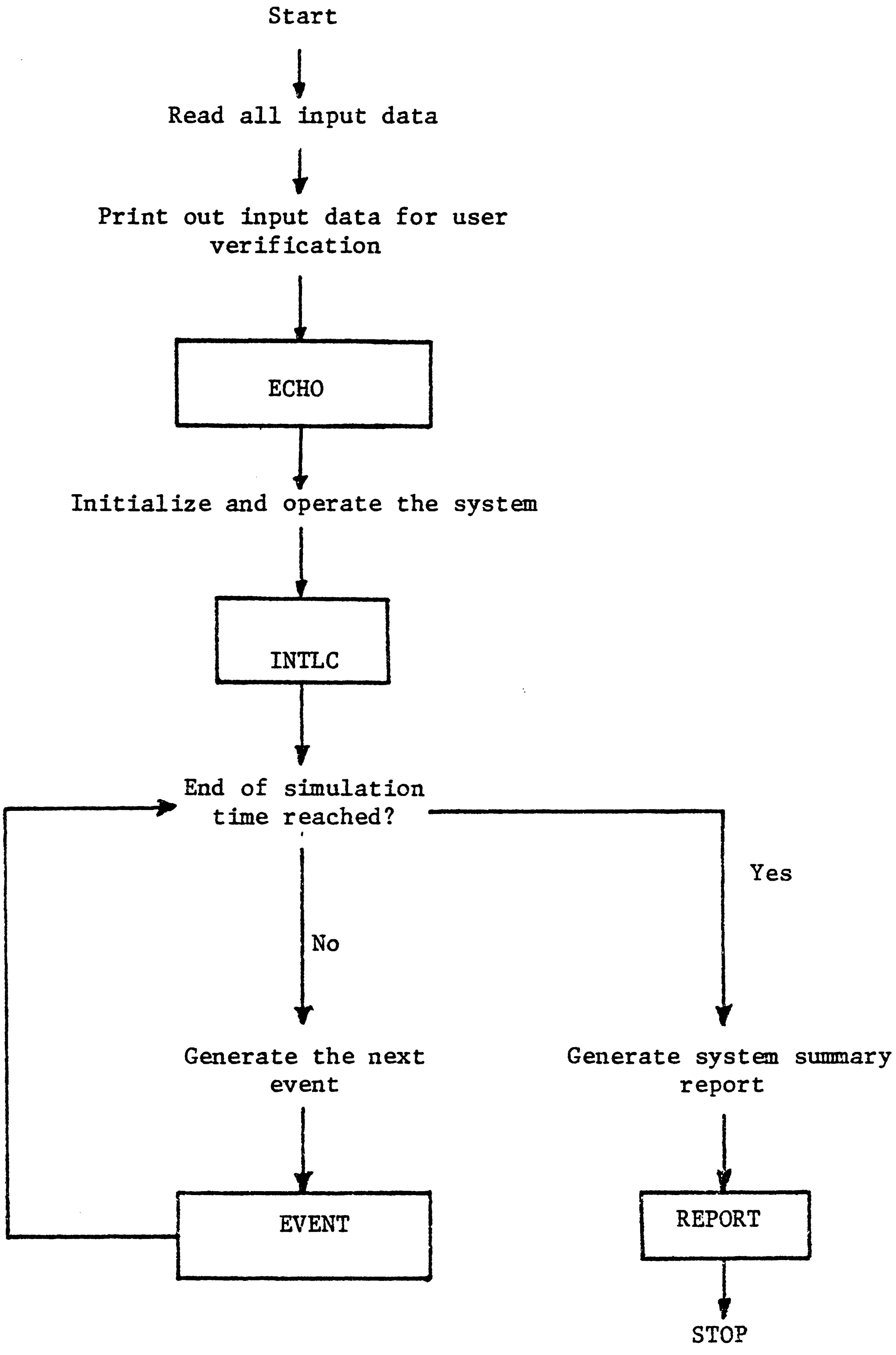
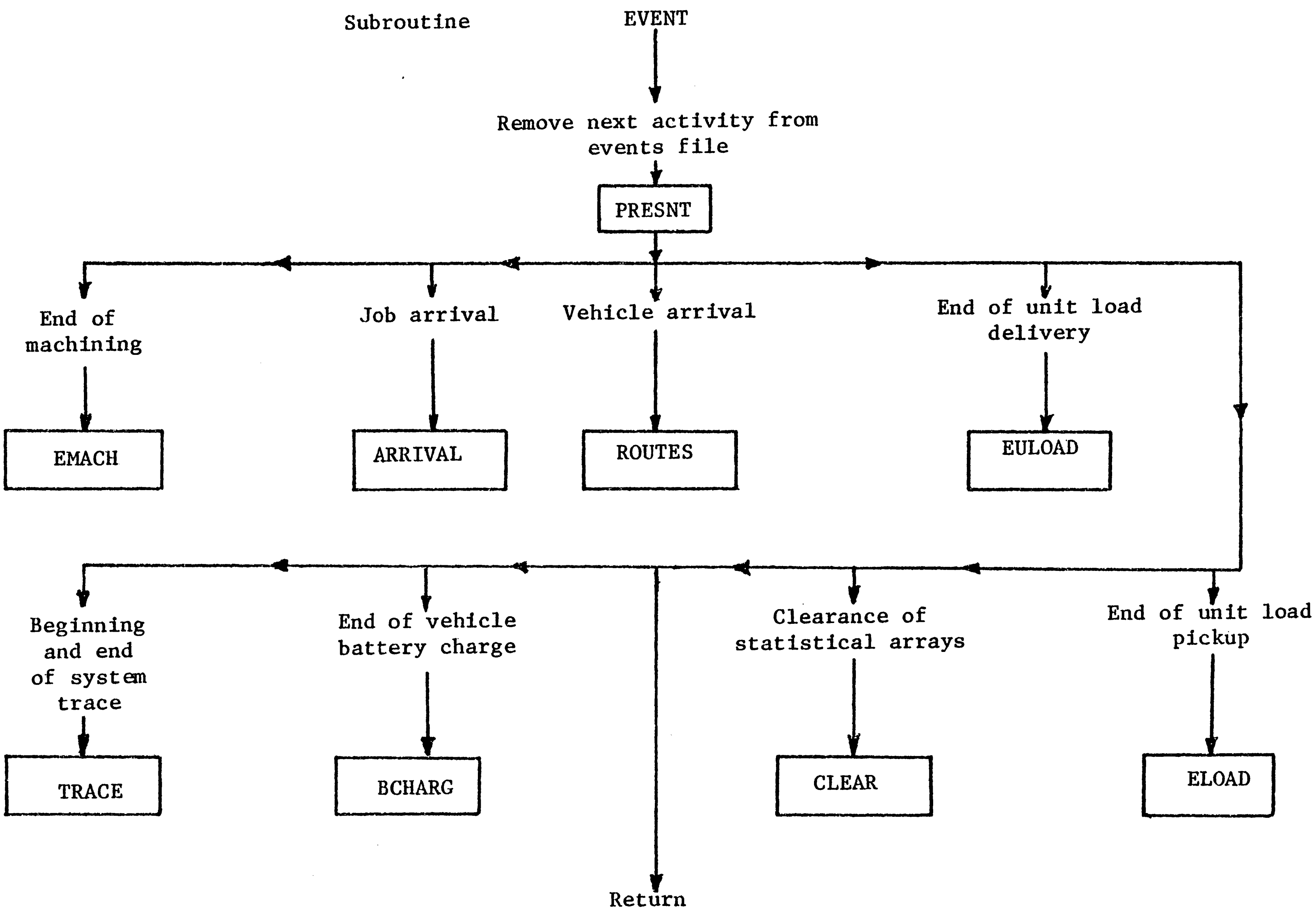
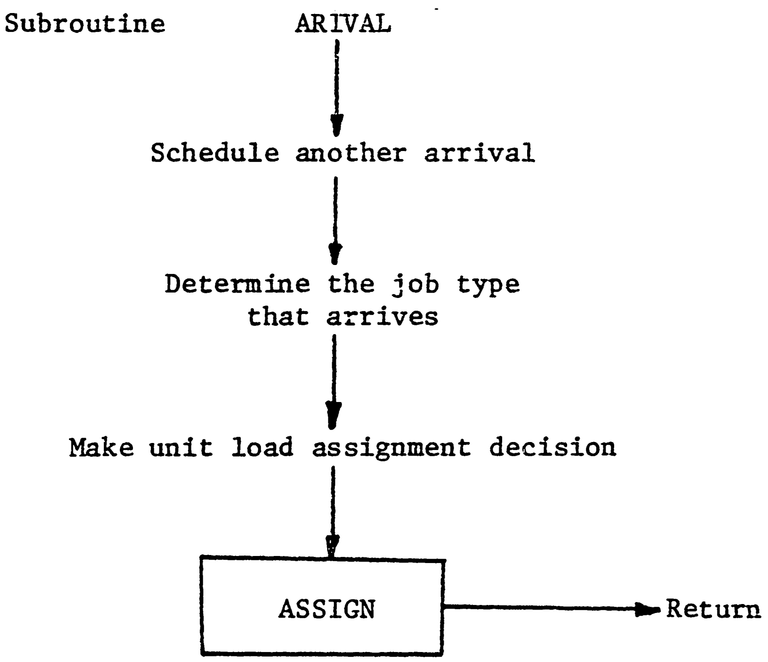
APPENDIX A

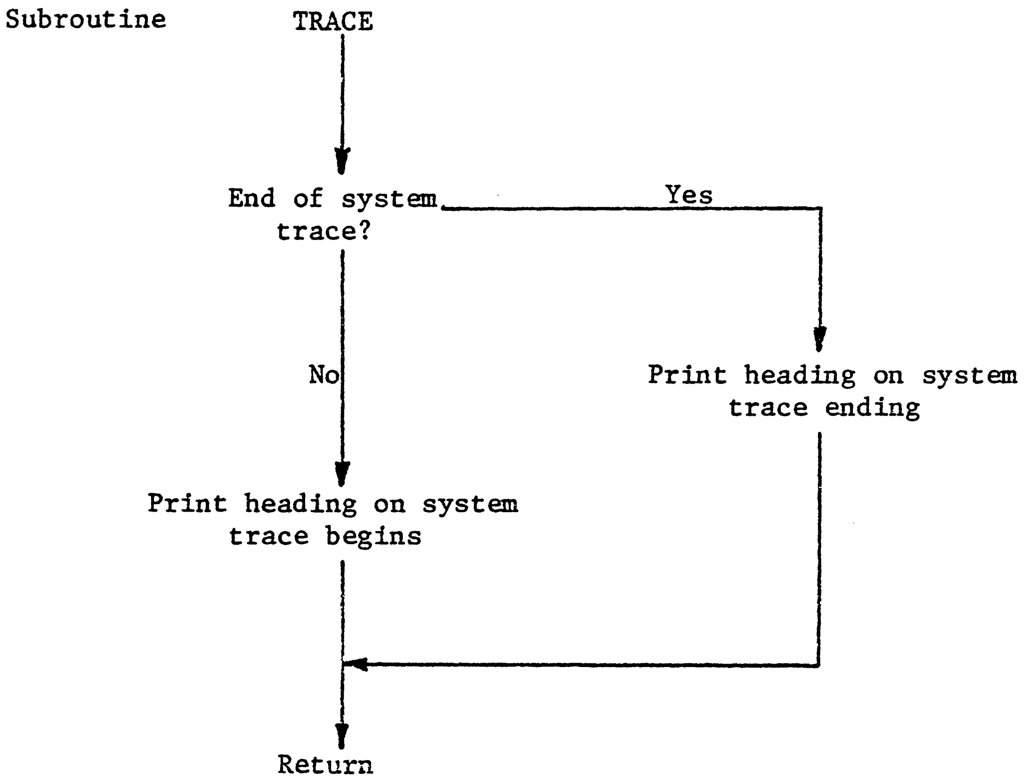
Simulator Flowcharts

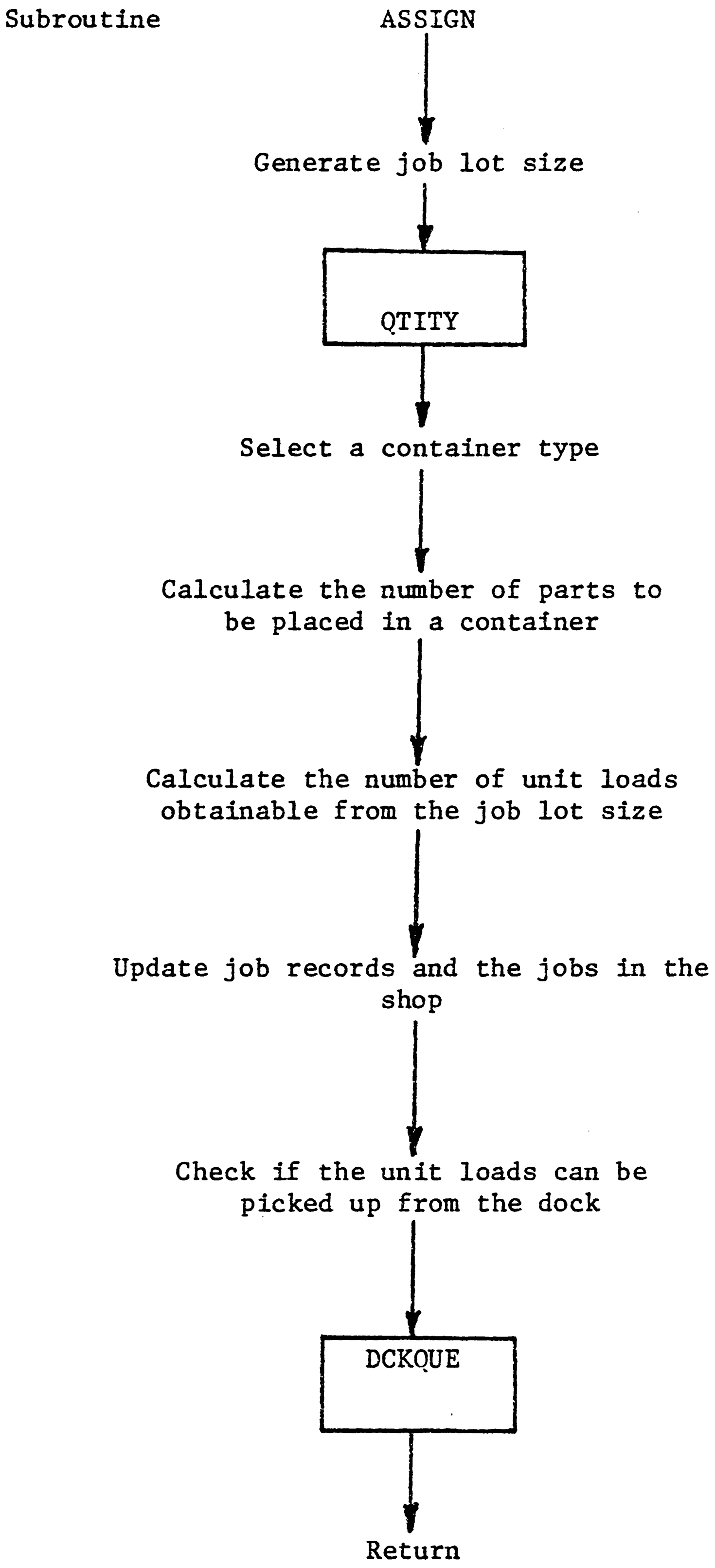
MAIN PROGRAM

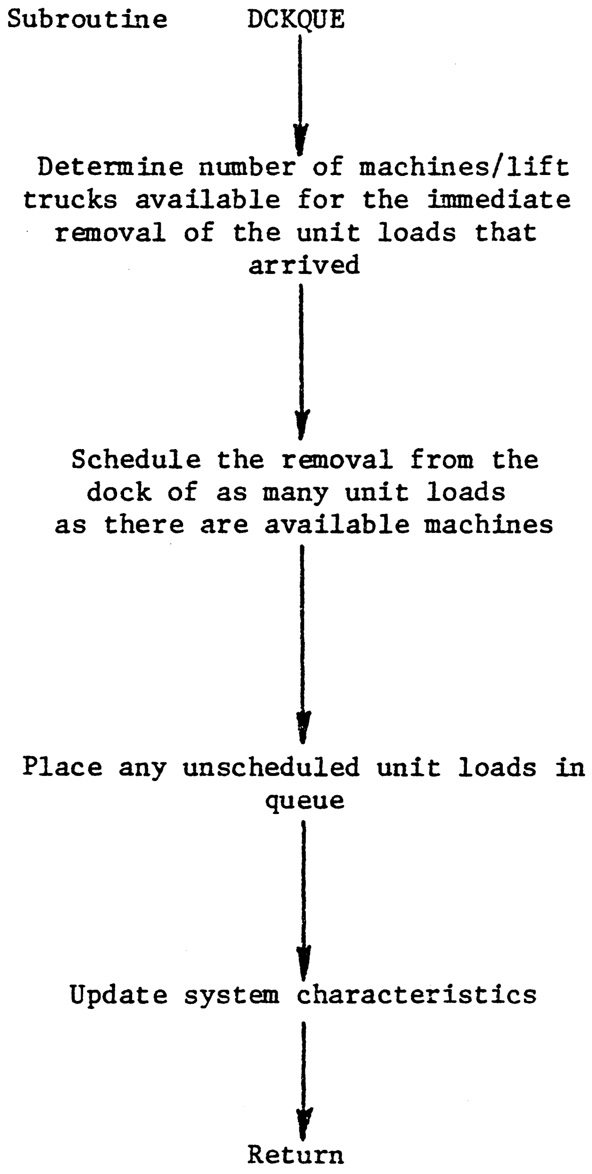


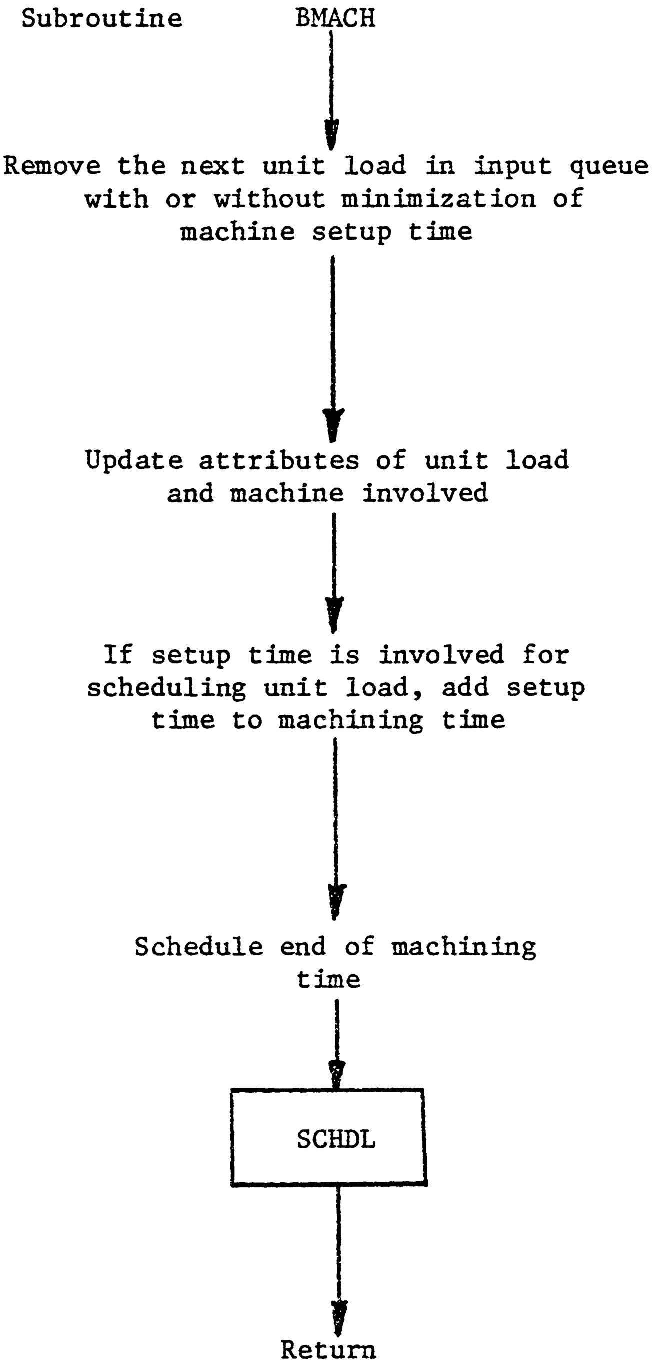

Subroutine EVENT
Remove next activity from events file
PRESNT
End of machining
Job arrival
Vehicle arrival
End of unit load delivery
EMACH
ARRIVAL
ROUTES
EULOAD
Beginning and end of system trace
End of vehicle battery charge
Clearance of statistical arrays
End of unit load pickup
TRACE
BCHARG
CLEAR
ELOAD
Return

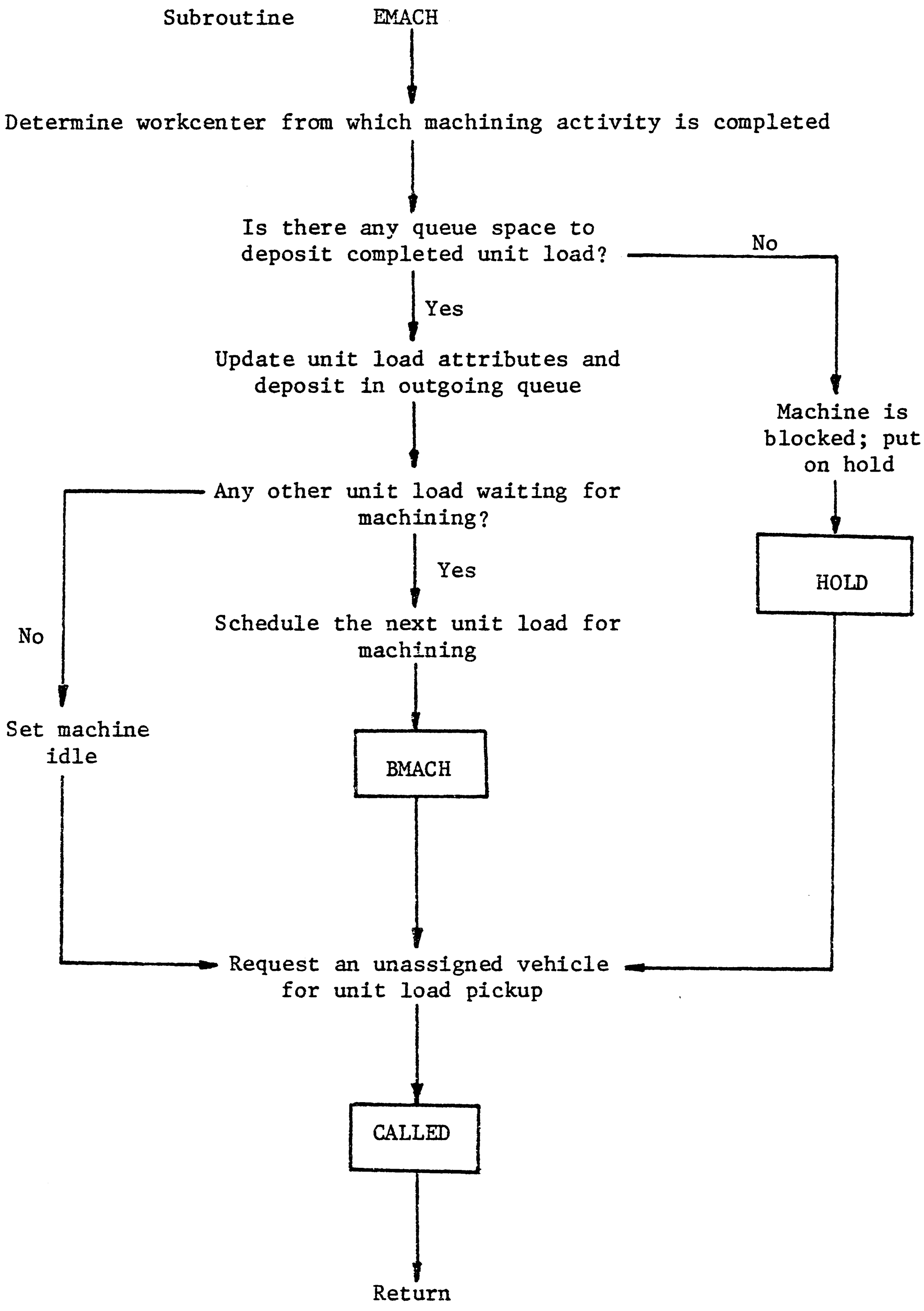

Subroutine
ARIVAL
Schedule another arrival
Determine the job type that arrives
Make unit load assignment decision
ASSIGN
Return

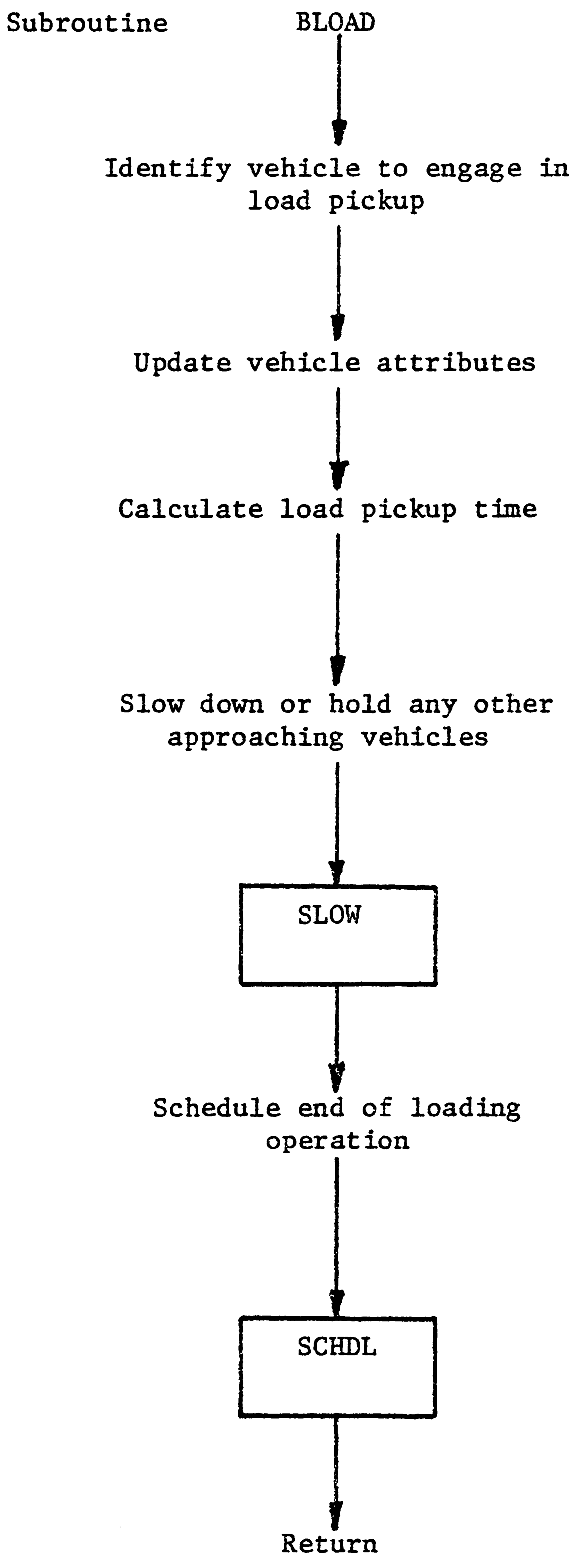

Subroutine
TRACE
End of system trace?
Yes
No
Print heading on system trace ending
Print heading on system trace begins
Return

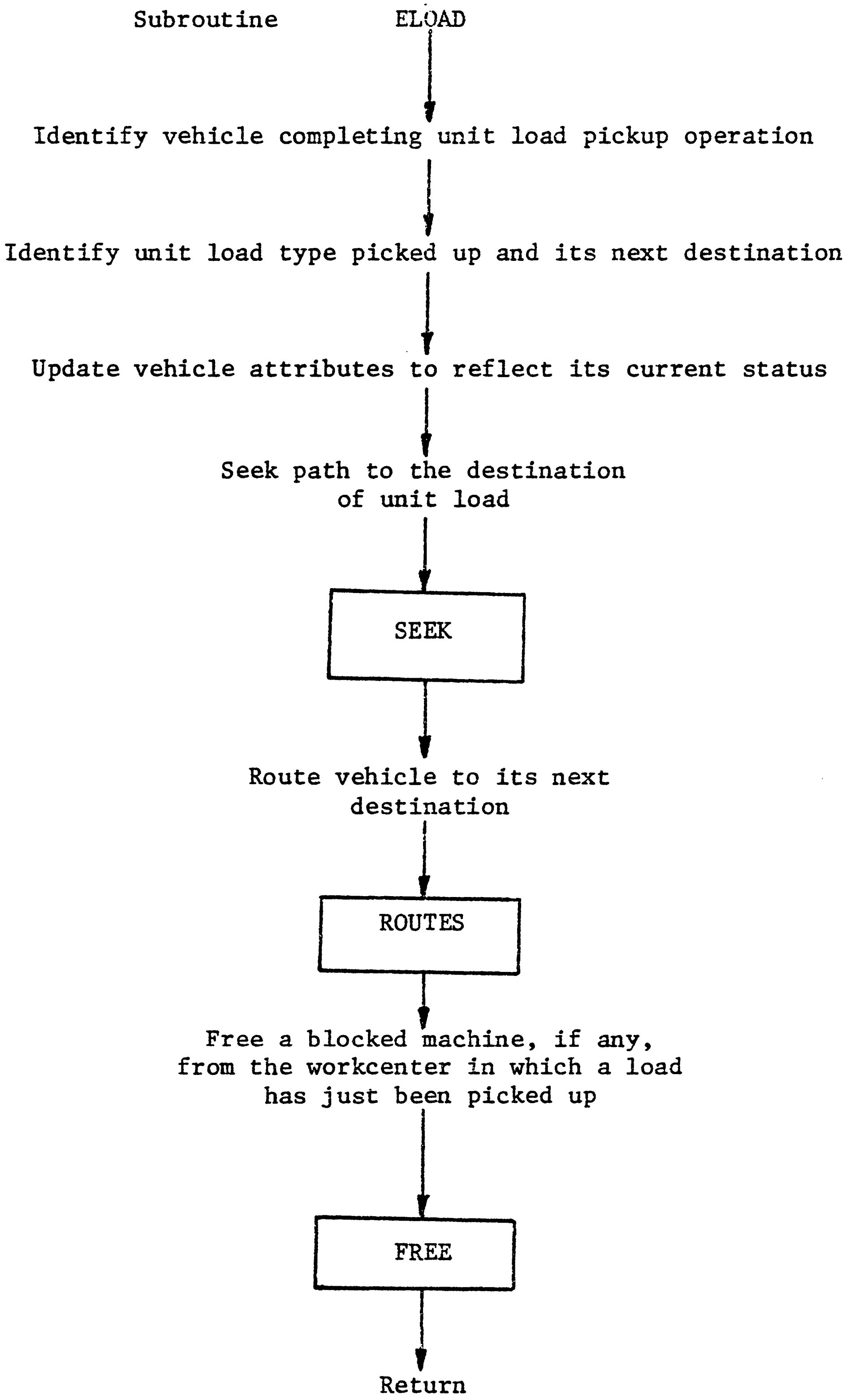

Subroutine
ASSIGN
Generate job lot size
QTITY
Select a container type
Calculate the number of parts to be placed in a container
Calculate the number of unit loads obtainable from the job lot size
Update job records and the jobs in the shop
Check if the unit loads can be picked up from the dock
DCKQUE
Return


Subroutine DCKQUE
Determine number of machines/lift trucks available for the immediate removal of the unit loads that arrived
Schedule the removal from the dock of as many unit loads as there are available machines
Place any unscheduled unit loads in queue
Update system characteristics
Return

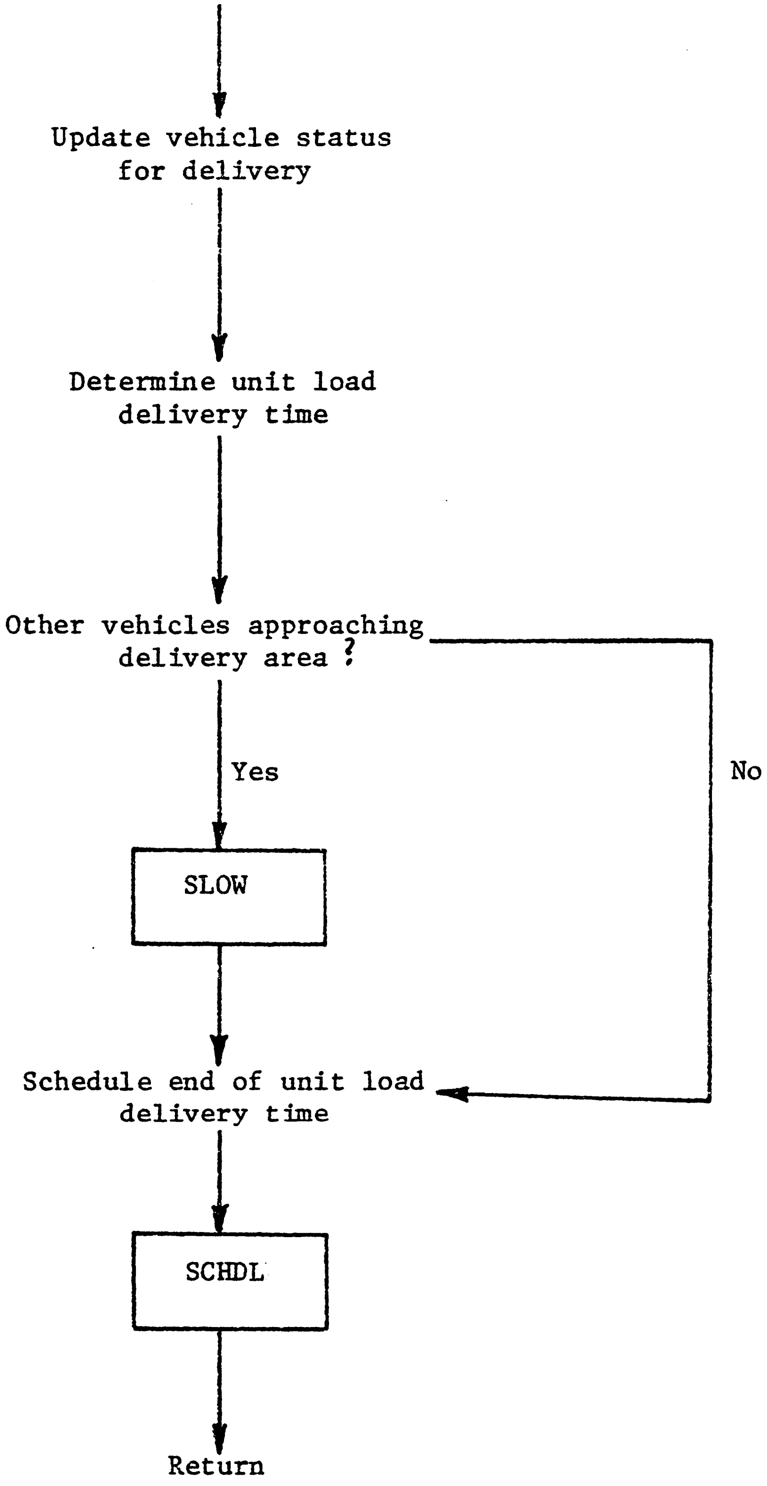

Subroutine BMACH
Remove the next unit load in input queue with or without minimization of machine setup time
Update attributes of unit load and machine involved
If setup time is involved for scheduling unit load, add setup time to machining time
Schedule end of machining time
SCHDL
Return

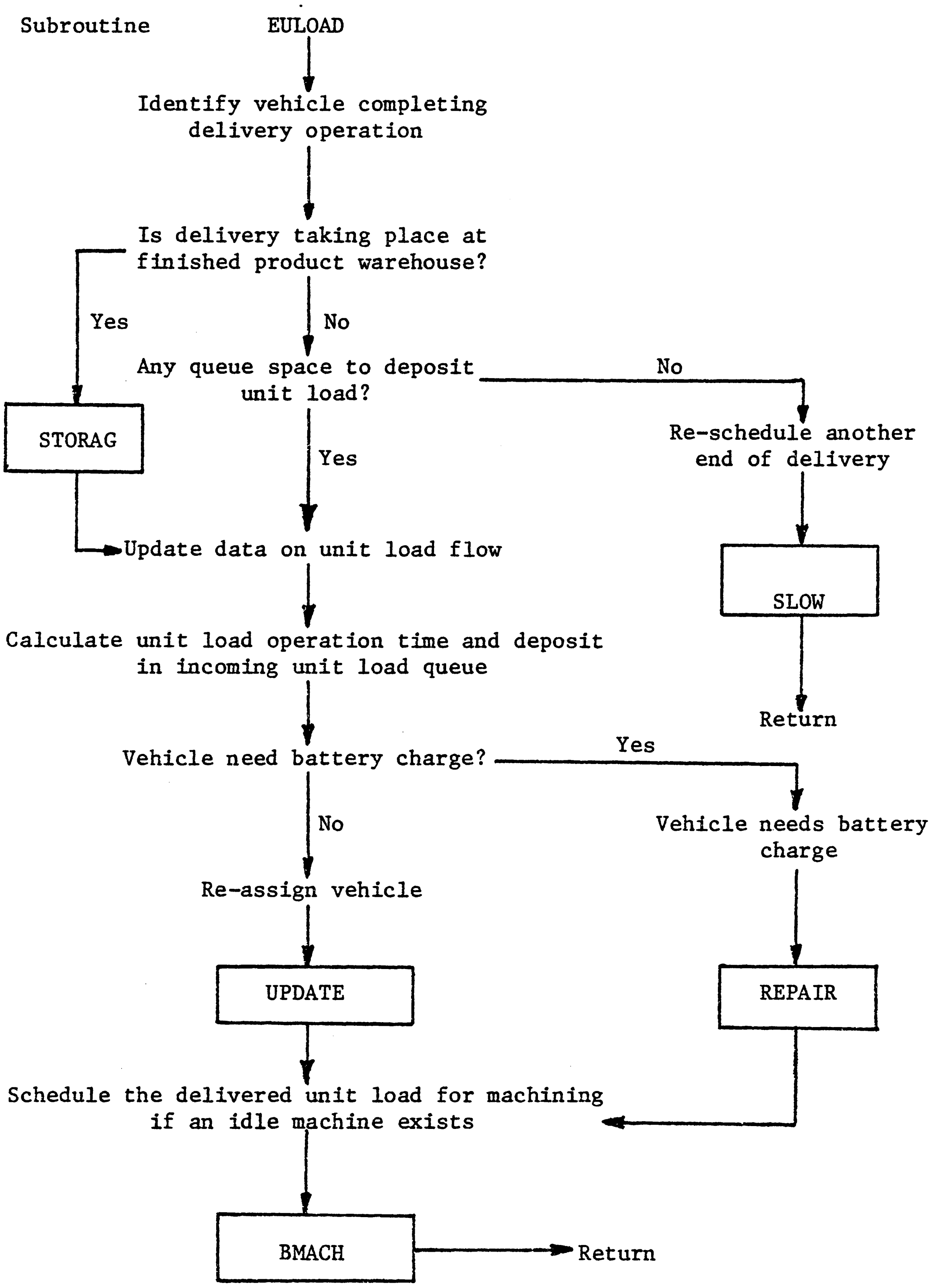

Subroutine EMACH
Determine workcenter from which machining activity is completed
Is there any queue space to deposit completed unit load?
No
Yes
Update unit load attributes and deposit in outgoing queue
Machine is blocked; put on hold
Any other unit load waiting for machining?
HOLD
Yes
No
Schedule the next unit load for machining
Set machine idle
BMACH
Request an unassigned vehicle for unit load pickup
CALLED
Return

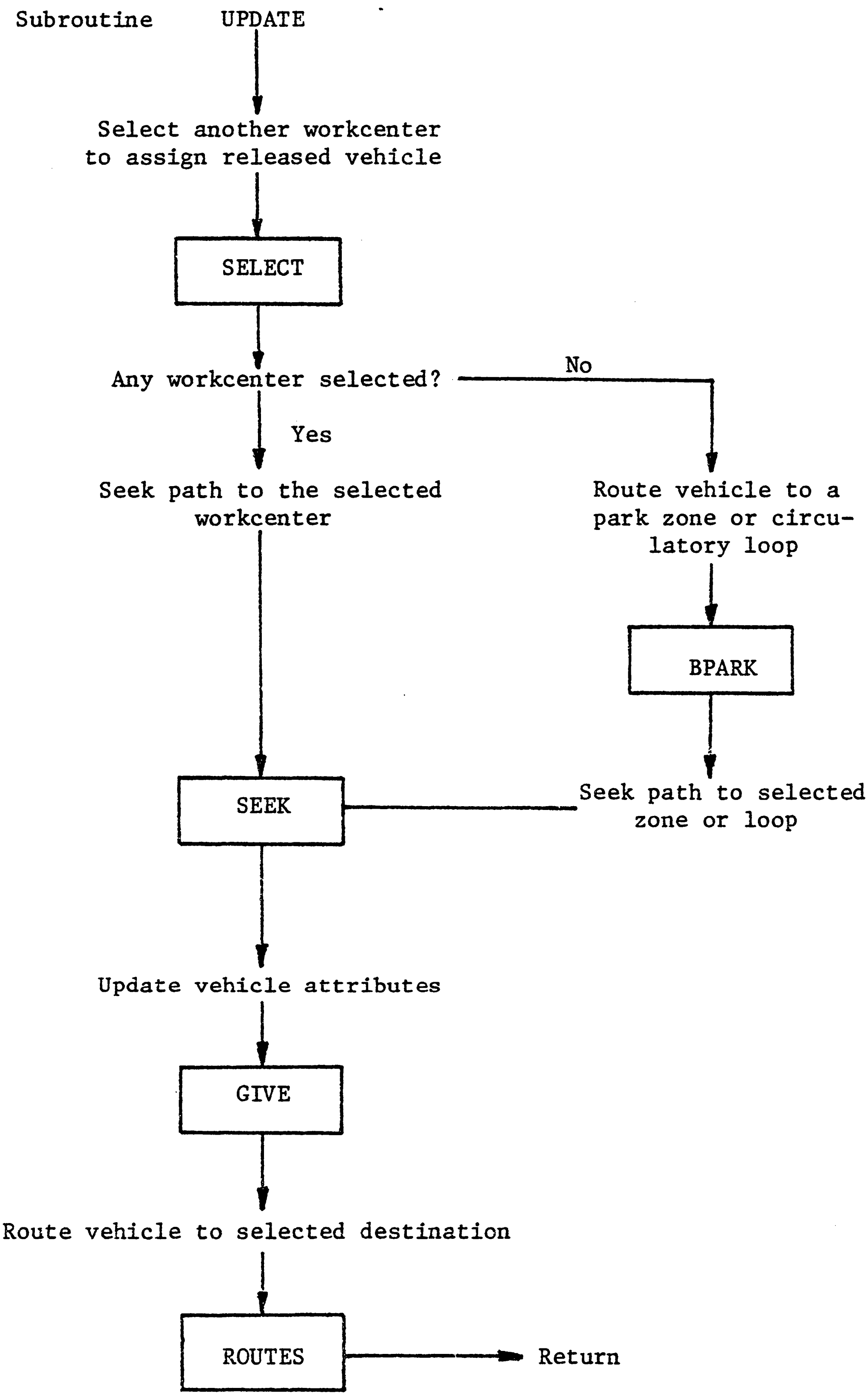

Subroutine BLOAD
Identify vehicle to engage in load pickup
Update vehicle attributes
Calculate load pickup time
Slow down or hold any other approaching vehicles
SLOW
Schedule end of loading operation
SCHDL
Return

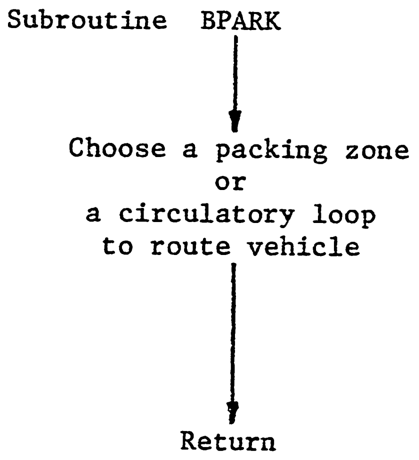

Subroutine ELOAD
Identify vehicle completing unit load pickup operation
Identify unit load type picked up and its next destination
Update vehicle attributes to reflect its current status
Seek path to the destination of unit load
SEEK
Route vehicle to its next destination
ROUTES
Free a blocked machine, if any, from the workcenter in which a load has just been picked up
FREE
Return

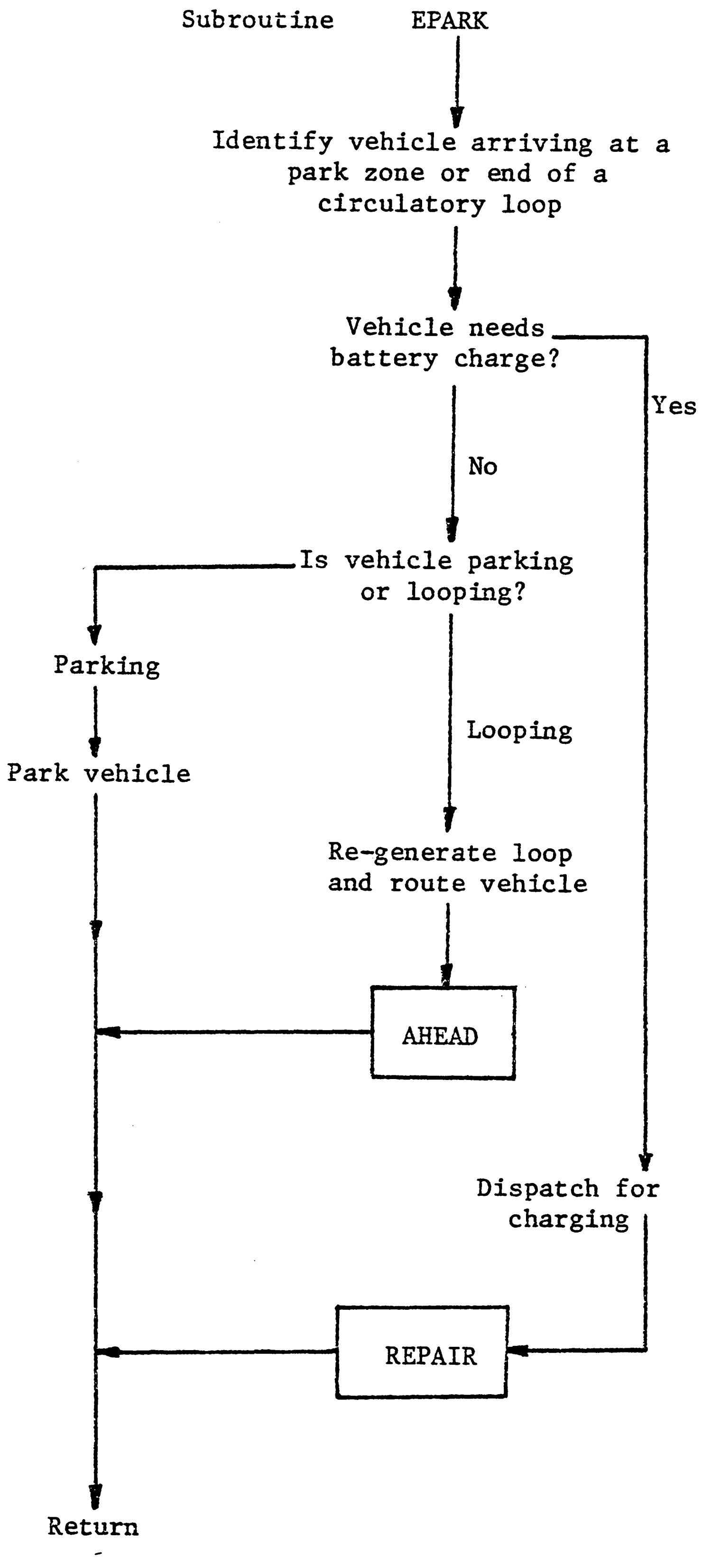
Subroutine UNLOAD

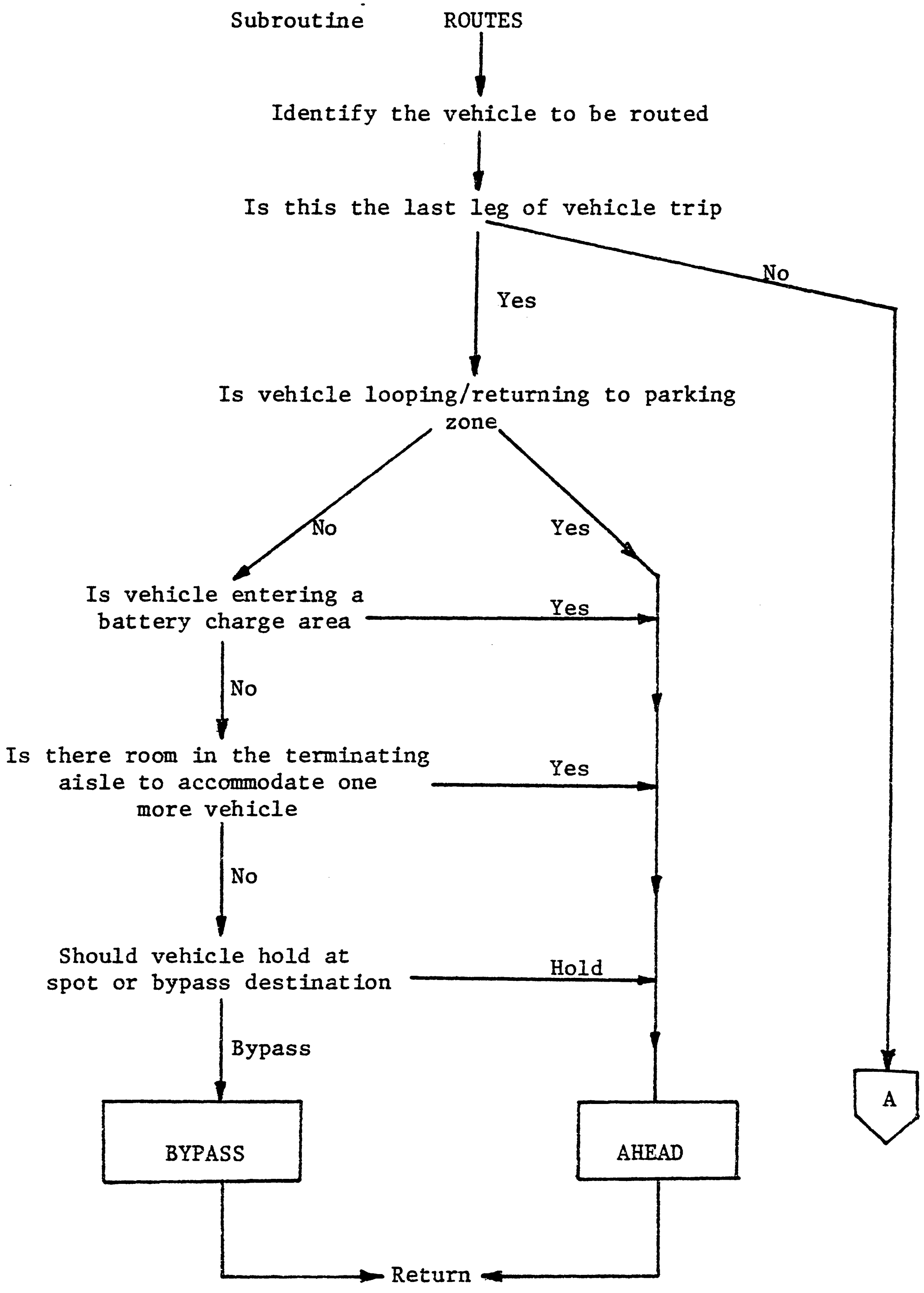



Subroutine
EULOAD
Identify vehicle completing delivery operation
Is delivery taking place at finished product warehouse?
Yes
No
Any queue space to deposit unit load?
No
STORAG
Re-schedule another end of delivery
Yes
Update data on unit load flow
SLOW
Calculate unit load operation time and deposit in incoming unit load queue
Return
Yes
Vehicle need battery charge?
No
Vehicle needs battery charge
Re-assign vehicle
UPDATE
REPAIR
Schedule the delivered unit load for machining if an idle machine exists
BMACH
Return

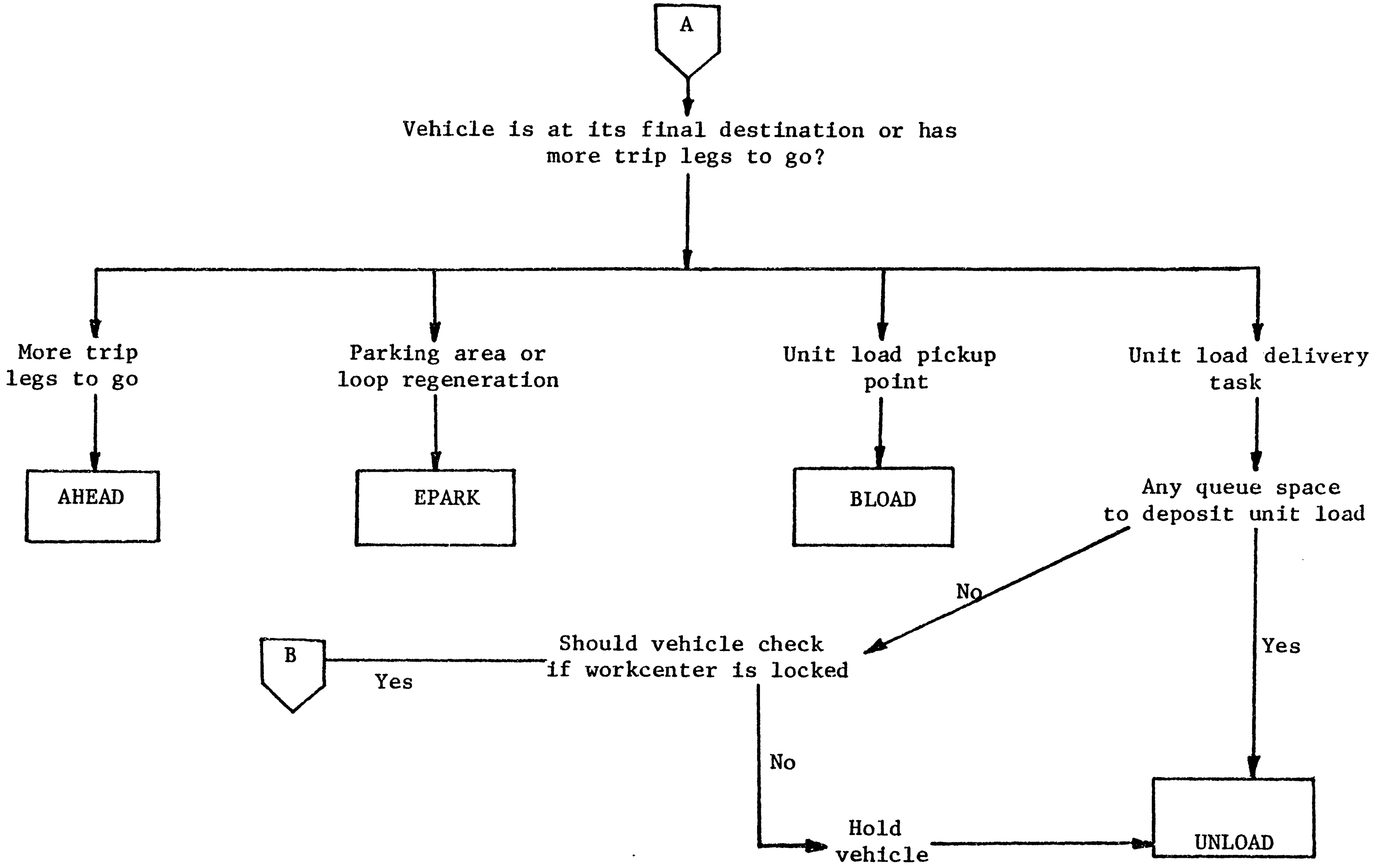

Subroutine UPDATE
Select another workcenter to assign released vehicle
SELECT
Any workcenter selected?
No
Yes
Seek path to the selected workcenter
Route vehicle to a park zone or circulatory loop
BPARK
SEEK
Seek path to selected zone or loop
Update vehicle attributes
GIVE
Route vehicle to selected destination
ROUTES
Return


Subroutine BPARK
Choose a packing zone
or
a circulatory loop
to route vehicle
Return

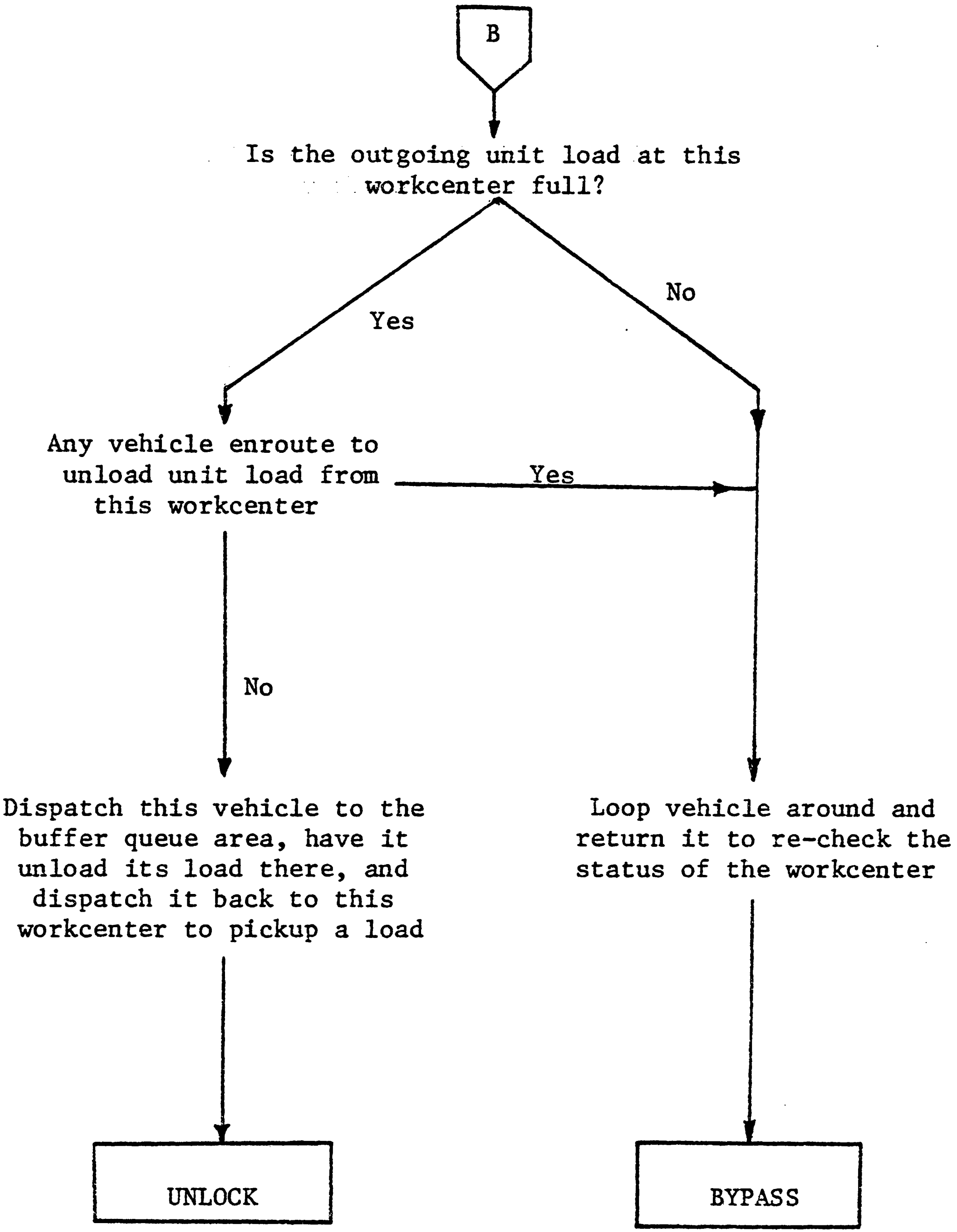

Subroutine EPARK
Identify vehicle arriving at a
park zone or end of a
circulatory loop
Vehicle needs
battery charge?
Yes
No
Is vehicle parking
or looping?
Parking
Park vehicle
Looping
Re-generate loop
and route vehicle
AHEAD
Dispatch for
charging
REPAIR
Return

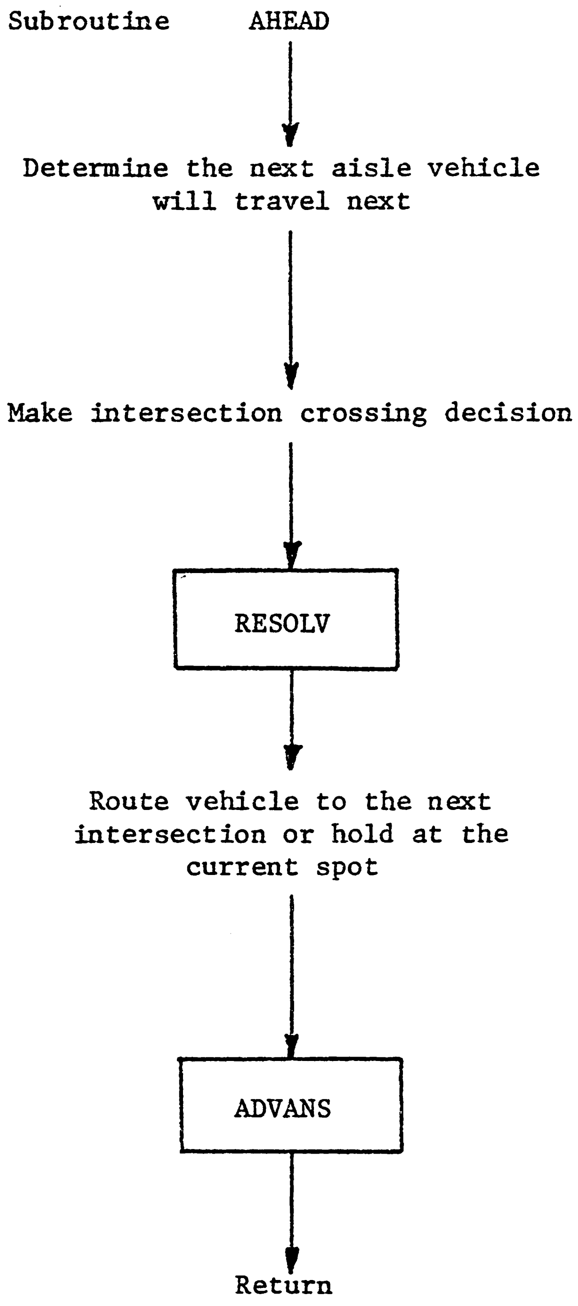

Subroutine ROUTES
Identify the vehicle to be routed
Is this the last leg of vehicle trip
Yes
No
Is vehicle looping/returning to parking zone
No
Yes
Is vehicle entering a battery charge area
Yes
No
Is there room in the terminating aisle to accommodate one more vehicle
Yes
No
Should vehicle hold at spot or bypass destination
Hold
Bypass
BYPASS
AHEAD
A
Return

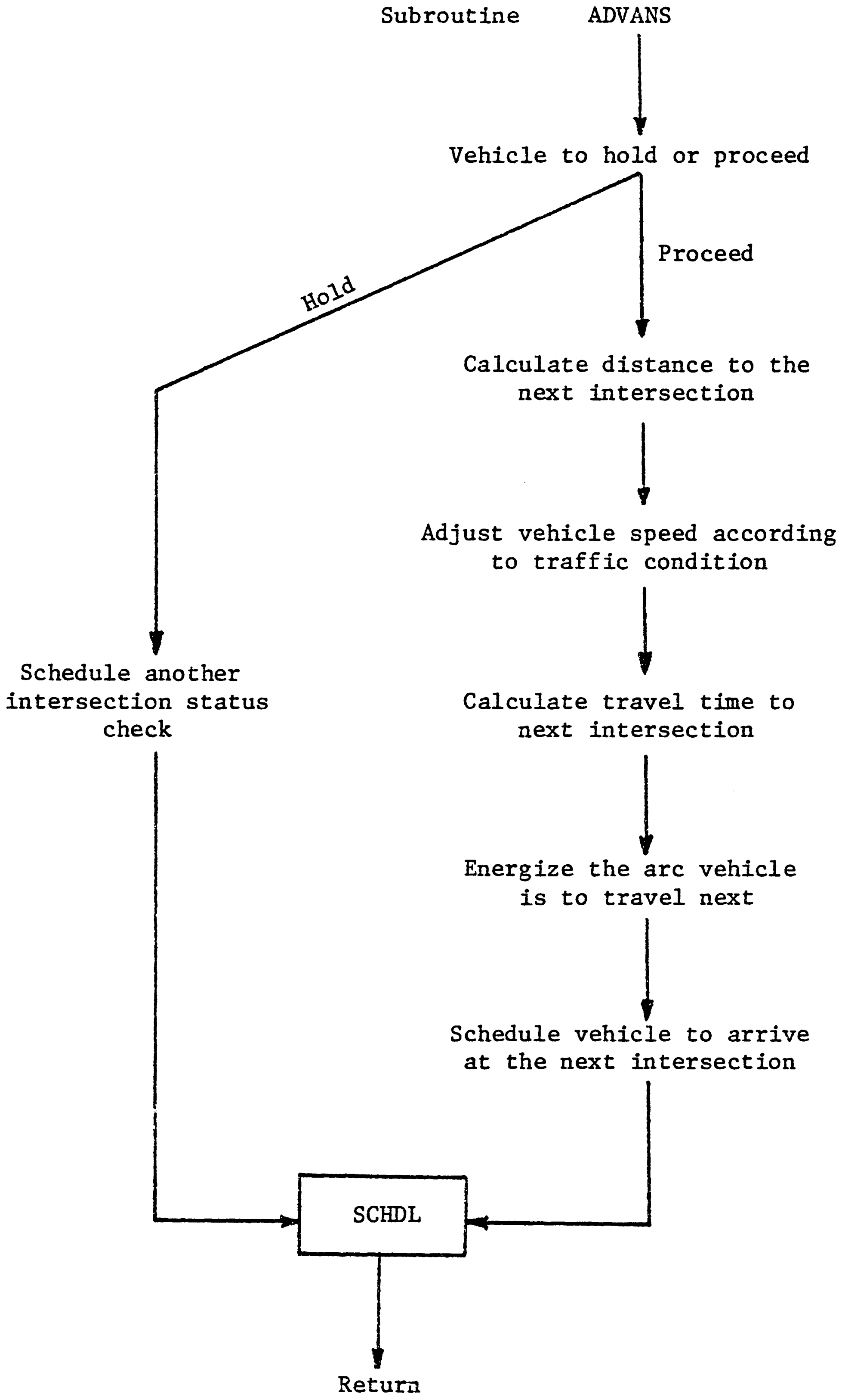
Subroutine ROUTES Continues

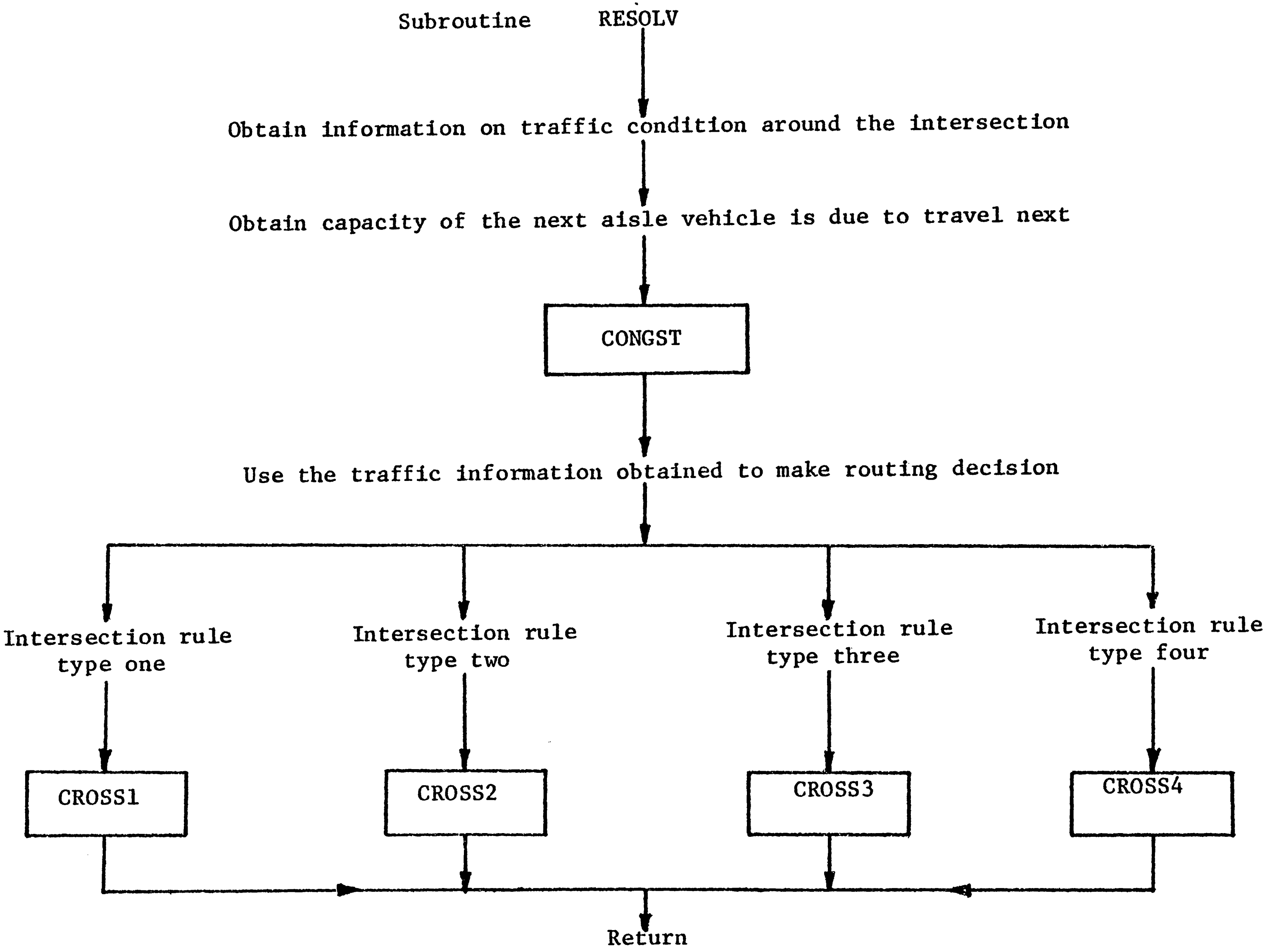


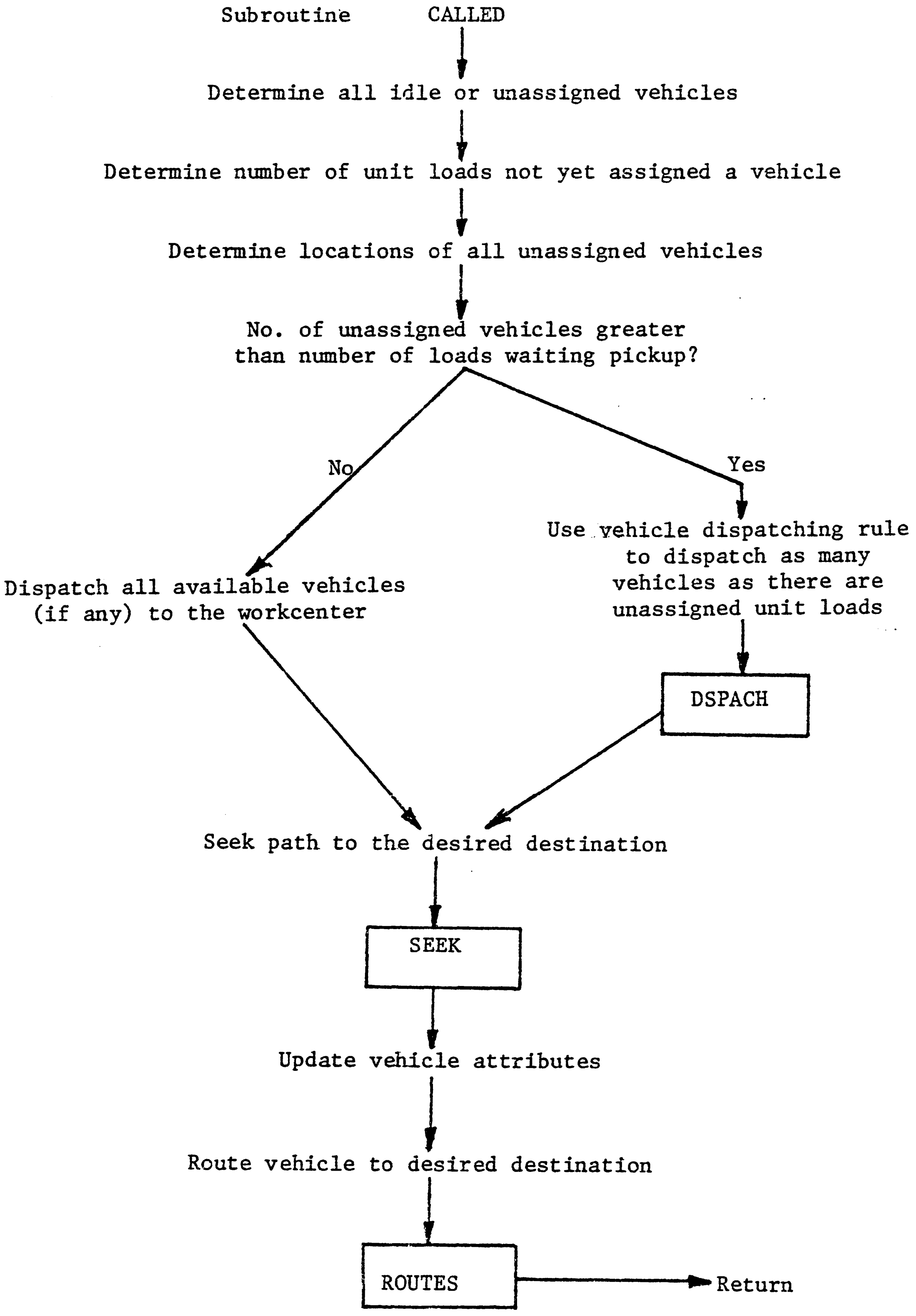
Subroutine ROUTES Continues



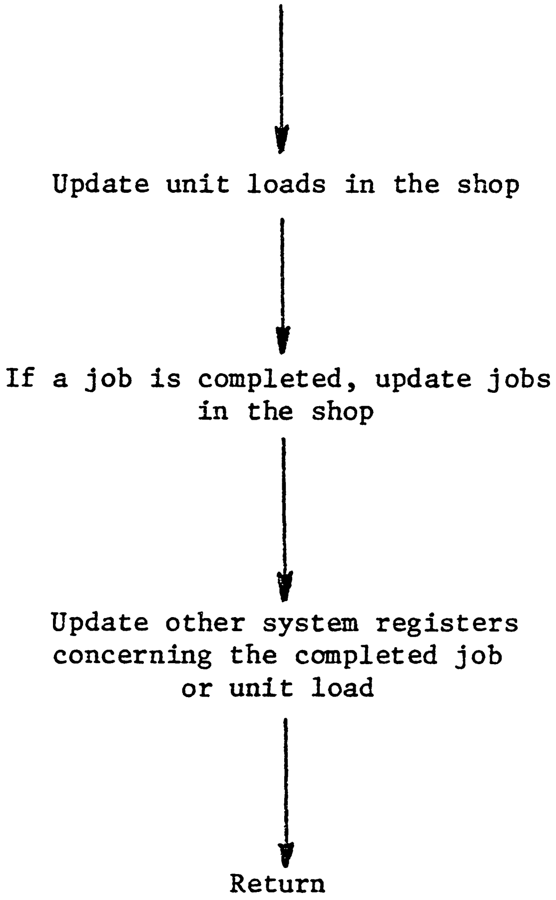

Subroutine AHEAD
Determine the next aisle vehicle will travel next
Make intersection crossing decision
RESOLV
Route vehicle to the next intersection or hold at the current spot
ADVANS
Return

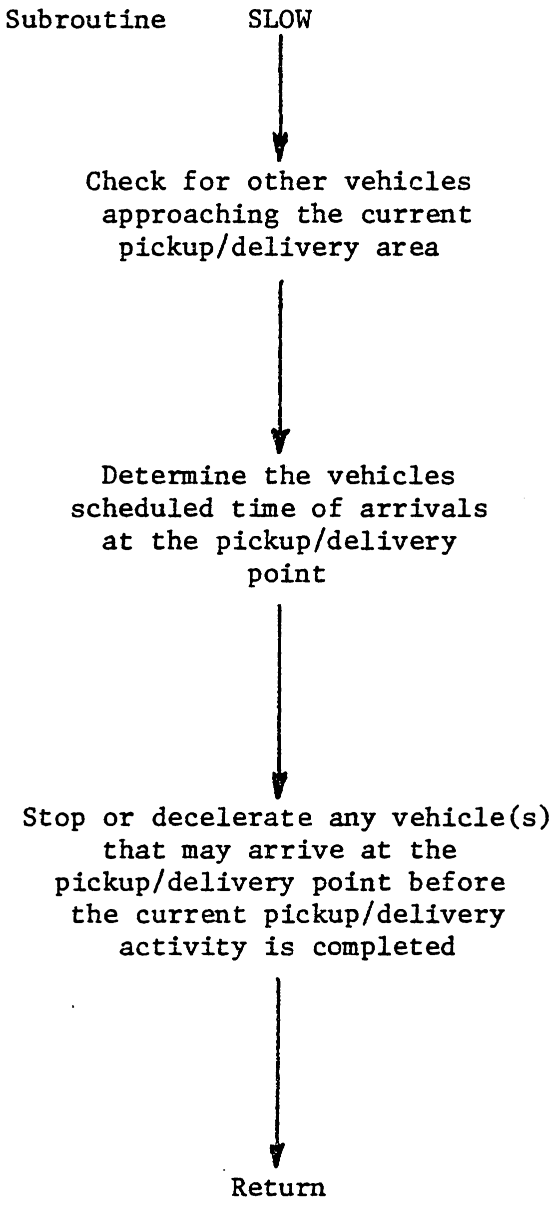

Subroutine ADVANS
Vehicle to hold or proceed
Hold
Proceed
Calculate distance to the next intersection
Adjust vehicle speed according to traffic condition
Calculate travel time to next intersection
Energize the arc vehicle is to travel next
Schedule vehicle to arrive at the next intersection
Schedule another intersection status check
SCHDL
Return

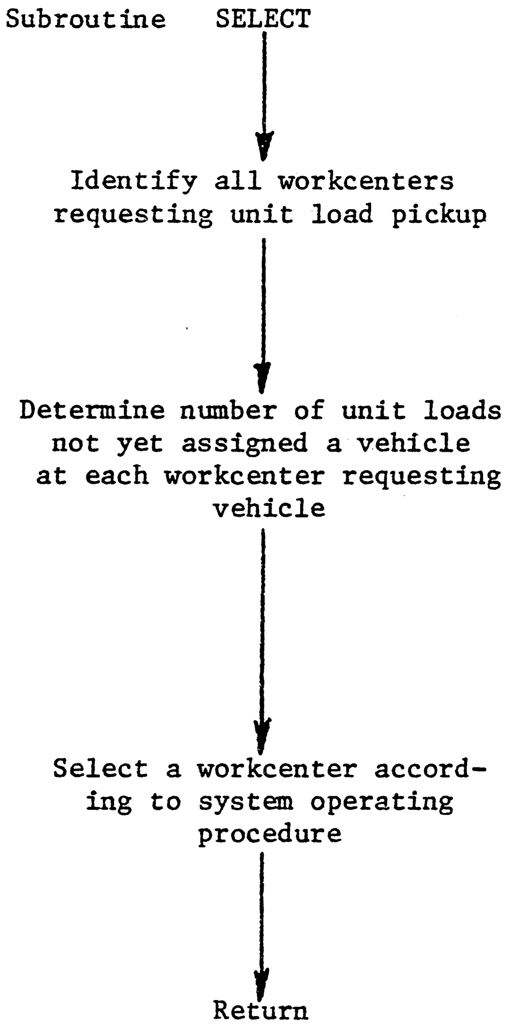

Subroutine RESOLV
Obtain information on traffic condition around the intersection
Obtain capacity of the next aisle vehicle is due to travel next
CONGST
Use the traffic information obtained to make routing decision
Intersection rule type one
Intersection rule type two
Intersection rule type three
Intersection rule type four
CROSS1
CROSS2
CROSS3
CROSS4
Return

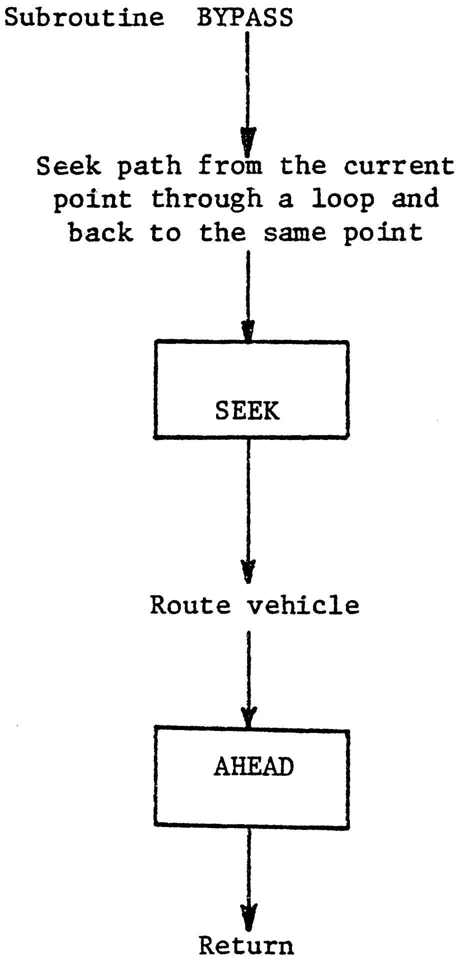

Subroutine CALLED
Determine all idle or unassigned vehicles
Determine number of unit loads not yet assigned a vehicle
Determine locations of all unassigned vehicles
No. of unassigned vehicles greater than number of loads waiting pickup?
No
Yes
Dispatch all available vehicles (if any) to the workcenter
Use vehicle dispatching rule to dispatch as many vehicles as there are unassigned unit loads
DSPACH
Seek path to the desired destination
SEEK
Update vehicle attributes
Route vehicle to desired destination
ROUTES
Return

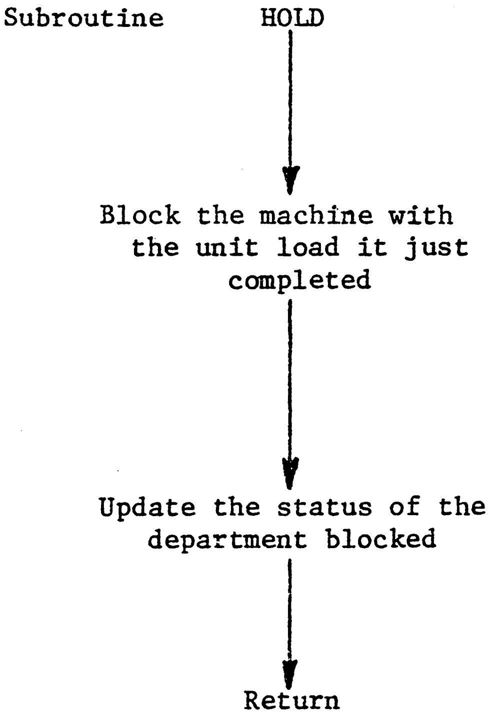
Subroutine STORAG



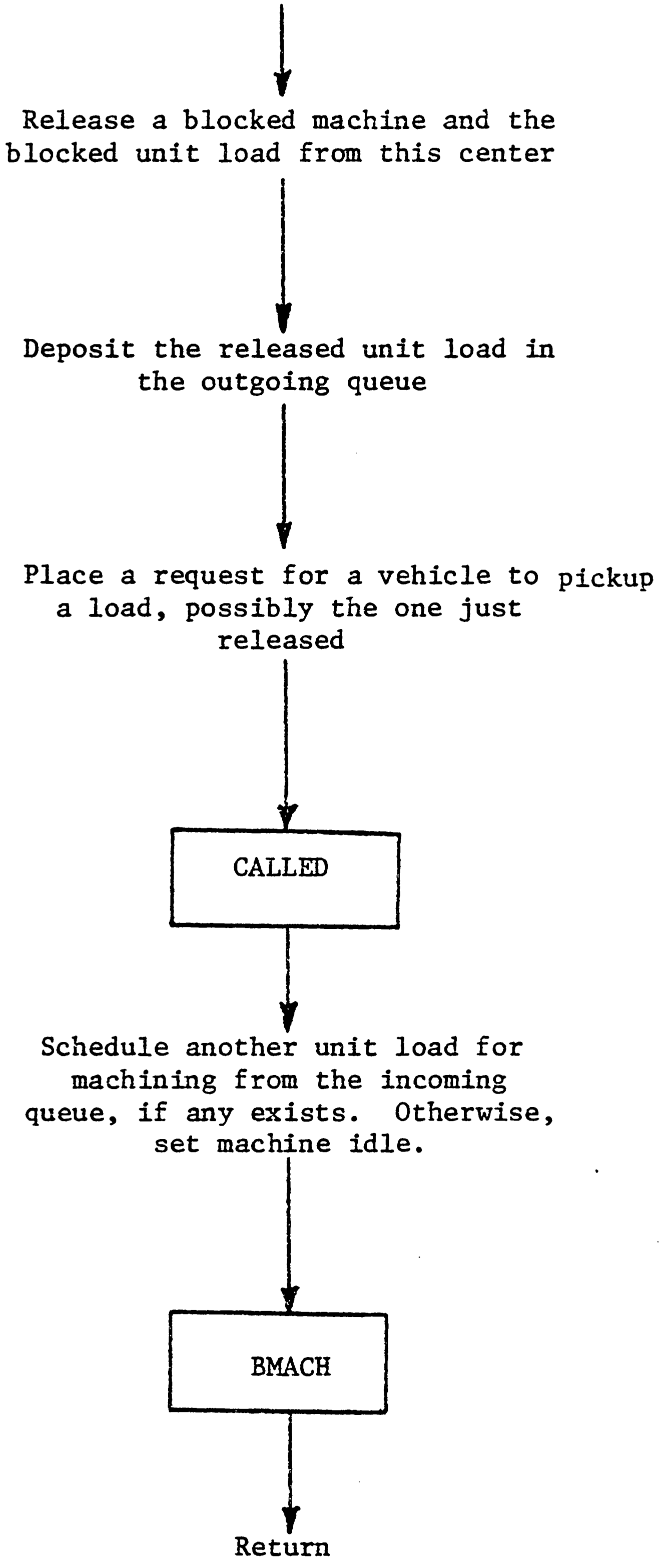

Subroutine SLOW
Check for other vehicles approaching the current pickup/delivery area
Determine the vehicles scheduled time of arrivals at the pickup/delivery point
Stop or decelerate any vehicle(s) that may arrive at the pickup/delivery point before the current pickup/delivery activity is completed
Return

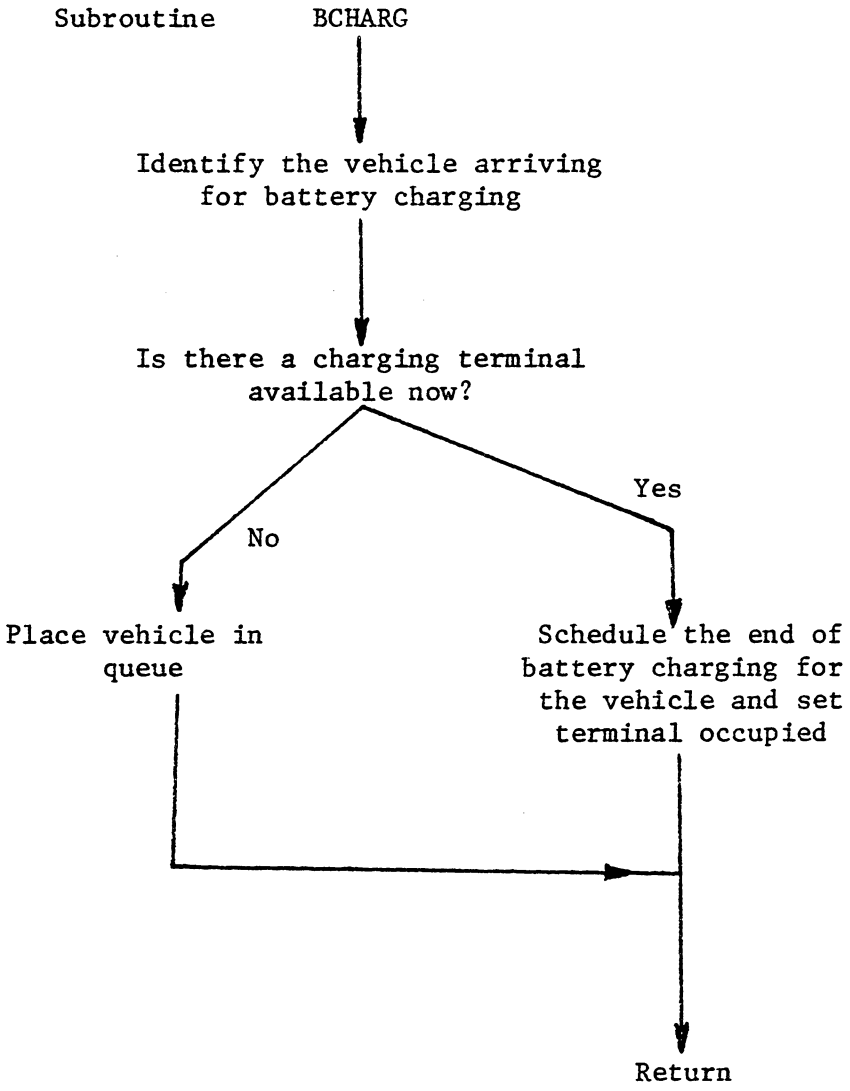

Subroutine SELECT
Identify all workcenters requesting unit load pickup
Determine number of unit loads not yet assigned a vehicle at each workcenter requesting vehicle
Select a workcenter according to system operating procedure
Return

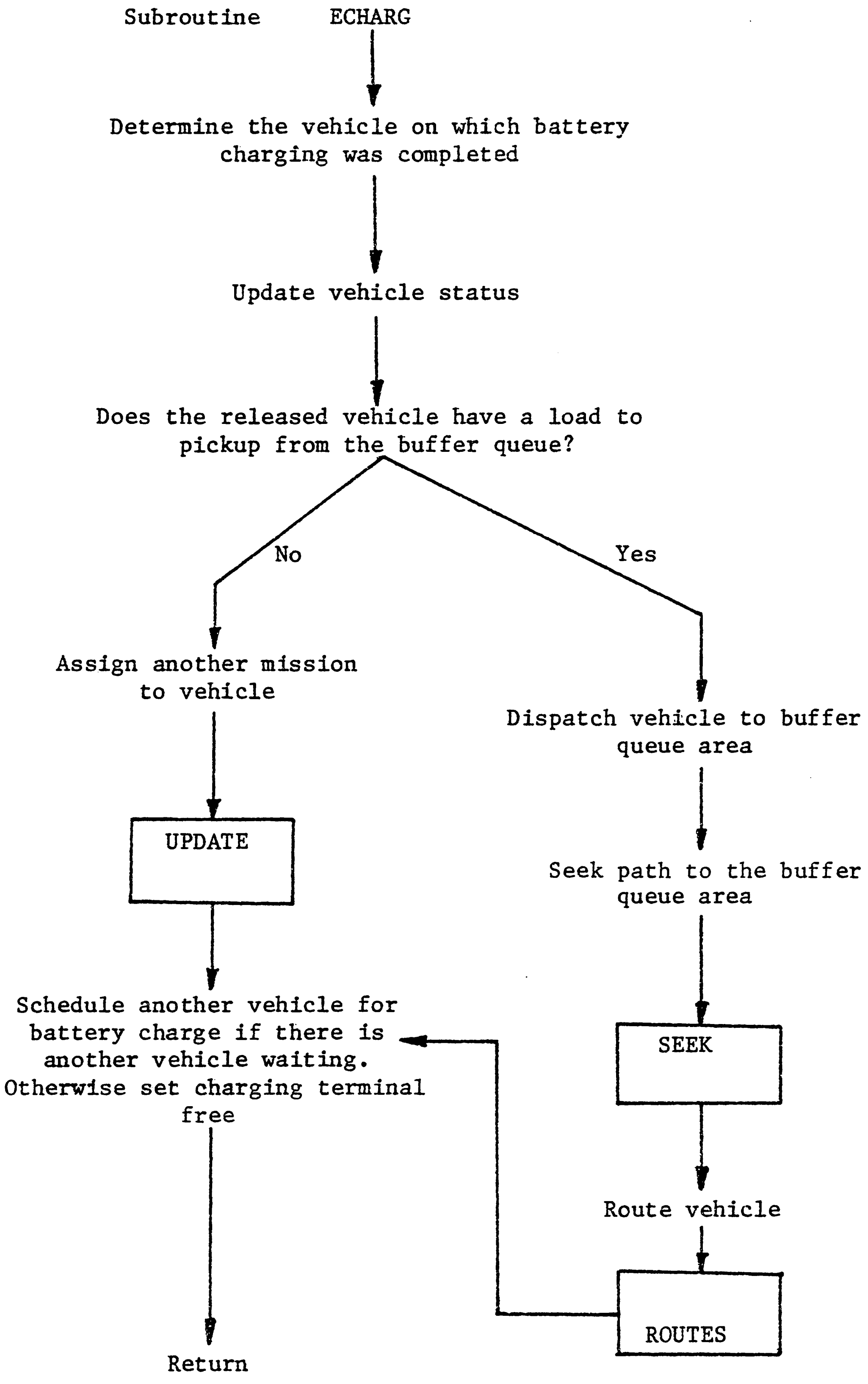

Subroutine BYPASS
Seek path from the current point through a loop and back to the same point
SEEK
Route vehicle
AHEAD
Return

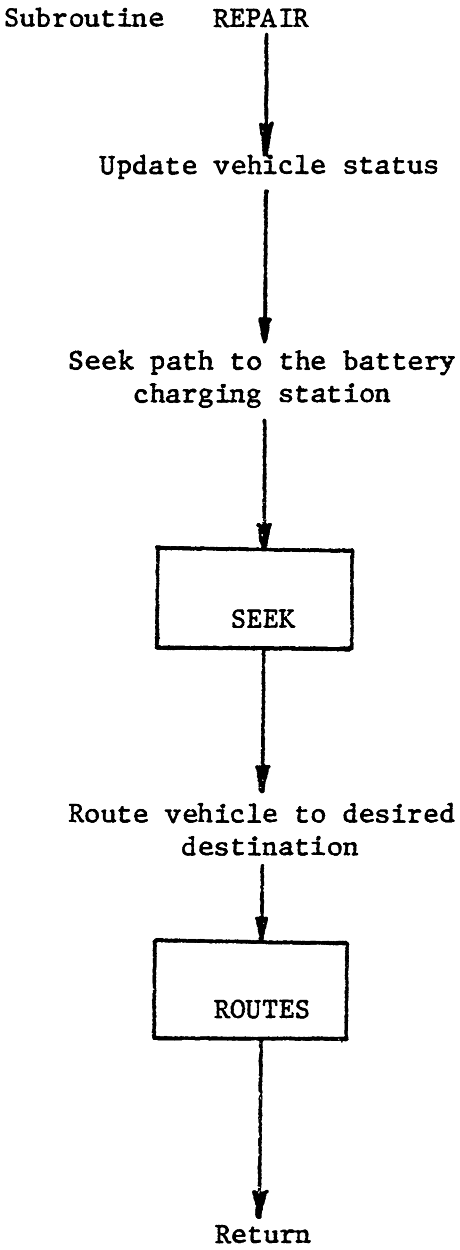

Subroutine HOLD
Block the machine with the unit load it just completed
Update the status of the department blocked
Return

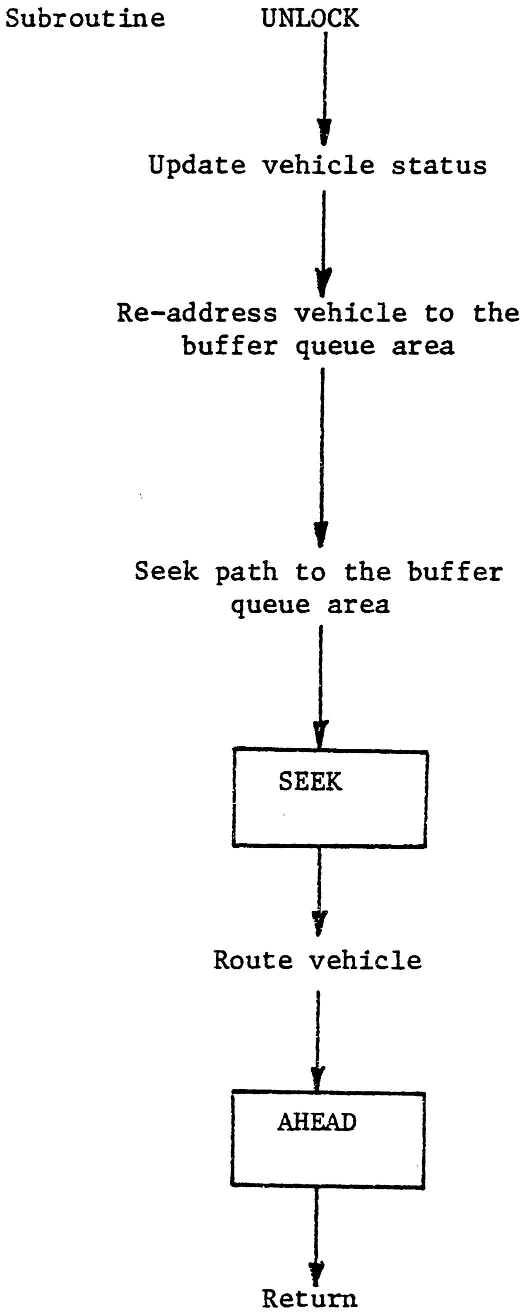
Subroutine FREE




Subroutine BCHARG
Identify the vehicle arriving for battery charging
Is there a charging terminal available now?
No
Yes
Place vehicle in queue
Schedule the end of battery charging for the vehicle and set terminal occupied
Return


Subroutine ECHARG
Determine the vehicle on which battery charging was completed
Update vehicle status
Does the released vehicle have a load to pickup from the buffer queue?
No
Yes
Assign another mission to vehicle
UPDATE
Schedule another vehicle for battery charge if there is another vehicle waiting. Otherwise set charging terminal free
Return
Dispatch vehicle to buffer queue area
Seek path to the buffer queue area
SEEK
Route vehicle
ROUTES


Subroutine REPAIR
Update vehicle status
Seek path to the battery charging station
SEEK
Route vehicle to desired destination
ROUTES
Return


Subroutine UNLOCK
Update vehicle status
Re-address vehicle to the buffer queue area
Seek path to the buffer queue area
SEEK
Route vehicle
AHEAD
Return

APPENDIX B

Automatic Guided Vehicle Systems Simulator (AGVSim) User's Guide

B.1 INTRODUCTION

AGVSim is a general purpose simulator for analyzing, planning, and designing Automatic Guided Vehicle based material handling systems. The theory underlying the development of the simulator is described in chapters 5 and 6 of this manuscript and in reference [31].

The fortran based simulator is essentially an evaluation program. It takes as input several descriptor or control variables of the system of interest and in return, produces a set of performance statistics of the system behavior based on the input conditions. The data input requirements include the following:

1. Location of workcenters or departments within the facility of interest.
2. Number of parallel processors or machines at each workcenter.
3. Technological contraints at each workcenter.
4. The job types or classes to be processed in the shop, including their routes, processing time requirements, physical characteristics, lot size distribution, and the ratio of each job class to all jobs (i.e. the probability of each job class arriving) in the shop. This ratio or probability for all jobs must sum to unity.
5. Layout of the Automatic Guided Vehicle System (AGVS) guidance network, including direction of traffic flow at various segments of the network.

6. Number of Automatic Guided Vehicles (AGVs) employed in the shop. This information also includes any technological constraints the vehicles might have (e.g. capacity constraint and speed).
7. Types of containers in use for conveying items through the shop, including their physical charateristics.
8. Shop operating policies, including
    a) vehicle routing policies,
    b) vehicle dispatching policies,
    c) container selection for parts unitization, and
    d) unit load dispatching rule at workcenters.

The output of the simulator is in the form of performance statistics of the shop, the individual workcenters, the vehicles, the guidance network, and the jobs processed through the shop. The various output statistics are:

1. Workcenter Performance Staistics
    a) machine utilization at each workcenter,
    b) machine blockings at each workcenter if capacitated queues are involved,
    c) Characteristics of incoming job queue at each workcenter, and
    d) characteristics of outgoing job queue at each workcenter.
2. Vehicle Performance Statistics

- a) utilization of each vehicle. This statistic is based on actual times a vehicle is under assignment regardless of whether vehicle is traveling loaded or empty.
- b) utilization of each vehicle if only actual conveying times are considered.
- c) unit loads in transit, and
- d) total vehicle interference time. This include time losses by vehicles due to interferences between vehicles and time losses by vehicles while holding at a delivery point for a queue space to open up if the delivery queue is full.

3. Jobs Performance Statistics
    - a) time spent in incoming job queue at each workcenter,
    - b) time spent in outgoing job queue at each workcenter,
    - c) flow time of unit loads at workcenters,
    - d) flow times of jobs through the shop,
    - e) number of jobs in the shop,
    - f) number of unit loads that entered and left the shop, and
    - g) number of jobs that entered and left the shop.
4. Network Performance Statistics
    - a) traffic flow through each intersection or node of the AGVS wire guidance network, and
    - b) level of traffic interference at each intersection.

Through the use of these statistical performance measures, system design or operating policy changes can be introduced by altering the values of the input parameters appropriately. By repetitively introducing these changes, a user can select the set of operating conditions that yield a good shop performance under the conditions specified. Optimization procedure can also be used to define search directions or directions of improvement on system performance. The statistical outputs can be employed for setting confidence limits for certain measures of performance at different operating conditions.

The AGVSim program is composed of two computer routines. The first routine (Routine A) acts as support system for the second routine (Routine B). From the implementation view point, these routines are easy to use, given that the data requirements have been provided in their proper input formats and types. It is instead, the logic in routine B that is complicated. Routine A is a simple program that organizes data for routine B. The interface requirements between A and B is not automatic but manual. It is Routine B that forms the heart of the simulator. It contains the logic that models the internal interfacing or linkage mechanisms of the AGV-based material handling systems. This scope is reflected also in the input data requirements. Routine B requires much more extensive data input than A. Detailed description of data input requirements for each routine will be presented subsequently. The description of each data type is immediately followed by an example to demonstrate the points raised.

B.2 ROUTINE A OF AGVSim

The function of Routine A is essentially the establishment of the shortest paths between points in the AGVS wire guidance network in the direction of traffic flow. It also provides the distances between the points along the path and outputs the data in a format conformable to Routine B. Because of its limited capability, the data input requirements for Routine A is very simple and limited.

The data input requirements for Routine A is based on the design of the AGVS guidance network as discussed in chapter 5 of this thesis or in [31]. In that development, a network is made up of nodes (i.e. intersection points of wire guide path) and arcs (i.e. segment of wire guide path between two nodes). Nodes include all points where the guide paths diverge, merge, or cross. It also include all load pickup and delivery points.

The location of a node is uniquely defined by giving its Cartesian co-ordinates (i.e. x- and y-axis) with respect to a reference point or point of origin. All node locations are given with respect to this origin. The origin does not necessarily have to be a node or lie on the guide path or even within the facility. The physical location of this reference point is immaterial. the Routine assumes all points lie on the same horizontal plane. Therefore, a third axis specification, the z-axis, is unnecessary.

The theory of the network design model is based on the assumption that no more than four arcs enter and leave any node. However, there must be at least one arc that enters a node and at least one arc that leaves a node. In essence, Routine A prohibits sink nodes or isolated nodes. This implies that the network is such that it is possible to travel from any node to any other node in the guide path and then return to the starting node. In other words, there exists at least a forward path and one backward path between any pair of nodes. All arcs in the system are unidirectional and can leave and enter nodes only along the x-axis or y-axis. Therefore, arcs that leave or enter nodes in directions other than those corresponding to 0 , 90 , 180 , and 270 degrees are invalid arcs. U-shaped arcs are also invalid. Parallel arcs between adjacent nodes is not permitted.

To ensure orderly flow of vehicles through the network, special vehicle control schemes are employed at several sections of the network. Node points are one example. Traffic control scheme around a node is facilitated by the principle of network zoning. By applying this principle, a zone referred to as check zone is constructed around every node. A check zone is a traffic clear zone around a node that can only be occupied by one vehicle at any point in time. This principle ensures that a vehicle entering a check zone for the purpose of crossing an intersection does so only when the check zone is safe for a vehicle to pass through the node.

The point where the check zone of a node intersects an arc entering the node is identified as a check point. Check points are decision points for vehicles in transit. At these points, vehicles check the traffic status around the node they are about to enter as well as the traffic condition in the next succeeding arcs of their trips. All check points are equidistant to the node they serve. The distances between the check points and the center of the node they serve are equal in all cases. Figure A.1 shows a representation of check zones, check points, and nodes.

At check points, vehicles make the following decisions:

i) hold at check point until traffic condition around the node or in the subsequent arc improves.

ii) enter the check zone, make a left or right turn and proceed to the next subsequent node in the travel route.

iii) enter check zone, make no turn and proceed to the next subsequent node.

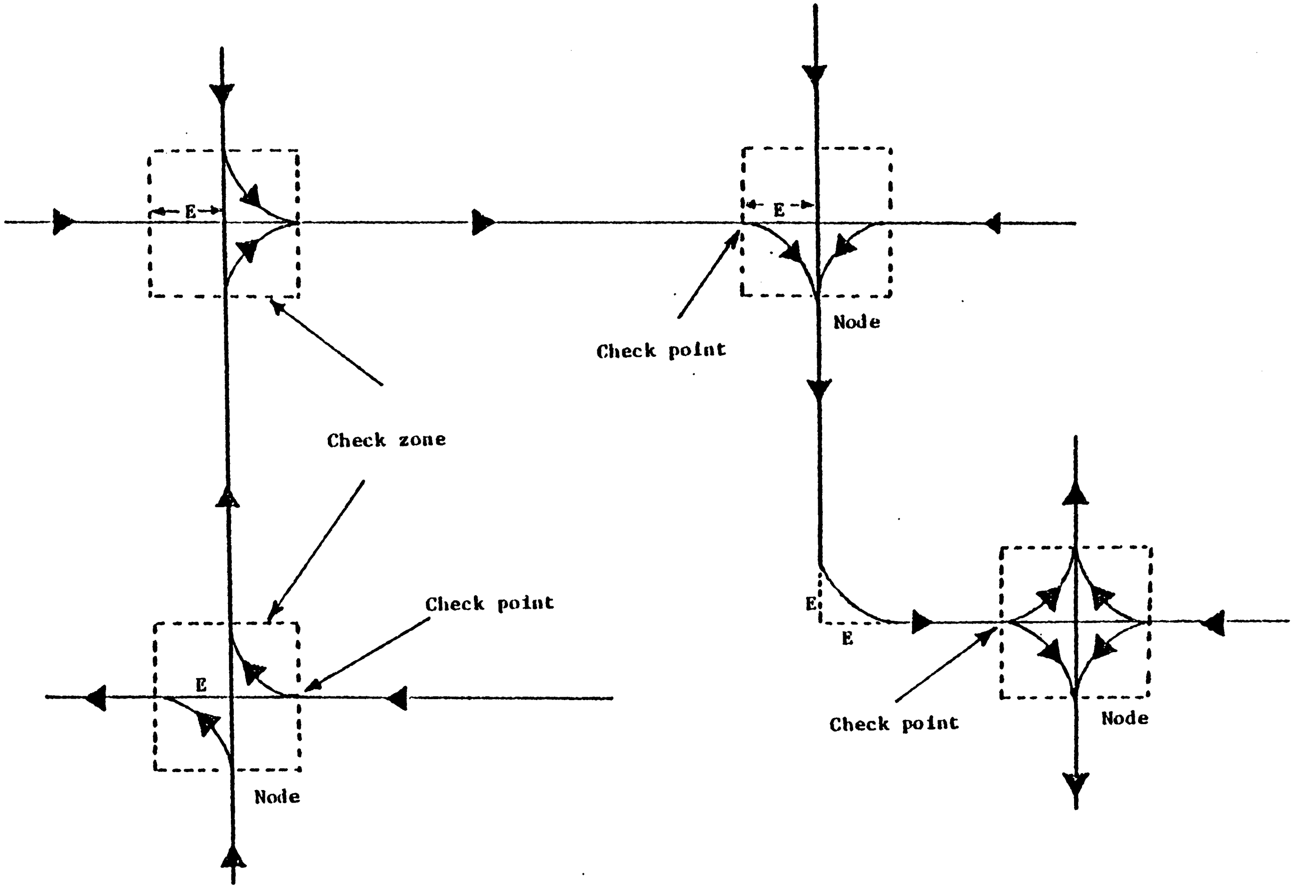


Figure A.1: AGVS Guide Path Showing Nodes, Check Points and Check Zones.

B.2.1 Data Input Requirements For Routine A

The data input to Routine A reflects the description presented above. the size of the input data is directly proportional to the number of nodes in the AGVS guidance network. In a network with N nodes, exactly (N+1) data cards are required. The last N of the (N+1) cards bear similar information that describe each node. In order to ensure ease and simplicity of use, all data inputs are under free format. Description of each data card form follows.

1. Data Card No. 1

There are four data points on the first data card. These points, in their sequence of entry are as described below.

Variable Number	Variable Name	Variable Type	Variable Descriptor
1	IPRINT	Integer	Unit number based on user computer system for printing out data.
2	IPUNCH	Integer	Unit number based on user computer system for punching data on cards or for writing on a tape or disk.
3	NUMNOD	Integer	Number of nodes in the AGVS network.
4	E	Real	Distance in feet between a check point and the node it serves.

The value of E is a function of the turning radius of the vehicles at maximum travel speed. E should be sufficiently long to ensure smooth turns. The value of E is used for calculating the length of switching arcs or interchange ramps at node points. Furthermore, two times the value of E should be greater than or equal to the length of any vehicle used in the system. This condition ensures that a vehicle can completely fit in a check zone. Also, the length of any arc less twice the value of E should be sufficiently long to completely fit a vehicle.

2. The 2nd-(N+1) Data Cards

Each of these data cards contains exactly nine data points. One data card is required for each node. Data on nodes should be provided sequentially in increasing node label or identification number beginning with node number one and terminating with node number N, where N is the number of nodes in the network. N is also the highest identification number assigned to a node in the network. Omission of any node number between one and N inclusive is not permitted. Data input is in free format. The description of the data points follow.

Variable Number	Variable Name	Variable Type	Variable Descriptor
1	N0	Integer	The node number for which data is provided.
2	N1	Integer	The first successor node to N0. If entered as zero, it implies that N1 does not exist.

3	N2	integer	The second successor node to N0. If entered as zero, the system assumes that N2 does not exist.
4	N3	Integer	The third successor node to N0. If entered as zero, it implies that N3 does not exist.
5	M1	Integer	A variable indicating the initial direction of move along the x- or y-axis to travel from N0 to N1. M1 = 1 implies initial move is along the x-axis, M1= -1 implies initial move is along the y-axis; M1= 0 if N1 equals zero.
6	M2	Integer	M2 is the defined for N2 in the same manner as M1 is defined for N1.
7	M3	Integer	M3 is defined for N3 as M1 is defined for N1
8	X0	Real	The x-co-ordinate of node N0 measures in feet from a reference point.
9	Y0	Real	The y-co-ordinate of node N0 measured from the same reference point.

All node co-ordinates should have a common reference point.

In order for N0 to be a non-sink node, it is required that at least one of the nodes N1, N2, and N3 be positive. Negatively labeled nodes are prohibited. To guard against data input errors, some data consistency checks are performed. The program will abort if the data of any node is omitted within the node interval of 1 and N, or node data are not provided in increasing chronological sequence. The system will also abort with the detection of a sink node, an isolated node, nodes having more than three successor nodes, nodes with more than three predecessor nodes, or nodes whose sum of successor and predecessor nodes exceed four. However, Routine A does not have the facility to identify if a node, say N1, entered as a successor to N0 is indeed a valid or true successor to N0.

Illustrative Example 1A

To demonstrate the data input format for Routine A, imagine that the network of Figure A.2 represents a simple AGVS guide path. There are five nodes, numbered 1 through 5 in the network. The pair of bracketed numbers beside each node are co-ordinates of the particular node. Suppose the variables E, IPRINT, and IPUNCH take the values of 3.0 feet, 6, and 7 respectively. The corresponding data input format for Routine A describing the network is as below.

```
6,7,5,3.0
1,2,3,0,1,-1,0,100.,100.
2,4,0,0,-1,0,0,0.,50.
3,2,4,5,1,-1,1,100.,50.
4,5,0,0,1,0,0,100.,0.
5,1,0,0,-1,0, 0,200.,50.
```

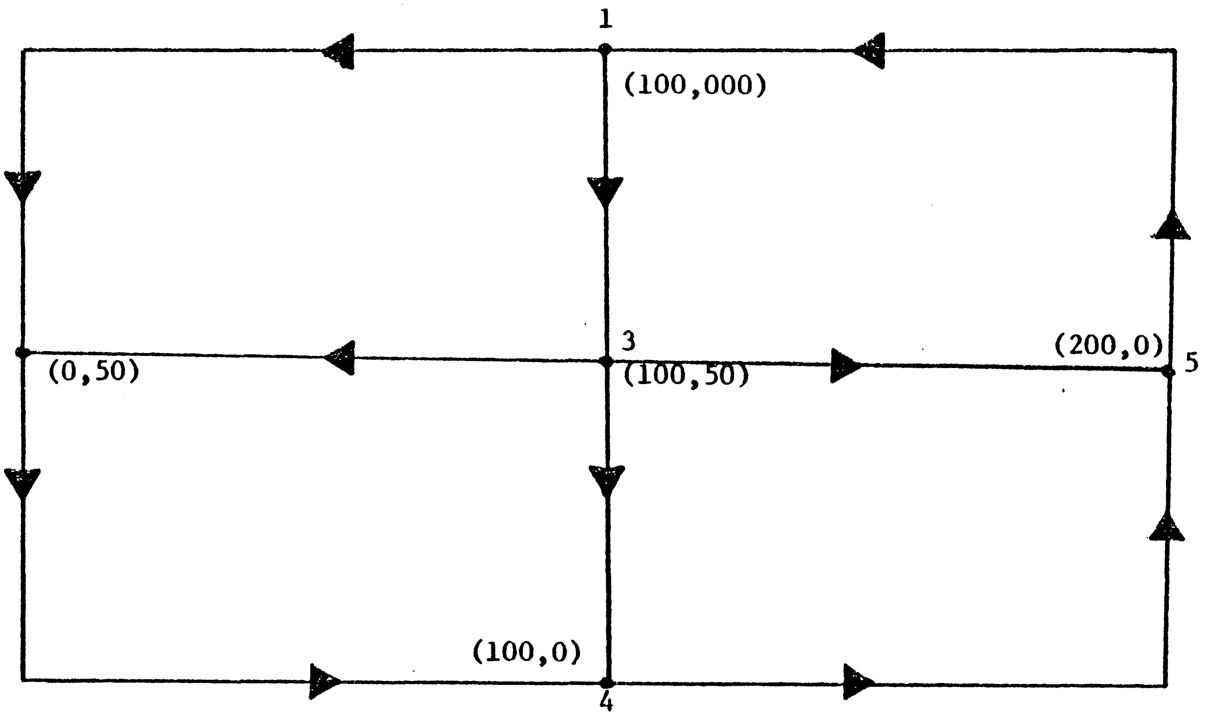


Figure A.2: AGVS Network For Example Problem

B.2.2 Data Output from Routine A

Two forms of outputs are provided by Routine A. The first class of data output are merely system diagnostic information. It consists of a reprint or reproduction of the data entered by the system user on the input data cards as read by the routine. It also contains error messages on any data inconsistencies spotted. The minimum and the maximum abscissa and ordinate (i.e. x- and y-co-ordinates) associated with the nodes are also printed out. Any data inconsistency in the input recognized by the routine causes a programming error and will abort the program.

The second output form is the input to Routine B (to be discussed subsequently). This data is provided in punched format on cards to be read by Routine B.

The two output forms can be modified by users. For example, instead of a hardcopy printout or card punch of the data, two separate tape or disk files can be created for each run of Routine A. One file will contain the diagnostic outputs while the other contains the data to be read by Routine B. However, a user doing so must have to communicate to Routine B the sources of the input data through the appropriate Job Control Language (JCL). This procedure eliminates the problem of having to deal with bulky punched data cards.

It should be noted that any changes made to the guide wire system will require a rerun of Routine A since such changes could affect existing system layout, paths, and distances between nodes in the network.

Illustrative Example 2A

Tables A.1 and A.2 represent the printed and punched outputs from Routine A by using the data entered in Example 1A. Table A.1 is the diagnostic output while Table A.2 is the punched output.

Table A.1: Diagnostic Printed Output

```
 INPUT DATA ECHO CHECK


      1    2    3    0    1   -1    0        100.0000        100.0000
      2    4    0    0   -1    0    0          0.0            50.0000
      3    2    4    5    1   -1    1        100.0000         50.0000
      4    5    0    0    1    0    0        100.0000          0.0
      5    1    0    0   -1    0    0        200.0000         50.0000

LOWEST CORDINATE ON THE X-AXIS =       0.0
LOWEST CORDINATE ON THE Y-AXIS =       0.0
HIGHEST CORDINATE ON THE X-AXIS =    200.000
HIGHEST CORDINATE ON THE Y-AXIS =    100.000
```

Table A.2: Punched Output

```
  2        4        2        5        1
  3        0        4        0        0
  0        0        5        0        0
  1       -1        1        1       -1
 -1        0       -1        0        0
  0        0        1        0        0
100.00      0.0    100.00   100.00   200.00
100.00     50.00    50.00     0.0     50.00
  1        3        4        2        5
  0        1        3        1        3
  2        4        5        1        3
  0        2        4        5        1
  3        4        5        2        1
  0        3        3        3        5
  4        5        1        3        2
  0        4        5        1        1
  5        1        3        4        2
  0        5        1        3        1
   0.0   148.71    54.71   109.42   159.42
446.13     0.0    500.84   148.71   297.42
253.42   104.71     0.0     54.71   104.71
297.42   446.13   352.13     0.0    148.71
148.71   297.42   203.42   258.13     0.0
```

B.3 ROUTINE B OF AGVSim

Routine B is the heart of the simulator. It is the integrator of all the subsystems that define the AGV-based material handling system. This includes the unit load assignment model, the vehicle-unit load transport system, machine center model, guide path layout model, and all other aspects of the manufacturing environment considered pertinent to the system. The definition of the various forms of the parts that can be processed in the shop, including their physical characteristics, machining and routing requirements are also input to the routine. All system design parameters that define the operating policies of the shop being modeled are input requirements. Due to the extensive details of manufacturing activities embedded into this model, a detailed description of the anatomy of this routine will not be presented in any length. The theory that forms the basis of the material handling model implemented in this routine is contained in chapters 5 and 6 of this manuscript or in reference [31].

The input requirements for Routine B is defined by the model assumptions and facts underlying the theory that forms its basis. Outlined below are some of the assumptions.

1. The shop processes multiple classes of jobs.
2. Jobs arrive into the shop stochastically according to the Poisson distribution (i.e. time between job arrivals is defined by the exponential distribution) or at constant time intervals.

3. Each job that arrives into the shop is composed of multiple identical parts that require similar operations. The number of parts in a job define the lot size of the job.
4. Lot sizes are broken down into transportable or portable quantities that are containerized or packaged to form a unit load.
5. Each job class has a unique job route defined by its technological requirements. All unit loads belonging to the same job class follow identical job route.
6. Repeat visit by unit loads to workcenters is permitted. However, consecutive (back to back) visits to the same workcenter is prohibited (i.e. the Kth and $(K^{+}1)$th operation on any unit load cannot be performed at the same workcenter).
7. The mean, variance, and probability distribution of operation times of parts (a unit load may consist of several parts) on workcenters along their routes are known. Processing times can be constant or follow the normal, uniform, or exponential distribution. However, if the number of parts in a unit load is sufficiently large and operation times follow a probability distribution, by applying the Central Limit Theorem, the operation times of unit loads are automatically sampled from the normal distribution.
8. Two unit loads queues (input and output) are kept at each workcenter. These queues can be capacitated or uncapacitated.

9. Handling of unit loads from the entering or arrival dock to the point where automatic handling begins is done by other mobile nonfixed path handling devices (e.g. lift trucks).
10. The input dock and the material handling devices that operate on it constitute the first workcenter in the facility.
11. The shipping or the output dock or the finished product storage area constitutes the last workcenter through the shop.
12. Any unit load that reaches the finished product storage area is assumed have completed its processing requirements and no further statistics will be kept on it.
13. Unit loads are both the transportable as well as the machining units in the shop.
14. Idle (unassigned) vehicles can be dispatched to designated parking areas or to circulatory loops depending on operating control procedure. Unassigned Vehicles can also be dispatched to make sequential visits to departments, quering for unit loads to be removed.
15. Vehicles require periodic battery charge to keep them operating.

B.3.1 Input Data Requirements for Routine B.

All the data input to Routine B are read under free format with the exception of the punched data set from Routine A as previously described. The sequence of data input is described next.

1. Data Type No.1

Variable Number	Variable Name	Varible type	Variable Descriptor
1	ISIZE	Integer	The value of this variable must be equal to the dimension of the array AKEEP. All entities (machines, jobs, unit loads, etc.) are stored in this array. Maximum number of entities that can be stored simultaneously in AKEEP is equal to (ISIZE/15)=NSTORE. Attempt to store (NSTORE+1) entities in AKEEP causes an error and will abort the program.
2	IASEED	Integer	First random number stream.
3	ICSEED	Integer	Second random number stream.
4	IDSEED	Integer	Third random number stream.

Illustrative Example 1B

To demonstrate the input format described for Data Type No.1, suppose for a particular application the user specifies the following: ISIZE=10000; IASEED=731113; ICSEED=317411; IDSEED=53791. The input entry format for this example is

10000,731113,317411,53791

2. Data Type No.2

Variable Number	Variable Name	Variable Type	Variable Descriptor
1	SIMTIM	Real	Total required simulation time (hours).
2	XMEAN	Real	Mean time (hours) between job arrivals at the dock. Interarrival times are exponentially ditributed or constant times.
3	CONST	Real	Constant handling time (minutes) required to process a unit load at the entry dock.
4	PICK	Real	Constant dwell time (seconds) required for an AGV to pickup a unit load from a load stand.
5	DELIV	Real	Constant dwell time (seconds) required for an AGV to deliver a unit load at a delivery station.

6	SEETUP	Real	Machine setup time when two unit loads of different product types follow one another consecutively on any given machine.

Illustrative Example 2B

Suppose in a particular instance, forty hours of simulation time is required. XMEAN, CONST, PICK, DELIV, and SEETUP are estimated as 0.50 hours, 6.0 min., 15.0 sec., 15.0 sec., and 1.0 min. respectively. The input format for this illustration is as shown below:

```
40.,0.50,6.0,15.,15.,1.0
```

3. Data Type No.3

Variable Number	Variable Name	Variable Type	Variable Decriptor
1	BTRACE	Real	Time (hour) when system trace should begin. $0 \leq BTRACE \leq ETRACE$.
2	ETRACE	Real	Time (hour) when system trace should end. ETRACE = 0 implies no trace is required.
3	ITRACE	Integer	Selector of trace type. If ITRACE = 1, every system activity will be traced. If ITRACE = 2, only a

			particular job class will be traced. ITRACE = 3 implies only a particular AGV will be traced. If no trace is required, ITRACE should be set to zero.
4	NTRACE	Integer	Identification number of the job class or vehicle to be traced depending on whether ITRACE equals 2 or 3. NTRACE equals zero if ITRACE equals zero or one.
5	TCLEAR	Real	Time (hour) when system statistics collection should begin.

Illustrative Example 3B

Assume that in a particular application, system trace is required between the hours of 10 and 12 of simulation time. Trace of vehicle number two only is required. Furthermore, statistics collection should commence at the fourth hour of simulation time. The data input format for this description is given by:

10.0,12.,3, 2,4.0

4. Data Type No.4

Variable Number	Variable Name	Variable Type	Variable Descriptor

1	NUMJOB	Integer	Number of distinct job classes that can be processed in the shop.
2	MCENTR	Integer	Number of departments or workcenters in the shop. The receiving dock and the finished goods warehouse should each be considered a department.
3	NUMVEH	Integer	Number of vehicles in use.
4	IPACH	Integer	Rule for selecting an unassigned vehicle to dispatch to a workcenter requesting a vehicle for load pickup. IPACH = 0, if vehicles are preprogrammed to visit workcenters sequentially for load pickup. If IPACH equals zero, then the value of LPARK (see Data Type No.5) must be two (2). IPACH = 1, random vehicle (RV) assignment rule. IPACH = 2, nearest vehicle (NV) rule. IPACH = 3, farthest vehicle (FV) rule.

			IPACH = 4, longest idle vehicle (LIV) rule IPACH = 5, if user wants to provide, code and implement his own user subprogram to model the workcenter initiated task assignment rule.
5	ICROSS	Integer	Rule for routing vehicles through the node. ICROSS = 1, FCFS rule. ICROSS = 2, Restricted FCFS (RFCFS) rule. ICROSS = 3, Relaxed or Activity control (RTC or AC) rule. ICROSS = 4, Train Routing (TR) rule.
6	MRULE	Integer	Rule for selecting a workcenter by a vehicle for load pickup when a vehicle becomes available. MRULE = 0, if vehicles are preprogrammed to visit workcenters sequentially for load pickup. If MRULE equals 0, then the value of LPARK (see Data Type No.5) must be two (2).

			MRULE = 1, Random Workcenter (RW) rule. MRULE = 2, Maximum Outgoing Queue Size (MOQS) rule. MRULE = 3, Shortest Travel Time/Distance (STT/D) rule. MRULE = 4, Longest Travel Time/Distance (LTT/D) rule. MRULE = 5, Minimum Remaining Outgoing Queue Space (MROQS) rule. MRULE = 6, Relaxed or Modified FCFS (MFCFS) rule. MRULE = 7, if user wants to provide his own user subprogram to model the vehicle initiated task assignment rule.
7	NUMBOX	Integer	Number of distinct container types that can be used in the facility.
8	ICRULE	Integer	Rule for selecting a container type. ICRULE = 1, Random container selection rule. ICRULE = 2, Maximum volume container selection.

ICRULE = 3, Maximum supporting weight container selection.

ICRULE = 4, Minimum volume container selection.

ICRULE = 4+K, if the Kth container is to be selected.

Illustrative Example 4B

Imagine a five department facility that processes only two classes of jobs. Three automatic guided vehicles are involved for parts movement via four possible container sizes. Suppose operational policies are such that IPACH = 4, ICROSS = 1, MRULE = 3, and ICRULE = 1. The data input format describing this scenario is as below.

2,5,3,4,1,3,4,1

5. Data Type No.5

Variable Number	Variable Name	Variable Type	Variable Descriptor
1	LPARK	Integer	Vehicle parking or looping option selector. LPARK = 0, if vehicle are to be parked when idle. LPARK = 1, if idle vehicles are to loop in a circulatory loop.

			LPARK = 2, if idle vehicle are pre-programmed to visit workcenters sequentially for load pickup. If LPARK equals 2, IPACH and MRULE must be set to zero. Also if IPACH and MRULE are non-zero, LPARK cannot be assigned a value of two.
2	NUMPAK	Integer	Number of distinct parking areas in the facility. NUMPAK must be zero if LPARK = 1 or 2.
3	NUMLOP	Integer	Number of distinct circulatory loops in the facility. NUMLOP must be set to zero if LPARK = 0 or 2.
4	NUMNOD	Integer	Number of nodes in the AGVS network. This includes all pickup and delivery points, merges, diverges, and guide path crossings.
5	IDIST	Integer	Service time distribution indicator at workcenters. IDIST = 1, implies constant service times. IDIST = 2, if service times are uniformly distributed.

			IDIST = 3, if service times follow exponential distribution. If a unit load contains a sufficient number of parts, total service time for the unit load will be approximated from the normal distribution if IDIST equals 2 or 3.
6	KRANK	Integer	Attribute number of unit loads by which the incoming unit load queue at a workcenter is ranked (i.e. unit load scheduling rules at workcenters). KRANK = -1, implies LIFO is applied at each workcenter. KRANK = 0, implies FCFS rule is applied at every workcenter. KRANK > 0, implies unit loads in input queue at a workcenter are ranked or ordered according to attribute number corresponding to KRANK. Refer to the section on unit load attributes in this user's guide to find out what each attribute number stands for.

7	KVALUE	integer	Order of ranking for the attribute number specified by KRANK. If KRANK > 0 and KVALUE = 0, queues are ranked according to the low value of attribute KRANK. If KRANK > 0 and KVALUE = 1, ranking is by high value of attribute KRANK. If KRANK is less than or equal to zero, KVALUE must be zero.
8	MSCHDL	integer	An indicator for a two stage unit load selection/scheduling procedure from the incoming unit load queue at a work center. MSCHDL = 1, implies that a machine that completed service on a unit load will search the incoming unit load queue for another unit load of the same job class as the type it completed. If the search proves positive (i.e. if such unit load is present in the queue), the unit load will be scheduled for service immediately regardless of its position in the

			queue. If the search proves negative, the regular unit load scheduling rule in force is defaulted to. MSCHDL = 0, implies unit load selection from the incoming job queue is purely according to the rule in force.
9	ISIDE	Integer	ISIDE = 1, if there are delivery and pickup points located on the main traveling aisles of the AGVS network. ISIDE = 0, if there are no pickup and delivery points on main aisles. That is to say that all delivery and pickup points are of the standard types and are all located at ingresses (sidings) off the main aisles. Pickup and delivery points should not be located at nodes where two or more arcs converge.
10	IBYPAS	Integer	Network arcs or sidings leading to pickup and delivery points have fixed capacities on the number of

vehicles they can hold or buffer. If a vehicle desiring to enter such siding arrives when the siding is full, such a vehicle can be held on the main aisle, possibly blocking traffic until there is room in the siding. Alternatively, the vehicle can bypass the siding, loop around in the network and subsequently returning to the same point to recheck the traffic condition in the siding.

If IBYPAS = 0, vehicle holding option on main aisle will be implemented.

If IBYPASS = 1, the vehicle bypass and looping option will be inplemented.

IBYPASS defaults to zero if ISIDE is assigned a value of one.

Illustrative Example 5B

Suppose the variables take the following values: LPARK = 0; NUMPAK = 2; NUMLOP = 0; NUMNOD = 14; IDIST = 1; KRANK = 2; KVALUE = 0; MSCHDL = 0; ISIDE = 0; IBYPASS = 1. The input format for this scenario is given below.

0,2,0,14,1,2,0,0,0,1

6. Data Type No.6

The sixth data type is a listing of the nodes corresponding to pickup and delivery points for each workcenter. For an N workcenter facility (dock and finished goods storage area inclusive), exactly 2N data points are required. Delivery and pickup nodes of workcenters should be entered sequentially beginning with the first workcenter (i.e. the dock) and terminating at the last workcenter (i.e. the finished goods warehouse). These data points should be entered serially on the same data card and continued on subsequent data cards as the need may be. The delivery and pickup nodes of one workcenter should be completely specified before that of another center follows. The first node entered for each workcenter should correspond to the delivery node, then followed by the pickup node. Pickup and delivery nodes for a workcenter need not be distinct but no two workcenters can share a common pickup or delivery nodes. Two data points are expected for each workcenter regardless of whether the pickup and delivery nodes are distinct or not. All data points are integers, entered under free format.

Illustrative Example 6B

Imagine a three department facility with an AGV network having 14 nodes. Suppose the following information is available.

	Workcenter Number		
	1	2	3
Delivery Nodes	5	10	7
Pickup Nodes	6	10	7

The data input format for this scenario is as shown below:

5,6,10,10,7,7

7. Data Type No.7

The seventh data type is a descriptor of nodes. It contains as many data points as there are nodes in the AGVS guide path network. Nodes are classified as 'conflict' or 'non-conflict' nodes. Conflict nodes include all guide path crossings and merges. Non-conflict nodes are guide wire divergent points and pickup and delivery points. For each node, a value of one (1) is assigned if the node is a conflict node, and zero (0), if otherwise. These boolean variables should be entered in chronological sequence of node numbering (i.e. identification), beginning with node number one and terminating with the highest numbered node. The data points should be entered serially on the same data card, separated by commas or blanks and continued on subsequent cards if necessary.

Illustrative Example 7B

Using the data format just described, the corresponding data input format for the AGVS network represented by Figure A.3 is as shown below.

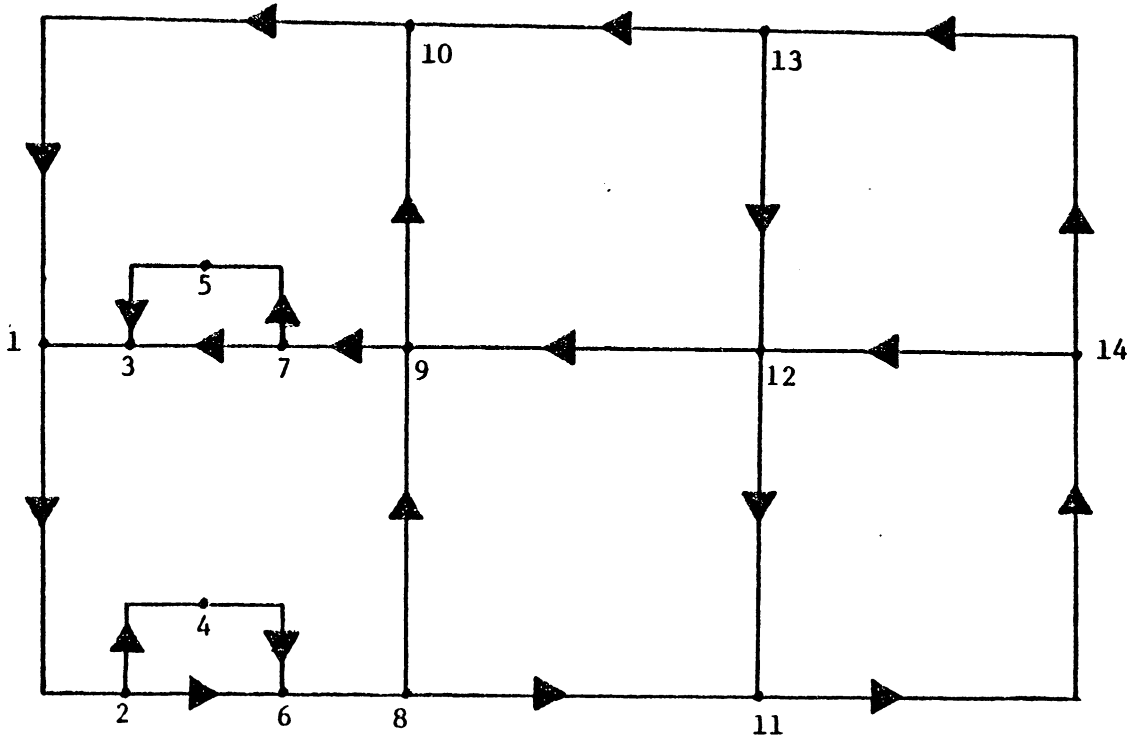


Figure A.3: AGVS Network

1,0,1,0,0,1,0,1,0,1,1,1,0,0

8. Data Type No.8

The eight data set gives the nodes representing parking areas or strings of nodes contained in circulatory loops, or the departmental sequence idle vehicles have to visit querying for unit loads to be picked up. The actual form of the eight data set depends the value of LPARK (see Data Type No.5). LPARK can take integer values between zero and two inclusive.

Case 1: LPARK = 0

When LPARK equals zero, the routine expects a list of nodes, each representing a parking area for idle vehicles. These nodes should be entered serially on the input data card, separated by commas or blanks. If the data cannot be contained on one card, it should be continued on subsequent cards as the need may be. The total number of nodes entered as parking areas should be equal to NUMPAK (see Data Type No.5). The system assumes that parking areas have infinite capacity. The data set requires integer format.

Illustrative Example 8B-0

Using the network of Figure A.3, suppose LPARK, NUMPAK, and NUMLOP are respectively equal to 0, 2, 0. Furthermore, suppose nodes 10 and 13 are designated as parking nodes for idle vehicles. The data input format is simply as entered below.

10,13

Case 2: LPARK = 1

When LPARK equals one (1), the routine expects string(s) of nodes, with each string representing a circulatory loop for idle vehicles. A circulatory loop consists of a sequence of nodes and arcs that define a feasible path along the direction of traffic flow in the AGVS guide path network such that the first node specified in the path is also a successor of the last node in the path. The total number of loops for which data is provided should be equal to NUMLOP (see Data Type No.5). A separate data card is required to specify the nodes that makeup a particular loop. Data on a particular loop are continued on subsequent card if necessary. For each loop, the first data point entered on the card should specify the number of nodes contained in the loop. This should be followed by a serial entry of the nodes in the loop. The listing of the nodes should conform to the adjacency requirements of the nodes in the loop. Again, the data input format is integer.

Illustrative Example 8B-1

Imagine again that the network of Figure A.3 were a facility. Two circulatory loops are earmarked for idle vehicles. The path defined by nodes number 1,2,6,8,9,10 and back to 1 is a designated loop. Another loop corresponds to the path defined by nodes number 1,2,6,8,11,14,12,9,7,3, and back to 1. The data entry format for this scenario is

6,1,2,6,8,9,10

10,1,2,6,8,11,14,12,9,7,3

Note that NUMLOP equals two in the above illustration.

Case 3: LPARK = 2

When LPARK takes a value of two (2), the system expects that idle vehicles have been pre-programmed to visit workcenters in some pre-defined sequence for load pickup. If a unit load is present, it is removed by the visiting vehicle. If no load exists, the vehicle simply proceeds to the next department in the sequence. The sequence forms a loop among the departments such that a vehicle continues to circulate between the departments until it meets an assignment in a department. When LPARK equals two (2), IPACH and MRULE (see Data Type No.4) must each be set to zero. Even if these variable assume values other than zero, the specifications will not be utilized for any vehicle assignment so long as LPARK has a value of 2.

Illustrative Example 8B-2

Suppose in a six department facility, vehicles have been pre-programmed to visit departments in the following sequence.

1-▸6-▸4-▸5-▸2-▸3-▸1

The data input format for this illustration is as shown below.

6,3,1,5,2,4

9. Data Type No.9

The ninth data set defines the routes and processing times of each job class that can be processed by the shop. There should be at least two data cards for each job class. These two cards must follow one another consecutively.

For each job class, the first data card should specify the number of workcenters in the job route, followed by the listing of the job route itself. If any workcenter appears more than once on the job route, it should be counted as many times as it appears in specifying the number of workcenters on the job route. Workcenter revisits that follow one another consecutively is not permitted. All data points are integer.

The second card for each job class gives operation time information at each workcenter on the job route. If a job class visits a workcenter more than once on its route, the operation time information should be provided for each visit. For a job that has N workcenters on its route, operation time information is required for only N-2 of the workcenters. This reduced data requirement comes from the assumption that all jobs go through the first and the last workcenters (i.e. the dock and the finished product storage). No unit load processing within the finished goods warehouse is considered in this model and the processing time at the input dock had earlier been provided as the constant term CONST (see Data Type No.2).

With the exception of the first and the last workcenters mentioned in the last paragraph, operation time data is provided in pairs for each visit a unit load (job) makes to a workcenter on its route. Operation time data should be serially entered on a card for each workcenter on the job route and in the same sequence as the workcenters appear on the job route. Data can be continued on subsequent cards if the need arises. The two data points for each workcenter should follow one another consecutively. In other words, data for one center should be completely specified before that of a subsequent center follows. The two data points give the mean and the variance of operation times respectively. If operation times are constants, the associated variance should be entered as zero. If operation times are uniformly distributed, the lower and the upper limits of the distribution should be entered instead of the mean and the variance. If exponentially distributed, the mean and the variance should be separately entered but with equal values. The operation time data provided should be in minutes and should be for processing one part, not one unit load. A unit load may consists of several parts. All data points should be entered as real values.

Note: A unit load that reaches the finished product storage area as shown on its route does not reappear into the shop.

Illustration Example 9B

To demonstrate the data input format described, imagine a shop with five departments. Two job types can be processed in the shop.

The departmental routing sequence for job type one is (1,3,4,3,5). For job class two, the routing is (1,2,5). All operation times are constant (i.e. IDIST = 1, see Data Type No.5). Each part of job class one requires 0.5 minutes of service at each department on its route. For job class two, the service time is 1.3 minutes per part at each workcenter it visits. Given the above scenario, the data input format is as shown below.

```
5,1,3,4,3,5
0.5,0.0,0.5,0.0,0.5,0.
3,1,2,5
1.3,0.0
```

NOTE: Every job route begins with the first department and terminates with the last.

10. Data Type No.10

The tenth data set specifies the number of machines at each workcenter or department. Machines at each workcenter are assumed to be identical. The number of machines at each of the departments should be entered serially on the data card, separated by commas or blanks. The order of data entry should correspond to the chronological sequence the workcenters are numbered. Since no part processing takes place at the finished product department, no machines need to be specified for that department. All data points are integer valued.

Illustrative Example 10B

Suppose machine population in the five department shop is as tabulated below:

Dept. No.	No. of Machines
1	2
2	4
3	5
4	3
5	-

The input data format for the machine population is as below:

2,4,5,3

11. Data Type No.11

With the exception of the input queue at the first department and the two queues associated with the finished product department, it is assumed by Routine B that all unit load queues are capacitated. Two queues (i.e. incoming and outgoing unit load queues) are kept at each department. The capacities in unit loads of the two queues should be entered one after the other, separated by commas or blanks. The first data specified for each center should correspond to the capacity of the input queue while the second is the capacity of the output queue. All data specifications should be entered serially on the data card and continued on subsequent cards if need be. The two input data points required by a particular department should be completely entered before that of a subsequent department is entered. The order of data specification for the departments should follow the chronological order of department labels or identification numbers. For uncapacitated queues, the corresponding capacity data entries should be made sufficiently large to avoid any queue capacity violation. The input queue at the dock is generally assumed by the routine to be uncapacitated. All data points are integer.

Illustrative Example 11B

Suppose queue capacities in unit loads in the five department example problem of the last section is as described in the table below:

Dept. No.	Incoming Queue Capacity	Incoming Queue Capacity
1	infinite	10
2	5	4
3	6	7
4	2	2
5	infinite	infinite

The data input format for this example is illustrated below.

```
8000,10,5,4,6,7,2,2,9000,11000
```

12. Data Type No.12

A unit load in the shop consists of a conveying container and the parts in the container. The twelfth data set contains information on each container type employed in the shop. A data card is required for each container type. The number of data cards should be equal to the number of containers, NUMBOX, specified on Data Type No.4. Six real valued data points are required for each container, all entered serially and separated by commas or blanks. The routine numbers the containers in the order they are entered. The data points are described below.

Variable Number	Variable Name*	Variable Type	Variable Descriptor
1	BOX(J,1)	Real	Length of container in inches.
2	BOX(J,2)	Real	Width of container in inches.
3	BOX(J,3)	Real	Height of container in inches
4	BOX(J,4)	Real	Weight of container material (lbs) per square inch of surface area. The system assumes all containers have six faces.
5	BOX(J,5)	Real	Maximum weight (lbs) container J can support without tearing or breaking.
6	BOX(J,6)	Real	Container fill-ratio. This is essentially the average space utilization

of a container when loaded with parts. It is a function of the geometry of the parts and the container. This value is greater than zero but less than one for all containers.

* J is the index for container type.

Illustration Example 12B

Suppose the data below describes three possible containers in use in the five department shop example.

	Container No.1	 No.2	 No.3
Length	24"	36"	36"
Width	18"	18"	24"
Height	12"	15"	12"
Container Material wt/sq in. of surface area	0.3 lb	0.2 lb	0.25 lb
Maximum Conveying Weight	1500lb	1200lb	1350lb
Container Fill-Ratio	0.70	0.75	0.70

The data entry format for the three containers is as below.

```
24.,18.,12.,0.3,1500.,0.7
36.,18.,15.,0.2,1200.,0.75
36.,24.,12.,0.25,1350.,0.70
```

13. Data Type No.13

Jobs in the shop are distinquished from one another by several factors, among these are the physical characteristics of the parts belonging to a job class. For each job class, one data card is required. The total number of data cards should be equal to the number of job classes, NUMJOB, specified on Data Type No.4. Three real valued data points are required for each job class. These three data points should be entered serially on the data card. The order of data card input for the jobs should conform to the order followed for Data Type No.9.

Variable Number	Variable Name	Variable Type	Variable Descriptor
1	AJOB(J,1)	Real	Weight (lbs) per part belonging to job class J.
2	AJOB(J,2)	Real	Volume (cubic inch.) per part belonging to job class J.
3	AJOB(J,3)	Real	Proportion of jobs in the shop belonging to job class J. It is a measure of the probability of job class J arriving into the shop. The sum of probabilities for all jobs must be unity. A proportion of 1.0/NUMJOB for all jobs implies all jobs have equal chance of arriving.

Illustrative Example 13B

Suppose the example shop can process four different classes of jobs. If Wj and Vj respectively denote the weight and the volume per part in job class j. Pj is the proportion of all jobs in the shop that belong to job class j under steady state condition. The tabulated data below describes each job class.

Job Class	Wj (lb)	Vj (cu. inch)	Pj
1	2.0	12.5	0.30
2	1.5	10.8	0.15
3	2.35	18.6	0.35
4	0.5	8.0	0.20

Pj = 1.0

The data input format describing the job classes is given by

```
2.,12.5,0.30
1.5,10.8,0.15
2.35,18.6,0.35
0.5,8.0,0.20
```

14. Data Type No. 14

Job lot sizes are assumed to follow a probability distribution. For each job class, two data points are required. These data points correspond to the mean and variance respectively of the lot sizes. Data for all job classes should be entered serially on a data card, continueing on subsequent cards as the need arises. The data for a job class should be comletely specified before that of a subsequent job class is entered. The mean of the lot size of a job class should be entered first, then followed by the variance. If constant lot sizes are involved, the associated variances are zeros. If uniformly distributed lot sizes are involved, the lower and the upper limits of the distribution should be specified rather than the mean and the variances respectively. Four distributions are available for generating lot sizes, namely, uniform, exponential, normal, and constant. Only one distribution can be specified during each run of Routine B. All data points should be entered as real.

Illustrative Example 14B

Suppose the four job classes of example 13B have constant lot sizes as tabulated below.

Job Class	Lot Size
1	4000
2	2500
3	1900
4	3300

The data entry format describing the lot sizes is as below.

```
4000.,0.,2500.,0.,1900.,0.,3300.,0.
```

15. Data Type No.15

The fifteenth data type requires only one data card. Five data points separated by commas or blanks are contained on the card as described in the chart below.

Variable Number	Variable Name	Variable Type	Variable Descriptor
1	E	Real	Distance (feet) from a check point to the center of the node it serves.
2	SPEED	Real	Traveling speed of vehicles in feet per minute (fpm).
3	VLENGT	Real	Length (feet) of an AGV measured from bumper to bumber.
4	FACTOR	Real	Minimum distance separation factor between adjacent vehicles. If FACTOR = α, the minimum separation distance is equal to αVLENGT.
5	WEIGHT	Real	Rated weight carrying capacity of an AGV.

Illustration Example 15B

Suppose in a certain application, the variables take the following values: E = 3.0 feet; SPEED = 120.0 feet per minute; VLENGT = 5.0 feet; FACTOR = 0.5; WEIGHT = 4000 lbs. The data input format for this illustration is as shown below.

3.0,120.0,5.0,0.5,4000.

16. Data Type No. 16

Only one data card is required for this data set. It is a fact that the batteries that provide the power required to operate the vehicles do run down after a certain length of time of continuous or non-stop operation. This data card gives vehicle battery charging information. Four data points are required on this card. The data points are as described below.

NBATRY = Node number corresponding to the vehicle battery charging area. This node can correspond to a node designated as a parking area. Battery charging area is assumed to have infinite capacity to accomodate vehicles.

CHARGE = A constant lenght of time required to charge a vehicle, in hours.

TCHARG = The cummulative vehicle running time required before a battery recharge is in order. The cummulative running time only includes the time a vehicle is operating, not time in park. Power consumption when a vehicle is in park is assumed to be zero.

NTERM = Number of vehicle charging terminals in the charging area. This is equivalent to the number of vehicles the battery charging facility can charge simultaneously.

The variables NBATRY and NTERM are integer valued while CHARGE and TCHARG are real valued.

Illustrative Example 16B

Let the assumption be that in the shop example previously cited, the battery charging station corresponds to node number 14 of the AGVS network. The batteries borne by the vehicles generally run down after about eight hours of continuous operation. It takes half an hour to recharge any vehicle. Any of two charging ports operating independently can be used to service any vehicle. The data entry format for this example is

14,0.5,8.0,2

17. Data Type No.17

The seventeenth data card contains exactly three data points, all integers and separated by commas. The first variable is LOTX, followed by IRRIVS, and finally by ILOCK. LOTX describes the distribution of lot sizes for jobs while IRRIVS is a descriptor of job interarrival time distribution into the shop. In general,

$$\text{LOTX} = \begin{cases} 0, & \text{if lot sizes are constants.} \\ 1, & \text{if lot sizes are uniformly distributed.} \\ 2, & \text{if lot sizes are exponentially distributed.} \\ 3, & \text{if lot sizes are normally distributed.} \end{cases}$$

IRRIVS = 0, if interarrival times follow exponenential distribution

IRRIVS = 1, if interarrival times are constants.

ILOCK is differently defined from LOTX and IRRIVS. Occasionally in Automatic Guided Vehicle based systems, because of the operating characteristics of a shop, some departments may be blocked because of insufficient queue space and may remain blocked for extended period of time. The worst scenario is when the entire shop locks. When this happens, the flow of materials through the shop seizes and new part completions stop. Unless there is some form of intervention (manual or automatic) to free the shop or the department, the whole facility remains deadlocked. In this simulator, automatic intervention capability is built into the vehicle to recognize critical operating conditions that may produce shop locking. When such condition is detected, the vehicles will initiate a procedure to relieve the situation. Therefore, ILOCK is a facility antilock selector. The definition is as below.

ILOCK = 0, system will not be checked for shop locking conditions. Even if the shop locks, no intervention will be applied to release the lock.

ILOCK = 1, system will check for conditions that may lead to shop or department locking. If the shop locks, action will be taken by the vehicles to unlock it. If a department is locked, action will also be taken to unlock it.

When a shop locks or a department locks, to unlock the department, the vehicles will remove some unit loads from the affected department, store them temporarily at a buffer area in the warehouse and subsequently retrieve them when the locking or condition ceases to exist.

Illustrative Example 17B

Suppose job lot sizes follow normal distribution and job interarrival times is a constant. The AGV system has the intelligence to discourage any department or the shop from locking, the data input format for this scenario is as below.

3,1,1

18. Punched Data Set From Routine A

The last set of data to Routine B is the punched output from Routine A. The punched output consists of the following data subsets in the sequence presented below.

a) Incidence matrix of AGVS guide path network, denoted by INCID.

b) Direction matrix of the network denoted by IDIREC. This matrix gives the initial or starting move axis (x- or y-axis) to travel from a predecessor node to its successor nodes.

c) Co-ordinate matrix, denoted by CORD. This matrix contains the x and y co-ordinates of nodes as entered by the user in Routine A.

d) Shortest path matrix, given by ISHORT. Within this matrix, the shortest paths between any two nodes in the network are stored.

e) Distance matrix, denoted by FROMTO. This matrix provides the distance measures between any pair of nodes in the network. Distance calculation is along the shortest path.

The punched data set is the only input data to Routine B with formatted input requirements. The order of the punched data cards should not be tampered in any form since the punched output format of Routine A should conform to the input format of Routine B. However, the output/input formats can be modified according to the user's needs by adjusting the format numbers 100 and 101 in both Routines A and B. Format number 100 is the output/input format for the integer matrices INCID, IDIREC, and ISHORT. Format number 101 is used for outputting/inputting the real valued matrices CORD and FROMTO.

User's that have their data read on a tape or on disk while running Routine A will have to use the appropriate Job Control Language (JCL) suitable to their computer system to communicate to Routine B the device from where data is to be read.

B.4 COMPREHENSIVE EXAMPLE

To unify the examples presented above, consider the manufacturing environment described below:

1. Number of Departments = 4
2. Number of Distinct Job classes shop can process = 3
3. Job Characteristics

Job Class No.	Wt/part(lb)	Vol/part(in)	Proportion
1	1.3	3.0	0.334
2	2.5	9.0	0.333
3	4.1	8.4	0.333

4. Distribution of Lot sizes for Jobs = uniform

Job Class No.	Lower Limit	Upper Limit
1	2000	4500
2	1800	2100
3	3500	4000

5. Job Routes

Job Class No.	Route
1	1,2,4
2	1,3,2,3,4
3	1,2,3,4

6. Job Operation Times (minutes) per part at Departments

Job Class No.	2		3			
			First Visit		Second Visit	
	Mean	Var.	Mean	Var.	Mean	Var.
1	0.50	0.0	-	-	-	-
2	0.70	0.0	0.40	0.0	0.50	0.0
3	0.90	0.0	0.60	0.0	-	-

7. Departmental Data

Dept. No.	No. of Machines	Incoming Queue Capacity	Outgoing Queue Capacity
1	1	Infinite	10
2	2	5	4
3	3	6	5
4	-	Infinite	Infinite

8. AGVS Guide Path Layout: See Figure A.4

9. Pickup and Delivery Points (nodes) for each Department

Dept. No.	Delivery Node	Pickup Node
1	4	5
2	6	6
3	17	18
4	14	14

10. Co-ordinates of Nodes

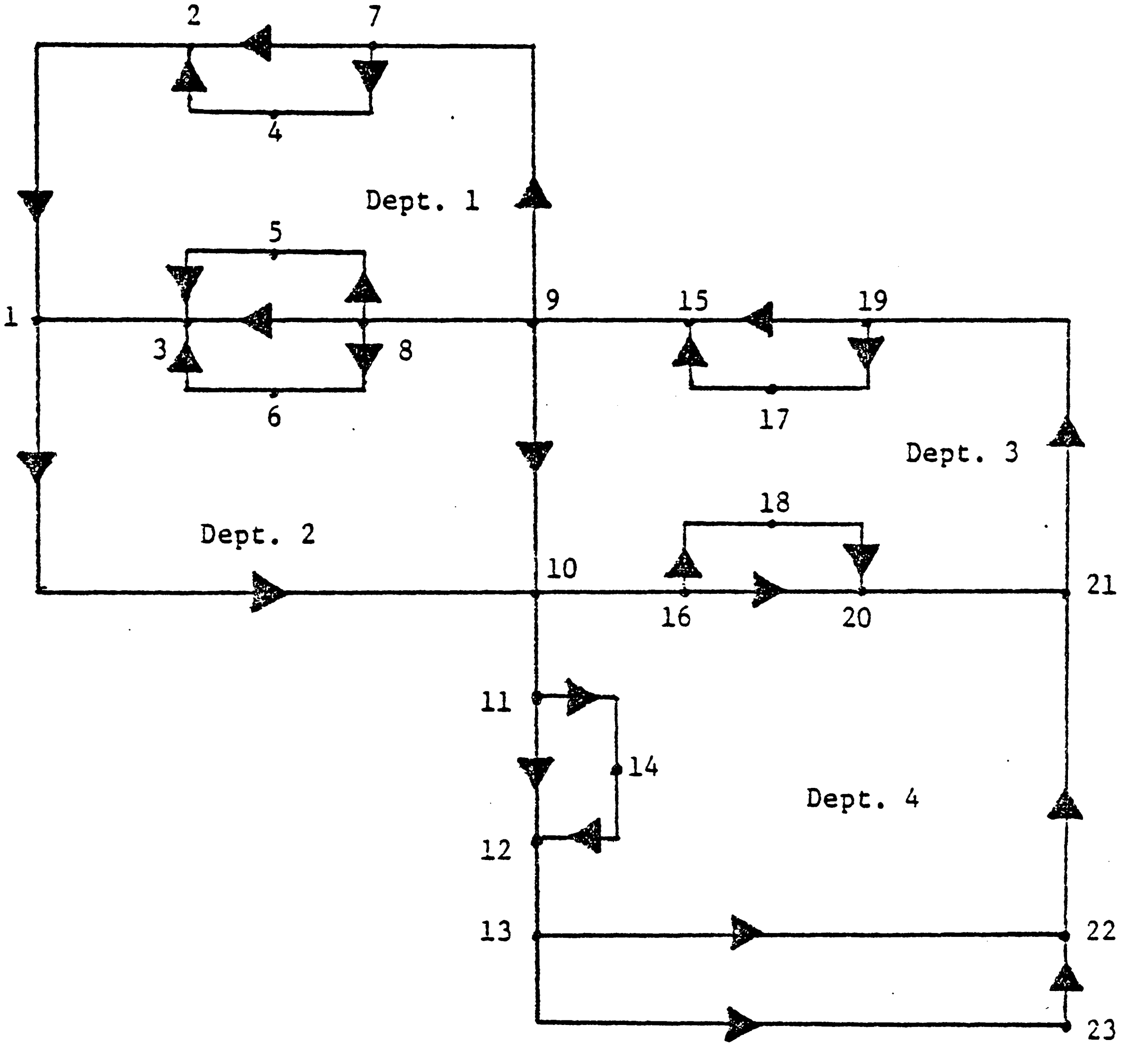


Figure A.4: AGVS Guide Path Layout.

Node No.	1	2	3	4	5	6	7	8	9
X-Coord	0.	15.	15.	25.	25.	25.	35.	35.	60.
Y-Coord	80.	120.	80.	110.	90.	70.	120.	80.	80.

Node No.	10	11	12	13	14	15	16	17	18
X-Coord.	60.	60.	60.	60.	70.	80.	90.	90.	90.
Y-Coord.	50.	35.	15.	0.	25.	80.	50.	70.	50.

Node No.	19	20	21	22	23
X-Coord.	100.	100.	130.	130.	130.
Y-Coord.	80.	50.	50.	0.	-15.

11. Number of nodes designated as parking zone = 0

Number of circulatory loops = 2

	Nodes in loop
Loop No.1	1,10,16,20,21,19,15,9,8,3
Loop No.2	10,11,12,13,21,19,15,9

12. Number of Possible Containers for Conveying Parts = 1

Container Data:

Length = 36"; Width = 36"; Height = 18"

Wt./sq. in. of surface area = 0.02 lb

Live wt. = 1200lbs; Fill Ratio = 0.75

13. Other System Parameters:

Number of vehicles, NUMVEH = 3

Required simulation time, SIMTIM = 10.0 hours

**Time between job arrivals, XMEAN = 0.5 hour

Handling time at the dock area per unit load, CONST = 7 minutes.

Unit load pickup time by an AGV, PICK = 15.0 seconds

Unit load delivery time by an AGV, DELIV = 15.0 seconds

Vehicle traveling speed, SPEED = 150.0 fpm

Length of an AGV (bumper to bumper), VLENGT = 5.0 ft.

Vehicle rated capacity, WEIGHT = 3000 lbs

Minimum separation factor between vehicles, FACTOR = 0.5

Distance between a node and its check points, E = 3.0 ft

Node corresponding to battery charging station, NBATRY = 23

Battery recharging time, CHARGE = 0.5 hour

Number of battery charging ports, NTERM = 2

Operation times required before a vehicle is
to be recharged, TCHARG = 8.0 hours

Shop has intelligent vehicles capable of relieving the shop any condition that may produce shop locking (i.e. ILOCK=1)

14. Other Decision Parameters

BTRACE = 7.0 hours; ITRACE = 1; TCLEAR = 0.0
ETRACE = 7.02 hours; NTRACE = 0; MSCHDL = 0
ISIZE = 10000; IASEED = 31511; ICSEED = 75139
IDSEED = 513197; IPACH = 2; MRULE = 5
ICRULE = 2; KRANK = 0; KVALUE = 0; ICROSS = 1

**NOTE: LPARK = 1; NUMNOD = 23; IDIST = 1

Interarrival times for jobs follow exponential distribution and job lot sizes are uniformly distributed.

Tables A.3 through A.9 show the input and output data for the comprehensive example. Table A.5 is the punched output from Routine A and also the input to Routine B. Output from Routine B commences from Table A.7.

Table A.3: Network Input Data to Routine A

```
6,8,23,3.
1,10,0,0,-1,0,0,0.,80.
2,1,0,0,1,0,0,15.,120.
3,1,0,0,1,0,0,15.,80.
4,2,0,0,1,0,0,25.,110.
5,3,0,0,1,0,0,25.,90.
6,3,0,0,1,0,0,25.,70.
7,2,4,0,1,-1,0,35.,120.
8,3,6,5,1,-1,-1,35.,80.
9,8,10,7,1,-1,-1,60.,80.
10,11,16,0,-1,1,0,60.,50.
11,12,14,0,-1,1,0,60.,35.
12,13,0,0,-1,0,0,60.,15.
13,22,23,0,1,-1,0,60.,0.
14,12,0,0,-1,0,0,70.,25.
15,9,0,0,1,0,0,80.,80.
16,18,20,0,-1,1,0,80.,50.
17,15,0,0,1,0,0,90.,70.
18,20,0,0,1,0,0,90.,50.
19,15,17,0,1,-1,0,100.,80.
20,21,0,0,1,0,0,100.,50.
21,19,0,0,-1,0,0,130.,50.
22,21,0,0,-1,0,0,130.,15.
23,22,0,0,-1,0,0,130.,-15.
```

Table A.4: Diagnostic Output from Routine A

```
INPUT DATA ECHO CHECK


  1  10   0   0  -1   0   0       0.0         80.0000
  2   1   0   0   1   0   0      15.0000     120.0000
  3   1   0   0   1   0   0      15.0000      80.0000
  4   2   0   0   1   0   0      25.0000     110.0000
  5   3   0   0   1   0   0      25.0000      90.0000
  6   3   0   0   1   0   0      25.0000      70.0000
  7   2   4   0   1  -1   0      35.0000     120.0000
  8   3   6   5   1  -1  -1      35.0000      80.0000
  9   8  10   7   1  -1  -1      60.0000      80.0000
 10  11  16   0  -1   1   0      60.0000      50.0000
 11  12  14   0  -1   1   0      60.0000      35.0000
 12  13   0   0  -1   0   0      60.0000      15.0000
 13  22  23   0   1  -1   0      60.0000      0.0
 14  12   0   0  -1   0   0      70.0000      25.0000
 15   9   0   0   1   0   0      80.0000      80.0000
 16  18  20   0  -1   1   0      80.0000      50.0000
 17  15   0   0   1   0   0      90.0000      70.0000
 18  20   0   0   1   0   0      90.0000      50.0000
 19  15  17   0   1  -1   0     100.0000      80.0000
 20  21   0   0   1   0   0     100.0000      50.0000
 21  19   0   0  -1   0   0     130.0000      50.0000
 22  21   0   0  -1   0   0     130.0000      15.0000
 23  22   0   0  -1   0   0     130.0000     -15.0000

LOWEST CORDINATE ON THE X-AXIS =      0.0
LOWEST CORDINATE ON THE Y-AXIS =    -15.000
HIGHEST CORDINATE ON THE X-AXIS =    130.000
HIGHEST CORDINATE ON THE Y-AXIS =    120.000
```

Table A.5: Output/Input Data from Routine A to Routine B

```
   10    1    1    2    3    3    2    3    8   11   12   13   22   12    9   18
   15   20   15   21   19   21   22
    0    0    0    0    0    0    4    6   10   16   14    0   23    0    0   20
    0    0   17    0    0    0    0
    0    0    0    0    0    0    0    5    7    0    0    0    0    0    0    0
    0    0    0    0    0    0    0
   -1    1    1    1    1    1    1    1    1   -1   -1   -1    1   -1    1   -1
    1    1    1    1   -1   -1   -1
    0    0    0    0    0    0   -1   -1   -1    1    1    0   -1    0    0    1
    0    0   -1    0    0    0    0
    0    0    0    0    0    0    0   -1   -1    0    0    0    0    0    0    0
    0    0    0    0    0    0    0
    0.0     15.00     15.00     25.00     25.00     25.00     35.00     35.00     60.00     60.00
   60.00     60.00     60.00     70.00     80.00     80.00     90.00     90.00    100.00    100.00
  130.00    130.00    130.00
   80.00    120.00     80.00    110.00     90.00     70.00    120.00     80.00     80.00     50.00
   35.00     15.00      0.0      25.00     80.00     50.00     70.00     50.00     80.00     50.00
   50.00     15.00    -15.00
    1   10   11   16   14   18   12   20   13   21   19   23   22   17   15    9
    8    5    6    3    7    4    2
    0    1   10   10   11   16   11   16   12   20   21   13   13   19   19   15
    9    8    8    8    9    7    7
    2    1   10   11   16   14   18   12   20   13   21   19   23   22   17   15
    9    8    5    6    3    7    4
    0    2    1   10   10   11   16   11   16   12   20   21   13   13   19   19
   15    9    8    8    8    9    7
    3    1   10   11   16   14   18   12   20   13   21   19   23   22   17   15
    9    8    5    6    7    4    2
    0    3    1   10   10   11   16   11   16   12   20   21   13   13   19   19
   15    9    8    8    9    7    7
    4    2    1   10   11   16   14   18   12   20   13   21   19   23   22   17
   15    9    8    5    6    3    7
    0    4    2    1   10   10   11   16   11   16   12   20   21   13   13   19
   19   15    9    8    8    8    9
    5    3    1   10   11   16   14   18   12   20   13   21   19   23   22   17
   15    9    8    6    7    4    2
    0    5    3    1   10   10   11   16   11   16   12   20   21   13   13   19
   19   15    9    8    9    7    7
    6    3    1   10   11   16   14   18   12   20   13   21   19   23   22   17
   15    9    8    5    7    4    2
    0    6    3    1   10   10   11   16   11   16   12   20   21   13   13   19
   19   15    9    8    9    7    7
    7    4    2    1   10   11   16   14   18   12   20   13   21   19   23   22
   17   15    9    8    5    6    3
    0    7    7    2    1   10   10   11   16   11   16   12   20   21   13   13
   19   19   15    9    8    8    8
    8    5    6    3    1   10   11   16   14   18   12   20   13   21   19   23
   22   17   15    9    7    4    2
    0    8    8    8    3    1   10   10   11   16   11   16   12   20   21   13
   13   19   19   15    9    7    7
    9    8   10    5    6   11    3   16    7   14   18    1   12    4   20    2
   13   21   19   23   22   17   15
    0    9    9    8    8   10    8   10    9   11   16    3   11    7   16    7
   12   20   21   13   13   19   19
   10   11   16   14   18   12   20   13   21   19   23   22   17   15    9    8
    5    6    3    7    1    4    2
    0   10   10   11   16   11   16   12   20   21   13   13   19   19   15    9
    8    8    8    9    3    7    7
   11   14   12   13   23   22   21   19   17   15    9    8   10    5    6    3
   16    7   18    1    4   20    2
    0   11   11   12   13   13   22   21   19   19   15    9    9    8    8    8
   10    9   16    3    7   16    7
   12   13   23   22   21   19   17   15    9    8   10    5    6   11    3   16
    7   14   18    1    4   20    2
    0   12   13   13   22   21   19   19   15    9    9    8    8   10    8   10
```

Table A.5 continues

```
  9   11   16    3    7   16    7
 13   23   22   21   19   17   15    9    8   10    5    6   11    3   16    7
 14   18    1   12    4   20    2
  0   13   13   22   21   19   19   15    9    9    8    8   10    8   10    9
 11   16    3   11    7   16    7
 14   12   13   23   22   21   19   17   15    9    8   10    5    6   11    3
 16    7   18    1    4   20    2
  0   14   12   13   13   22   21   19   19   15    9    9    8    8   10    8
 10    9   16    3    7   16    7
 15    9    8   10    5    6   11    3   16    7   14   18    1   12    4   20
  2   13   21   19   23   22   17
  0   15    9    9    8    8   10    8   10    9   11   16    3   11    7   16
  7   12   20   21   13   13   19
 16   18   20   21   19   17   15    9    8   10    5    6   11    3    7   14
  1   12    4    2   13   23   22
  0   16   16   20   21   19   19   15    9    9    8    8   10    8    9   11
  3   11    7    7   12   13   13
 17   15    9    8   10    5    6   11    3   16    7   14   18    1   12    4
 20    2   13   21   19   23   22
  0   17   15    9    9    8    8   10    8   10    9   11   16    3   11    7
 16    7   12   20   21   13   13
 18   20   21   19   17   15    9    8   10    5    6   11    3   16    7   14
  1   12    4    2   13   23   22
  0   18   20   21   19   19   15    9    9    8    8   10    8   10    9   11
  3   11    7    7   12   13   13
 19   17   15    9    8   10    5    6   11    3   16    7   14   18    1   12
  4   20    2   13   21   23   22
  0   19   19   15    9    9    8    8   10    8   10    9   11   16    3   11
  7   16    7   12   20   13   13
 20   21   19   17   15    9    8   10    5    6   11    3   16    7   14   18
  1   12    4    2   13   23   22
  0   20   21   19   19   15    9    9    8    8   10    8   10    9   11   16
  3   11    7    7   12   13   13
 21   19   17   15    9    8   10    5    6   11    3   16    7   14   18    1
 12    4   20    2   13   23   22
  0   21   19   19   15    9    9    8    8   10    8   10    9   11   16    3
 11    7   16    7   12   13   13
 22   21   19   17   15    9    8   10    5    6   11    3   16    7   14   18
  1   12    4   20    2   13   23
  0   22   21   19   19   15    9    9    8    8   10    8   10    9   11   16
  3   11    7   16    7   12   13
 23   22   21   19   17   15    9    8   10    5    6   11    3   16    7   14
 18    1   12    4   20    2   13
  0   23   22   21   19   19   15    9    9    8    8   10    8   10    9   11
 16    3   11    7   16    7   12
    0.0   369.39   335.39   363.39   329.39   329.39   344.68   310.68   280.97    88.71
 108.42   133.13   152.84   127.13   256.26   113.42   250.26   128.13   231.55   138.13
 172.84   236.55   236.55
  53.71      0.0   389.10   417.10   383.10   383.10   398.39   364.39   334.68   142.42
 162.13   186.84   206.55   180.84   309.97   167.13   303.97   181.84   285.26   191.84
 226.55   290.26   290.26
  19.71   389.10      0.0   383.10   349.10   349.10   364.39   330.39   300.68   108.42
 128.13   152.84   172.55   146.84   275.97   133.13   269.97   147.84   251.26   157.84
 192.55   256.26   256.26
  72.42    18.71   407.81      0.0   401.81   401.81   417.10   383.10   353.39   161.13
 180.84   205.55   225.26   199.55   328.68   185.84   322.68   200.55   303.97   210.55
 245.26   308.97   308.97
  38.42   407.81    18.71   401.81      0.0   367.81   383.10   349.10   319.39   127.13
 146.84   171.55   191.26   165.55   294.68   151.84   288.68   166.55   269.97   176.55
 211.26   274.97   274.97
  38.42   407.81    18.71   401.81   367.81      0.0   383.10   349.10   319.39   127.13
 146.84   171.55   191.26   165.55   294.68   151.84   288.68   166.55   269.97   176.55
 211.26   274.97   274.97
  78.42    24.71   413.81    18.71   407.81   407.81      0.0   389.10   359.39   167.13
 186.84   211.55   231.26   205.55   334.68   191.84   328.68   206.55   309.97   216.55
 251.26   314.97   314.97
```

Table A.5 continues

44.42	413.81	24.71	407.81	18.71	18.71	389.10	0.0	325.39	133.13
152.84	177.55	197.26	171.55	300.68	157.84	294.68	172.55	275.97	182.55
217.26	280.97	280.97							
74.13	88.42	54.42	82.42	48.42	48.42	63.71	29.71	0.0	34.71
54.42	79.13	98.84	73.13	202.26	59.42	196.26	74.13	177.55	84.13
118.84	182.55	182.55							
266.39	280.68	246.68	274.68	240.68	240.68	255.97	221.97	192.26	0.0
19.71	44.42	64.13	38.42	167.55	24.71	161.55	39.42	142.84	49.42
84.13	147.84	147.84							
350.10	364.39	330.39	358.39	324.39	324.39	339.68	305.68	275.97	310.68
0.0	24.71	44.42	18.71	251.26	335.39	245.26	350.10	226.55	360.10
167.84	128.13	128.13							
325.39	339.68	305.68	333.68	299.68	299.68	314.97	280.97	251.26	285.97
305.68	0.0	19.71	324.39	226.55	310.68	220.55	325.39	201.84	335.39
143.13	103.42	103.42							
305.68	319.97	285.97	313.97	279.97	279.97	295.26	261.26	231.55	266.26
285.97	310.68	0.0	304.68	206.84	290.97	200.84	305.68	182.13	315.68
123.42	83.71	83.71							
344.10	358.39	324.39	352.39	318.39	318.39	333.68	299.68	269.97	304.68
324.39	18.71	38.42	0.0	245.26	329.39	239.26	344.10	220.55	354.10
161.84	122.13	122.13							
98.84	113.13	79.13	107.13	73.13	73.13	88.42	54.42	24.71	59.42
79.13	103.84	123.55	97.84	0.0	84.13	220.97	98.84	202.26	108.84
143.55	207.26	207.26							
241.68	255.97	221.97	249.97	215.97	215.97	231.26	197.26	167.55	202.26
221.97	246.68	266.39	240.68	142.84	0.0	136.84	14.71	118.13	24.71
59.42	350.10	350.10							
117.55	131.84	97.84	125.84	91.84	91.84	107.13	73.13	43.42	78.13
97.84	122.55	142.26	116.55	18.71	102.84	0.0	117.55	220.97	127.55
162.26	225.97	225.97							
231.68	245.97	211.97	239.97	205.97	205.97	221.26	187.26	157.55	192.26
211.97	236.68	256.39	230.68	132.84	216.97	126.84	0.0	108.13	14.71
49.42	340.10	340.10							
123.55	137.84	103.84	131.84	97.84	97.84	113.13	79.13	49.42	84.13
103.84	128.55	148.26	122.55	24.71	108.84	18.71	123.55	0.0	133.55
168.26	231.97	231.97							
216.97	231.26	197.26	225.26	191.26	191.26	206.55	172.55	142.84	177.55
197.26	221.97	241.68	215.97	118.13	202.26	112.13	216.97	93.42	0.0
34.71	325.39	325.39							
182.26	196.55	162.55	190.55	156.55	156.55	171.84	137.84	108.13	142.84
162.55	187.26	206.97	181.26	83.42	167.55	77.42	182.26	58.71	192.26
0.0	290.68	290.68							
221.97	236.26	202.26	230.26	196.26	196.26	211.55	177.55	147.84	182.55
202.26	226.97	246.68	220.97	123.13	207.26	117.13	221.97	98.42	231.97
39.71	0.0	330.39							
256.68	270.97	236.97	264.97	230.97	230.97	246.26	212.26	182.55	217.26
236.97	261.68	281.39	255.68	157.84	241.97	151.84	256.68	133.13	266.68
74.42	34.71	0.0							

Table A.6: Input Data Type No. 1 Through No. 17 to Routine B

```
10000,31511,75139,513197                               DATA TYPE NO. 1
10.0,0.5,7.,15.,15.,1.0                                DATA TYPE NO. 2
7.,7.02,1,0,0.0                                        DATA TYPE NO. 3
3,4,3,2,1,5,1,2                                        DATA TYPE NO. 4
1,0,2,23,1,0,0,0,0,1                                   DATA TYPE NO. 5
4,5,6,6,17,18,14,14                                    DATA TYPE NO. 6
1,1,1,0,0,0,0,0,0,1,0,1,0,0,1,0,0,0,0,1,1,1,0          DATA TYPE NO. 7
10,1,10,16,20,21,19,15,9,8,3                           DATA TYPE NO. 8
9,10,11,12,13,22,21,19,15,9
3,1,2,4                                                DATA TYPE NO. 9
0.5,0.0
5,1,3,2,3,4
0.40,0.0,0.7,0.0,0.5,0.0
4,1,2,3,4
0.90,0.0,0.6,0.
1,2,3                                                   DATA TYPE NO. 10
13000,10,5,4,6,5,13000,13000                            DATA TYPE NO. 11
36.,36.,18.,0.02,1200.,0.75                             DATA TYPE NO. 12
1.3,3.0,0.334                                           DATA TYPE NO. 13
2.5,9.0,0.333
4.1,8.4,0.333
2000.,4500.,1800.,2100.,3500.,4000.                     DATA TYPE NO. 14
3.0,150.,5.0,0.5,3000.                                  DATA TYPE NO. 15
23,0.5,8.,2                                             DATA TYPE NO. 16
1,0,1                                                   DATA TYPE NO. 17
```

Table A.7: Diagnostic Output from Routine B

```
   VALUES OF  ISIZE,IASEED,ICSEED,IDSEED

       10000          31511          75139          513197


   VALUES FOR SIMTIM,XMEAN,CONST,PICK,DELIV,SETUP

10.000     0.500     7.000     15.000     15.000     1.000

   VALUES FOR BTRACE,ETRACE,ITRACE,NTRACE,TCLEAR

     7.00000         7.02000          1          0              0.00000

   VALUES FOR NUMJOB,MCENTR,NUMVEH,IPACH,ICROSS,MRULE,  NUMBOX,ICRULE

3    4    3    2    1    5    1    2

   VALUES FOR LPARK,NUMPAK,NUMLOP,NUMNOD,IDIST,KRANK,   KVALUE,MSCHDL,ISIDE,IBYPAS

1    0    2   23    1    0    0    0    0    1
   NODES CORRESPONDING TO DELIVERY AND PICKUP NODES

4    5    6    6   17   18   14   14

   NODE CLASSIFICATION-- (CONFLICT VS. NON-CONFLICT

1    1    1    0    0    0    0    0    0    1    0    1    0    0    1    0    0    0    0    1    1    1    0
```

Table A.7 continues

```
   CIRCULATORY LOOPS

10    1   10   16   20   21   19   15    9    8    3
 9   10   11   12   13   22   21   19   15    9

   JOB ROUTES AND PROCESSING TIME DATA

 3    1    2    4
  0.500     0.000
 5    1    3    2    3    4
  0.400     0.000     0.700     0.000     0.500     0.000
 4    1    2    3    4
  0.900     0.000     0.600     0.000

   NUMBER OF MACHINES AT EACH CENTER

 1    2    3

   CAPACITIES OF INPUT AND OUTPUT QUEUES

13000       10        5        4        6        5   13000   13000

   CONTAINER PHYSICAL CHARACTERIZATION

 36.000    36.000    18.000     0.020  1200.000     0.750

   JOBS PHYSICAL CHARACTERISTICS

  1.300     3.000     0.334
  2.500     9.000     0.333
  4.100     8.400     0.333

   JOBS LOTSIZE DISTRIBUTION

2000.000  4500.000  1800.000  2100.000  3500.000  4000.000

   VALUES FOR E, SPEED, VLENGT, FACTOR, WEIGHT

  3.000   150.000     5.000     0.500  3000.000

   DATA ON NBATRY,CHARGE,TCHARG,NTERM

23               0.50000          8.00000          2

   DATA ON LOTX,IRRIVS,ILOCK

 1    0    1
```

Table A.8: System Trace Output from Routine B

```
************************************************************************************************************************************
                                                        NO. OF    UNIT
              NODE    NODE            JOB       JOB     UNIT      LOAD    WORK    PICK-            PARK    CIRC.   ACTIVITY
   TIME       FROM    TO      VEH.    CLASS     NO.     LOADS     NO.     CNTR    UP       DEL.    ZONE    LOOP    DESCRIPTOR
   ----       ----    ----    ----    -----     ---     -----     ----    ----    -----    ----    ----    -----   ----------

420.000000                                                                                                          00 SYSTEM TRACE BEGINS

420.061200     9       8       1                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
420.067600    15       9       2                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
420.088100     8       6       3                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
420.200900     9       8       2                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
420.204100     6       0       3                                                                                    16 VEH BLOCKED
------------------------------------------------------------------------------------------------------------------------------------
420.204100     6       3       3                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
420.227700     8       6       1                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
420.328600     3       1       3                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
420.343700     6       0       1                                                                                    16 VEH BLOCKED
------------------------------------------------------------------------------------------------------------------------------------
420.343700     6       3       1                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
420.367400     8       6       2                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
420.419900     1      10       3                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
420.468200     3       1       1                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
420.483300     6       0       2                                                                                    16 VEH BLOCKED
------------------------------------------------------------------------------------------------------------------------------------
420.483300     6       3       2                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
420.559500     1      10       1                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
420.607900     3       1       2                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
420.699200     1      10       2                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
421.002600    10      16       3                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
421.135900    16      20       3                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
421.142300    10      16       1                                                                                    05 INTERSECTION CROSSED
------------------------------------------------------------------------------------------------------------------------------------
421.199900                                                                                                          00 SYSTEM TRACE ENDS
************************************************************************************************************************************
```

Table A.9: System Statistical Output from Routine B

```
********************************************************************************

      CURRENT SIMULATION TIME =      600.000000MINUTES

           **********SYSTEM STATISTICS**********



***********TIME SPENT IN INCOMING UNIT LOAD QUEUE***************

  WORK-                        STANDARD        MINIMUM        MAXIMUM          NO. OF
  CENTER          MEAN         DEVIATION        VALUE           VALUE        OBSERVATION

     1          123.7397       126.9730         0.0000        505.3215             25
     2          221.3210       197.6519         0.0000        443.0085              6
     3            0.0000         0.0000         0.0000          0.0000              1


***********TIME SPENT IN OUTGOING UNIT LOAD QUEUE***************

  WORK-                        STANDARD        MINIMUM        MAXIMUM          NO. OF
  CENTER          MEAN         DEVIATION        VALUE           VALUE        OBSERVATION


     1         89.8358       146.4770         0.8618       417.2808            14
     2        234.2842         0.0000       234.2842       234.2842             1
     3          *****NO OBSERVATION IS MADE*****


***********TIME SPENT AT WORCENTERS BY UNIT LOADS***************

WORK-                        STANDARD        MINIMUM        MAXIMUM          NO. OF
CENTER          MEAN         DEVIATION        VALUE           VALUE        OBSERVATION

   1         148.8357       172.5494        35.2277       528.2808            14
   2         461.1838         0.0000       461.1838       461.1838             1
   3          *****NO OBSERVATION IS MADE*****


***********TIME SPENT IN THE SHOP BY JOBS***************
                             STANDARD        MINIMUM        MAXIMUM          NO. OF
                MEAN         DEVIATION        VALUE           VALUE        OBSERVATION

                *****NO OBSERVATION IS MADE*****
```

Table A.9 continues

```
******VEHICLE UTILIZATION ---(TOTAL MISSION STATISTICS)**********

                                 STANDARD          MINIMUM          MAXIMUM          CURRENT
 VEHICLE      MEAN UTIL.        DEVIATION          VALUE            VALUE            VALUE

    1            0.8348           0.3714           0.0000           1.0000             1
    2            0.8578           0.3493           0.0000           1.0000             1
    3            0.7455           0.4356           0.0000           1.0000             1


******VEHICLE UTILIZATION---(TRAVELING LOADED) **********

                                 STANDARD          MINIMUM          MAXIMUM          CURRENT
 VEHICLE      MEAN UTIL.        DEVIATION          VALUE            VALUE            VALUE

    1            0.8176           0.3862           0.0000           1.0000             1
    2            0.8307           0.3751           0.0000           1.0000             1
    3            0.7351           0.4413           0.0000           1.0000             1


              NO. OF VEHICLES CURRENTLY RECEIVING BATTERY CHARGE =      0
                      NO. OF VEHICLES CURRENTLY QUEUEING FOR BATTERY CHARGE =      0
NO. OF VEHICLES CURRENTLY DISPATCHED, QUEUEING, OR BEING CHARGED =      0


**************CURRENT LOCATION OF EACH VEHICLE***************

                  BETWEEN
 VEHICLE
  NUMBER        NODE     NODE

    1            15        9
    2            21       19
    3            20       21


**************INCOMING UNIT LOAD QUEUE LENGTH***************

  WORK-          MEAN            STANDARD          MINIMUM          MAXIMUM          CURRENT
  CENTER        LENGTH          DEVIATION          LENGTH           LENGTH           LENGTH

    1           57.1550          38.3309          14.0000         127.0000           127
    2            4.2323           1.7559           0.0000           5.0000             5
    3            0.0000           0.0000           0.0000           1.0000             0
```

Table A.9 continues.

```
**************OUTGOING UNIT LOAD QUEUE LENGTH***************

    WORK-          MEAN          STANDARD        MINIMUM        MAXIMUM        CURRENT
    CENTER        LENGTH        DEVIATION         LENGTH         LENGTH         LENGTH

      1           7.3958          3.9766          0.0000        10.0000           10
      2           1.0971          1.1729          1.0000         4.0000            3
      3           *****NO OBSERVATION IS MADE*****



******************MACHINE UTILIZATION*******************

    WORK-                        STANDARD        MINIMUM        MAXIMUM        CURRENT
    CENTER      MEAN UTIL.      DEVIATION         VALUE          VALUE          VALUE

      1           0.3317          0.4708          0.0000         1.0000            0
      2           1.7307          0.6800          1.0000         2.0000            2
      3           0.0952          0.2935          1.0000         1.0000            1



*************MACHINE BLOCKING AT EACH WORKCENTER***************

    WORK-          MEAN          STANDARD        MINIMUM        MAXIMUM        CURRENT
    CENTER       BLOCKING       DEVIATION       BLOCKING       BLOCKING       BLOCKING

      1           0.5983          0.4902          0.0000         1.0000            1
      2           *****NO OBSERVATION IS MADE*****
      3           *****NO OBSERVATION IS MADE*****


RATIO OF SETUP TIME AT MACHINING CENTERS TO AVAILABLEMACHINING TIME

                                 RATIO OF SETUP TIME TO
    WORK-                        AVAILABLE MACHINING TIME
    CENTER                       DUE TO LOAD CHANGEOVER

      2                                 0.00167
      3                                 0.00056


******************JOBS IN THE SHOP******************

                 MEAN          STANDARD        MINIMUM        MAXIMUM        CURRENT
                 NUMBER        DEVIATION        NUMBER         NUMBER         NUMBER

                 10.8582         6.3212          1.0000        21.0000          21



******************UNIT LOADS IN TRANSIT******************

                 MEAN          STANDARD        MINIMUM        MAXIMUM        CURRENT
                 NUMBER        DEVIATION        NUMBER         NUMBER         NUMBER

                  2.3834         1.1052          0.0000         3.0000           3

 **********UNIT LOADS IN THE BUFFER QUEUE**********


                 MEAN          STANDARD        MINIMUM        MAXIMUM        CURRENT
                 NUMBER        DEVIATION        NUMBER         NUMBER         NUMBER

     4            0.0085         0.0919          0.0000         1.0000           0
```

Table A.9 continues.

```
                   ******************* NODE STATISTICS *******************
                                  NO. OF VEHICLE CROSSES AND INTERFERENCES AT EACH NODE


                   NODE NUMBER        1      2      3      4      5      6      7      8      9     10     11     12     13

         NO. OF VEH. CROSSINGS      727      0    727      0     14    645      0    727    748    751     28     28     28

     NO. OF VEH. INTERFERENCES        0      0      6      0      0      0      0      0      0      6      0      0      0



                   NODE NUMBER       14     15     16     17     18     19     20     21     22     23
         NO. OF VEH. CROSSINGS        2    749    723      1      0    749    723    750     28      4
     NO. OF VEH. INTERFERENCES        0      0      0      0      0      8      0      4      0      0



 TOTAL NO. BATCHES THAT ARRIVED         21
 TOTAL NO. OF BATCHES COMPLETED             0
 TOTAL NO. OF UNIT LOADS THAT ARRIVED       152
 TOTAL NO. OF UNIT LOADS COMPLETED       0
 TOTAL TIME VEHICLES ARE BLOCKED         1.4053
```

B.5 UNIT LOAD ATTRIBUTES

A unit load in the system has some unique characteristics. These characteristics are used for distinquishing the unit loads, identifying their technological needs, and their status in the system. These characteristics or attributes are stored in the array named ATRIB. When a unit load arrives into the shop as part of a batch, some of these attributes are immediately known while others reveal themselves as the unit load progresses through the shop. An example of attributes known at the time of entry into the shop for every unit load are the job class for which the unit load belongs and the time of arrival into the shop. Not known at the time of entry into the shop is the time when a unit load will enter a workcenter or when a unit load machining will be completed at a workcenter and deposited in the outgoing unit load queue ready for pickup by a vehicle. The form of some attributes remain the same as long as the unit load remains in the shop while others are dynamically changing over time as the number of transitions between machining centers increases. For example, the times of arrival at different workcenters by a unit load will obviously be different for each workcenter along its route. On the other hand, the arrival time into the shop by a unit load is a one time event that does not change over time. The location of each attribute in the array ATRIB is presented below. Only eleven positions of the attribute array are used for entity identification. The description here is intended to acquaint users of the attributes of unit loads while they queue at workcenters. These attributes can be used for ranking entities queueing for service at workcenters.

ATRIB(1) = Job class. Every job that arrives into the shop belongs to one of the NUMJOB (see Data Type No.4) classes of jobs specified. The job class is recorded as attribute one (1) in the array ATRIB.

ATRIB(2) = Batch number on which a unit load belongs. Batches that arrive into the shop are numbered sequentially. It is this sequence number that is represented by ATRIB(2).

ATRIB(3) = Number of parts contained in a unit load. For each unit load, this number depends on job class characteristics and the physical dimensions of the container selected.

ATRIB(4) = Unit load number relative to the batch to which it (unit load) belongs. A batch that arrives into the shop may consists of N unit loads. These loads are numbered one through N. The sequence number assigned to a particular unit load within the range of one through N is stored as ATRIB(4).

ATRIB(5) = The workcenter on which a unit load is currently queueing for processing or is being processed. If a unit load is in the outgoing queue at a workcenter, ATRIB(5) represents the next workcenter on the route of the unit load.

ATRIB(6) = The arrival time into the shop of the unit load, and hence the batch to which it belongs.

ATRIB(7) = Unit load arrival time at the workcenter it is currently at. This values changes as the unit load moves to a new workcenter.

ATRIB(8) = Time a unit load is deposited into the outgoing unit load queue of the workcenter on which it is currently at. This value is valid only if the load is in the outgoing queue.

ATRIB(9) = The value of this attribute changes depending on whether the unit load is in incoming unit load queue, outgoing unit load queue, or in transit. If in transit, ATRIB(9) represents the vehicle transporting the unit load. If unit load is in the incoming queue at a department, ATRIB(9) represents the sequence number relative to the unit load route of the current workcenter. If it is in outgoing unit load queue, it represents the sequence number relative to the route of the unit load of the next workcenter it is due.

ATRIB(10) = Weight of a unit load. This weight reflects the total weight of the number of parts that makeup the unit load.

ATRIB(11) = Operation time of a unit load in the center it is currently at. This value may change with change in workcenter.

Use can be made of these attributes for sequencing unit loads (entities) in the incoming unit load queue via the variables KRANK and KVALUE (see Data Type No.6). For example to rank unit loads in incoming unit load queues according to Shortest Operation Times (SOT), the variables KRANK and KVALUE will be assigned the values of 11 and 0 respectively. Values of 11 and 1 for KRANK and KVALUE respectively implies queue ranking according to Longest Operation Times (LOT). Further examples are tabulated below.

KRANK	KVALUE	Unit Load Sequencing Rule
-1	0	Last In-First Out (LIFO)
0	0	First Come-First Serve (FCFS)
6	0	First to enter the shop, first to be served.
6	1	Last to enter the shop, first to be served.
11	0	Shortest Operation Time (SOT)
11	1	Longest Operation Time (LOT)

By following the illustration above, a user can introduce his own unit load sequencing rules by using the attribute array just described. All sequencing rules are applicable only at the machine center levels.

APPENDIX C

Linking A User Supplied Routine To The Simulator

C.1 INTRODUCTION

In theory, job shops are general purpose production systems capable of processing many types of jobs with made variations in work content. Job shops have some unique characteristics that distinquish them from other forms of production systems (e.g. mass production). There are differences in the manner they are operated. This a fact well recognized in the building of this AGVS simulator. Different shops have different operating rules, perhaps, for handling unusual situations. As a result, in addition to the vehicle dispatching rules already implemented in the simulator, provision is made to allow a user to create, code, and implement his own rules for dispatching vehicles in the shop. This can be done through two user functions or subprograms that allow users to link their coded control logic to the main stream of the simulator. Through these subprograms, information storage cells as well as entities stored in files by the simulator can be accessed and manipulated according to the dictates of the user-coded control procedure. However, to effectively utilize this capability, it is necessary to communicate to the user how and where entities and their attributes are stored and updated as the status of the system changes. Therefore, the rest of the materials to follow will attempt to accomplish this objective.

C.2 THE FILES

All entities (i.e. jobs, unit loads, vehicles, machines) in the shop are stored in files or queues. All files share space in a common storage matrix, AKEEP(.). The maximum number of entities that can be stored simultaneously in this one dimensional matrix is equivalent to (J/15), where J is the dimension of AKEEP(.). The maximum number of files that can be kept by the simulator is equivalent to L, where L is the row (i.e. left) dimension of the two dimensional array ISTUS(.,3). In a shop with M workcenters, a total of $3(M+1)$ files are maintained. There are three files kept for each workcenter. These files correspond to incoming unit load queue, outgoing unit load queue, and queue for idle machines at the workcenter. There is an exception to this generalization and it applies to the last workcenter (i.e. the Mth workcenter). No files are maintained for this department under the assumption that it is merely a terminating point for all unit loads that entered the shop. The naming of the files will be presented next. The index K, $K<M$, in the naming of the files refer to a workcenter identification number while M refers to the number of workcenters in the shop.

<u>FILE NAME</u>	<u>FUNCTION OF FILE</u>
$3(K-1)+1$	Incoming unit load queue (file) at workcenter k, $k<M$.
$3(K-1)+2$	Outgoing unit load queue at workcenter K, $k<M$.
$3K$	Idle machine queue at workcenter K, $K<M$.
$3(M-1)+1$	An interdepartmental service queue that serves all departments in the shop. All machines that are blocked in the shop from any department are filed in this queue. Using the attributes of the machines in the file, their departmental sources can be uniquely identified.

$3(M-1)+2$	Queue for vehicles waiting for battery charge. When a vehicle arrives at the battery recharge station for battery charge and their is no free charging terminal at the time of arrival, the vehicle is queued in this file.
$3M$	A service-queue acting as a buffer for unit loads blocked from entering the departments of their destination when such departments are presumed locked. This temporary buffer queue is used only when the shop locks and the AGVs are equiped with antishop locking mechanisms. The queue is merely a temporal working area for unit loads in transit.
$3M+1$	Master file for all jobs (not unit loads) in the shop at any point in time. When a job enters the shop, a record is opened for it. When a unit load is completed, the record of the job to which the unit load belongs is updated. The completion of the last unit load of a job marks the completion of the job and the destruction of its associated record.
$3M+2$	Transit queue or queue for unit loads in transit.
$3(M+1)$	The EVENTS file. All scheduled activities or activities that require the passage of time are stored in this file. Every event in the EVENTS file is removed from the file at its corresponding event time.

C.2.1 Filing and Retrieving Information from Files

Entities in a file are distinquished from one another by their attributes. Jobs and unit loads are assigned attributes at the time of their arrivals at the shop. Vehicles, machines, and activities are also assigned attributes as their status changes. Through the subprograms FILEM, RMOVE, and XEROX, attributes of entities can be placed in files, removed from files, copied from files, manipulated and updated as may be necessary.

C.2.1.1 Subroutine FILEM

The subroutine FILEM is used for filing entities and their attributes in files. The syntax to invoke the routine is:

```
CALL FILEM(L,AAAA,LRANK,LV)
```

where

L = the index or name of the file into which an entity is to be placed.

AAAA = an array containing the attributes of the entity to be placed in file.

$$\text{LRANK} = \begin{cases} 0, & \text{if first come-first serve ranking is applied to file L.} \\ -1, & \text{if last in-first out ranking applies to file L.} \\ K, & \text{if ranking of entities in file L is according to attribute K.} \end{cases}$$

$$LV = \begin{cases} 0, & \text{if LRANK equals -1 or 0.} \\ 0, & \text{if ranking of file L using attribute K is by low value of AAAA(K) first.} \\ 1, & \text{if ranking of entities in file L using attribute K is by high value of AAAA(K) first.} \end{cases}$$

C.2.1.2 Subroutine RMOVE

The subroutine RMOVE removes from files entities and their attributes placed in file by the subroutine FILEM. The syntax for RMOVE is:

```
CALL RMOVE(J,L,AAAA)
```

where

L = the index or name of the file from which an entity is to be removed.

J = the rank of the entity to be removed from file L. If there are n entities in a file, the entity ranks range from 1 to n.

AAAA = the array into which the attributes of the entity removed from file L are buffered and returned to the system.

C.2.1.3 Subroutine XEROX

The subroutine XEROX copies the attributes of an entity in a file, buffers and returns them (the attributes) in the array AAAA. The syntax for XEROX is:

```
CALL XEROX(J,L,AAAA)
```

The argument J represents the rank in file L of the entity whose attributes are to be copied and L is the label of the file in which the entity resides.

C.2.1.4 Function NNQ

The function subprogram NNQ(L) returns the number of entities in file L. If the subroutines RMOVE and XEROX are called with an entity rank greater than NNQ(L), an execution error will occur and will terminate the program.

C.2.1.5 Illustrative Example

The following example illustrates the use of the subroutines FILEM, RMOVE, XEROX, and NNQ.

```
      DIMENSION AAAA(20)
      .....
      .....
      ....
      .....
      .....
c     CHECK IF NO. OF ENTITIES IN FILE 6 IS 2 OR LESS
      IF(NNQ(6).LE.2)RETURN
C      COPY THE ATTRIBUTES OF 3RD ENTITY IN FILE 6
      CALL XEROX(3,6,AAAA)
```

```
C       TEST THE VALUE OF THE 9TH ATTRIBUTE
        IF(AAAA(9).GT.6.0)GO TO 12
        RETURN
c       REMOVE THE THIRD ENTITY FROM FILE NO. 6
   12   CALL RMOVE(3,6,AAAA)
c       MODIFY THE VALUES OF THE NINTH AND TENTH ATTRIBUTES.
        AAAA(9)=5.0
        AAAA(10)=16.0
c       REPLACE THE ENTITY IN FILE NO. 5
        CALL FILEM(5,AAAA,7,1)
        RETURN
        END
```

The above example performs a test on the number of entities in file number 6. If the number of entities in the file does not exceed two, control is transfered away from the routine. Otherwise, the attributes of the third entity in the file are copied and a test is performed on attribute number 9. If the 9th attribute has a value less than or equal to 6.0, again control is transferred away from the routine. Otherwise, control is transferred to statement 12. Statement 12 removes the third entity from the file. Thereafter, the values of the 9th and 10th attributes are changed. Finally, the entity is placed in the 5th file instead of file number 6 where the entity was removed. The 5th file is ranked in decreasing order of the 7th attribute of the file entities.

C.2.2 The Events File

All activities that require the passage of time in the system are stored in the events file (i.e. file index 3(M+1)). Event activities in the events file are distinquished from each other by their event codes. Activities with the same event codes can be further distinquished using other attributes. The following event codes are assigned to the following activities as outlined below. With the aid of the event codes, the system recognizes each event type and automatically transfers control to appropriate regions of the simulator when an event activity occurs at an event time. The event time is the instant when an event occurs or is scheduled to occur at some future time.

EVENT CODE NO.	EVENT
1	Job arrival event.
2	Vehicle arrival at a node or intersection event.
3	End of unit load delivery event at a delivery station by a vehicle.
4	End of a unit load pickup event at a pickup station by a vehicle.
5	End of simulation time event.
6	System statistics clearance event.
7	Beginning or end of system trace event.
8	End of vehicle battery charging event.
8+K	End of unit load machining event at workcenter K, K<M.

When entities or activities in the events file are removed using the subprogram RMOVE or copied using XEROX, the event code associated with the activity is automatically returned as AAAA(12) and the corresponding event time as AAAA(13). Entities placed in the events file are always ordered or ranked in increasing value of AAAA(13) (i.e. LRANK

= 13 and LV = 0 as defined under subroutine FILEM). However, when the system removes an event entity from the events file at its propere event time, the associated attributes are returned in the event attribute array ATRIB(.).

C.3 VEHICLE STATUS

Information regarding vehicles in the shop are stored in arrays and files. The array VEHICL(.,.) is the chief data bank on vehicles. Information on a vehicle is kept in file if the vehicle is performing an activity, receiving service, or queueing for service. A vehicle performing a task has its attributes stored in the events file. This is also applicable to a vehicle receiving battery charge. A vehicle queueing for battery charge has its attributes stored in the file designated for vehicles waiting for battery charge. Parked idle vehicles do not have any attributes in files. Regardless of the status of a vehicle, its status are also continuously updated in the array VEHICL(.,.).

C.3.1 The Array VEHICL(.,.)

The array VEHICL(.,.) is the memory core of all vehicles. Its elements are continuously updated as the status of each vehicle in the system changes. Each row of the array is dedicated to a vehicle. The order in which the rows are assigned to the vehicles follow the same chronological naming (labeling) of the vehicles. For example, row two is assigned to the vehicle with identification number two. As many rows as there are vehicles are used in this matrix. Any excess rows, depending on the dimension of VEHICL(.,.) are not utilized. At least the row dimension of VEHICL has to be as large as the number of vehicles employed by the shop. The column dimension has to be at least as large as $(8+H)$, where H is the maximum number of nodes that a vehicle is expected to travel through before getting to its destination during any given trip. The value of H is conditioned by the paths traveled by vehicles and is estimated by the maximum number of nodes expected to be along any path between two nodes in the network. A trip is defined as a journey by a vehicle from a source node to the final destination node. A trip leg is a journey between two adjacent nodes. A trip may consist of several trip legs. If R is the maximum number of trip legs that can be in any path traveled by a vehicle, then $H = (R+1)$.

The column elements on any row of matrix VEHICL(.,.) assigned to a vehicle point to special features of the vehicle as described below.

Column No.	Identifier
1	1, if vehicle is idle and in park. 2, if vehicle is idle and returning to a parking area. 3, if vehicle is traveling empty but on a pickup assignment. 4, if vehicle is traveling loaded. 5, if vehicle is dwelling and unloading. 6, if vehicle is dwelling and loading.

	7, if vehicle is idle but looping in a circulatory loop or returning to a circulatory loop.
	8, if vehicle is enroute for battery charge, queueing for, or receiving battery charge.
2	0, if vehicle is not transporting any unit load.
	J, if vehicle is transporting a unit load belonging to job class J.
3	Origin (i.e. workcenter, park area, battery charging terminal, or circulatory loop) of a vehicle during any trip.
4	Destination of a vehicle (workcenter, etc.) during any trip.
5	Vehicle identification number.
6	Vehicle traveling speed.
7	Number of trip legs remaining for a vehicle to reach its destination.
8	The immediate past intersection or node on the path of a vehicle.
9	The next intersection or node a vehicle will arrive at if in motion. On the other hand, if a vehicle is dwelling or is in park, column 9 represents the node where the vehicle is located.
10	From column 10 to the right most dimensioned column contain a list of all remaining nodes on the path of a vehicle after the next node is crossed. If these ele-

ments are zeros, it implies a vehicle is either making its last trip leg or is already at its destination.

C.3.2 Vehicle Attributes Stored in Files

When a vehicle undertakes an activity, in addition to the record maintained in the array VEHICL(.,.), its attributes are also stored in the events file. The following are vehicular activities stored in the events file when they are in progress or ongoing.

1. Unit load delivery activity.
2. Unit load pickup activity.
3. Vehicle traveling activity. Traveling between nodes is an activity since it requires the passage of time.
4. Vehicle receiving battery charge. When a vehicle is being charged, it is actually being operated on by the charging terminal or machine. In this case, a vehicle is the entity receiving service rather than providing service.

The event codes associated with the different functions have been previously defined. A parked vehicle or a vehicle queueing for battery charge does not have its attributes stored in the events file. Otherwise, all vehicles with ongoing activities have their attributes stored in the events file. A vehicle queueing for battery charge has its attributes stored in the queue designated for this purpose. At the moment a parked vehicle is reassigned a task, its attributes are immediately recreated and placed in the events file. These attributes, as well as those stored in the array VEHICL(.,.) are continuously updated as the status of the vehicle changes over time.

At the instant an event associated with a vehicle occurs, the attributes of the corresponding vehicle as stored in the events file are removed and buffered in the array ATRIB(.). Thereafter, ATRIB(.) and the row assigned to the vehicle in the matrix VEHICL(.,.) are updated. The array ATRIB(.) is then filed back into the events file if the said vehicle resumes another activity immediately. Otherwise, the ATRIB(.) array is temporarily destroyed if the vehicle parks. If the vehicle queues for battery charge, its attributes in ATRIB(.) are filed in the queue for vehicles waiting for battery service. A vehicle reassigned a task after a period of dormancy has its attributes recreated using the array AAAA(.) before filing in the events file. Generally, the arrays ATRIB(.) or AAAA(.) and the array VEHICL(.,.) are updated simultaneously at the same simulation time or event time. Thus, for vehicle I, given that modification started with the array VEHICL(.,.), the relationships between ATRIB(.) or AAAA(.) and VEHICL(.,.) are as follow.

ATRIB(1) = VEHICL(I,2)
ATRIB(2) = VEHICL(I,3)
ATRIB(3) = VEHICL(I,4)
ATRIB(4) = VEHICL(I,5)
ATRIB(5) = VEHICL(I,6)
ATRIB(6) = Time vehicle left its destination
ATRIB(7) = VEHICL(I,9)

ATRIB(8) = VEHICL(I,8)

C.3.3 Auxillary Information Sources on Vehicles

The following storage locations in the arrays below maintain additional information on vehicles.

IVLOCK(I) = number of unit loads currently in the buffer queue dumped there by vehicle I.

UDELI(I,2) = total running time in minutes since vehicle I last received a battery charge.

C.3.4 Vehicle Utilization Information

Two forms of equipment utilization statistics are maintained on each vehicle. These are based on complete mission cycle time and partial mission cycle time. Complete mission cycle time is the time interval from the moment a vehicle was dispatched for a unit load pickup assignment at some department through the delivery of that unit load at its subsequent destination. The partial mission statistics is based only on the actual time a vehicle is transporting a unit load.

Statistics on average utilization of a vehicle at any point in time can be obtained by invoking the function subprogram UTIL(K), where

K = 1, if average utilization of vehicle I based on complete mission cycle time is required.

$K = (N+M+I) + 3(M+1)$, if average utilization of vehicle I based on partial mission time is required.

N = number of vehicles in the shop.

M = number of workcenters in the shop.

Time dependent variables describing vehicle utilization are maintained in the single dimensional array XX(.) and in the array positions XX(K), where $K = I$ or $(N+M+I)+3(M+1)$.

For $K = I$ corresponding to the Ith vehicle,

$$XX(K) = \begin{cases} 0, & \text{if vehicle I is currently unassigned.} \\ 1, & \text{otherwise.} \end{cases}$$

For $K = (N+M+I)+3(M+1)$, corresponding to the Ith vehicle,

$$XX(K) = \begin{cases} 0, & \text{if vehicle I is idle or already assigned but traveling empty.} \\ 1, & \text{otherwise.} \end{cases}$$

C.4 JOBS AND UNIT LOAD INFORMATION

When a job arrives at the shop, it is unitized into unit loads and a record is created for the job. The record created is placed in the job master file (i.e. file index 3M+1). The record is then available for manipulation just like any other file entity. Job records have the following attributes:

AAAA(1) = job class or job type.

AAAA(2) = job identification number assigned at the time of arrival at the shop. There is a unique number for each job that enters the shop.

AAAA(3) = job lot size. This attribute describes the number of parts contained in the job as of the time it arrived at the shop.

AAAA(4) = number of unit loads not yet completed by the shop that belong to the job whose identification number is recorded as AAAA(2). Each time a unit load belonging to a job is completed, AAAA(4) is updated. When AAAA(4) falls to zero, the last unit load of the job and hence the job itself is completed. When a job is completed, its record is erased from the file.

AAAA(5) = job arrival time at the shop.

AAAA(6) = number of unit loads originally contained in the job as of the time of arrival at the shop.

C.4.1 Unit Load Record

A unit load in the shop can be found in any one of the following areas.

1) incoming unit load queue at a workcenter.
2) outgoing unit load queue at a workcenter.

3) on a machine, being processed at a workcenter.
4) on a machine at a workcenter but blocked with the machine.
5) in transit, being transported by a vehicle, and
6) in unit load buffer queue, being held temporarily while in transit.

There is a unique file associated with each of the areas listed above as previously described on the section on files. As the unit loads move from one production stage to another in the shop, their attributes are updated and shuffled accordingly from one file to another. When placed, removed or copied from files, unit load attributes have the following features:

AAAA(1) = The job class to which the unit load belongs.

AAAA(2) = The identification number of the job to which the unit load belongs.

AAAA(3) = Number of parts contained in the unit load. Parts in a job, and hence in a unit load are assumed to be homogeneous.

AAAA(4) = The sequence or identification number of a unit load relative to all unit loads generated from the same job. Unit loads obtained from a job are sequentially numbered from one through n, where n is the total number of unit loads generated from the job at the time of arrival at the shop.

AAAA(5) = The value of AAAA(5) depends on the file a unit load is found. Unit loads undergoing machining operation at a workcenter are stored in the events file with their attributes, event code, and event time. When blocked with a machine at a workcenter after being processed, it is filed in the blocked machine queue with the proper attributes marked. If a unit load is in an incoming unit load queue, being processed, or blocked with a machine, AAAA(5) has a value equivalent to the identification number of the workcenter it is at. AAAA(5) has a value equivalent to the identification number of the next workcenter on the route of the unit load if it is in an outgoing queue, transit queue, or buffer queue.

AAAA(6) = The arrival time at the shop of the unit load, and hence the batch job to which it belongs.

AAAA(7) = The time a unit load arrived at a workcenter. If a unit load is in the buffer queue, AAAA(7) is the time it was dumped into the buffer queue. When in transit, AAAA(7) has the same value as it did at the preceding workcenter.

AAAA(8) = The value of AAAA(8) again depends on the file a unit load is found. In the outgoing queue at a workcenter, it is the time the unit load was deposited in the queue after machining completion by the workcenter. In the buffer or transit queue, it is the next production stage of the unit load. The number of production stages for any unit load is equivalent to the number of machine stations, not necessarily distinct, on the route of the unit load. In other files, AAAA(8) is not used.

AAAA(9) = If a unit load is in the incoming unit load queue, being processed, or in the blocked machine queue, AAAA(9) is equivalent to the current production stage of the unit load. In outgoing queue, AAAA(9) is the next processing stage for the unit load. When in transit or in the buffer queue, AAAA(9) identifies the vehicle transporting the load or had it dumped in the buffer queue.

AAAA(10) = The weight of the unit load.

AAAA(11) = In the incoming unit load queue at a workcenter, AAAA(11) is equivalent to the operation time required by the unit load at the workcenter.

AAAA(12) = In the blocked machine queue, AAAA(12) identifies the machine center from which the load was blocked. In the events file, AAAA(12) is the event code associated with the machining activity the unit load was undergoing. The event code for a machining operation at department K is given by $(8^{+}K)$.

AAAA(13) = In the blocked machine queue, this is the time a unit load, and hence the machine that processed it was blocked. In the events file, AAAA(13) is the event time for the end of a machining operation.

C.5 MACHINES AT WORKCENTERS

Machines at workcenters, along with their attributes, are stored in files. Like the other system files, these files can be manipulated and the machine attributes moved from one file to another as their (i.e. machines) operational status change. A machine can be in any one of three files, namely,

1) the idle machine file in each department,
2) the events file when it is processing a unit load. In essence, when a machine is operating on a unit load, the two entities (i.e. machine and unit load) are automatically considered as a single entity.
3) the blocked machine file when it is blocked. Again, when a machine is blocked, it is actually being blocked with a unit load. The blocked machine and the load are stored as a single entity in the blocked machine file.

In the events file, machines simply appear only as attributes of the unit loads they process (see the definition of AAAA(5) and AAAA(12) in the section on unit loads). In the blocked machine file, again machines are marked only as attributes of the unit loads being blocked with the machines.

However, in the idle machine file at each department, machines are explicitly stored as entities. When in these files, the machines have the following attributes.

AAAA(1) = Index of the machine center to which the machine belongs.

AAAA(2) = The job type that was last processed by the machine before it was set idle. This information is not kept for machines in workcenter number one.

AAAA(3) = The production stage to which the last unit load processed by the idle machine was relative to the route of the load.

AAAA(4) = The time the machine was set idle.

C.5.1 Machine Utilization

If K is the index for a machining center and M is the number of machining centers in the shop, K<M (the Mth workcenter is the finished product warehouse), information regarding machine center utilization and other characteristics of the center can be obtained using the following subprograms and arrays.

Function Subprogram	Function

NNQ(J)	Returns the number of idle machines at workcenter K, where J = 3k, K<M.
UTIL(J)	Returns the average utilization per machine at workcenter K, where J = N + 3K, K<M, and N is equal to the number of vehicles in the shop.
MACHIN(K)	Number of machines currently blocked at workcenter K, K<M.
XX(J)	NUmber of machines currently operating on jobs at workcenter K, J = N + 3K, K<M, and N is equal to the number of vehicles in the shop.
NROUTE(K)	Number of vehicles currently enroute to department K for load pickup, K<M. This value is also equivalent to the number of unit loads currently in the outgoing queue of department K that have already been assigned to vehicles for pickup. If more vehicles are assigned to a department than are outbound unit loads in that department, an error will occur when the last vehicle in that set reaches the destination. This is because the vehicle will not find any load in the queue when it gets there.

NODCEN(K,1)	The node index corresponding to unit load delivery station at workcenter K.
NODCEN(K,2)	The node index corresponding to unit load pickup station at workcenter K.
IQCAP(K,1)	Capacity of incoming unit load queue at workcenter K.
IQCAP(K,2)	Capacity of the outgoing unit load queue at workcenter K.

C.5.2 Other System Variables

TNOW	Current simulation time in minutes.
FROMTO(n,q)	Distance between node n and node q measured along the shortest path.
IARRIV	A counter that keeps track of the number of jobs (not unit loads) that have arrived at the shop as of time TNOW.
IOUT	Number of jobs completed by the shop as of time TNOW.
INNNN	Counter that records total number of unit loads that were obtained from the number of jobs that have arrived at the shop as of time TNOW.
ICMPLE	Number of unit loads completed by the shop as of time TNOW.

C.6 BUILDING USER CONTROL SUBPROGRAMS

The materials presented thus far were concerned on how information are stored and retrieved in the simulator. The descriptions were intended to acquaint the user with the basic structure of the simulator as well as to provide him the opportunity to develop and incorporate his own creative work in the area of vehicle dispatching rules for the operation of an Automatic Guided Vehicle System. Through the two user subprograms, WCTASK and VCTASK, additional vehicle dispatching rules as may be deemed appropriate can easily be coded and integrated as a decision making component of the simulator. These user subprograms when supplied will replace the two dummy subprograms, also named WCTASK and VCTASK, currently incorporated in the simulator.

C.6.1 Workcenter Initiated Task Assignment (Dispatching) Rules

When a workcenter makes a vehicle request for unit load pickup, a rule is required for selecting a vehicle to assign the task if multiple vehicles are available simultaneously. At any decision time, the status of each vehicle can easily be determined by querying the attribute arrays and the storage matrices bearing information on vehicles. The class of rules for selecting the preferred vehicle is addressed as 'Workcenter Initiated Task Assignment Rules.' These rules were discussed in Chapter 6 of this manuscript. In the simulator, five rules in this family were implemented to cater for the vehicle assignment problem of this kind. As presented in the User's Guide to the simulator, rule selection is done simply by assigning a value of zero (0) through four (4) to the input data control parameter IPACH. However, a value of five (5) assigned to IPACH automatically activates the system to expect a user coded subprogram where the vehicle selection decision logic will be expressed. Control will be transferred to this user supplied subprogram at all decision times that involve the selection of a vehicle. The subprogram which the simulator expects in the name of WCTASK has a syntax of the form below.

```
      SUBROUTINE WCTASK(MC,K)
      COMMON/SCOM1/ATRIB(20),KRANK,..........
      COMMON/EGBELU/NCLNR,TNOW,..............
      ..........
      ...........
      IL=0
      ..........
      ..........
      ..........
C       ASSIGN K THE INDEX OF THE SELECTED VEHICLE
      K=IL
      ..........
      ..........
      ..........
      RETURN
      END
```

The arguments of the subprogram are the following:

MC = the index of the workcenter that is placing a request for vehicle.

K = the identification number of the vehicle selected to be dispatched to workcenter MC according to user coded dispatching instructions. The value of K is defined in and returned

> by the user subprogram. If K is equal to zero (0), it implies that the vehicle request is not honored. This is the case when no vehicle is available to assign a mission.

The system assumes that a vehicle already assigned, or dispatched, queueing for, or receiving battery charge is not available for a new assignment until it is released from its ongoing activity.

For the user supplied subprogram to communicate freely with the other subroutines of the simulator, it is the user's responsibility to imbed the appropriate COMMON statements in the incorporated routine as they appear in the rest of the simulator.

C.6.2 Vehicle Initiated Task Assignment (Dispatching) Rules.

When a vehicle completes a unit load delivery assignment, it is considered to be available and can be immediately reassigned to a new task if there is any outstanding task in the facility. Otherwise, it is set idle. Suppose there are unattended pickup tasks available in at least two departments. The selection of a department to assign the released vehicle is a system control decision. A workcenter is a candidate for selection if and only if it has at least one outbound unit load to be removed but not yet assigned to any vehicle. The rules for selecting a workcenter are classified as 'Vehicle Initiated Task Assignment Rules.' These rules were presented in chapter 6 of this manuscript.

Seven rules in this family are currently incorporated in the simulator. The choice of a control rule for the use of the simulator is accomplished simply by assigning a value of zero (0) through six (6) to the input control parameter MRULE. However, a value of seven (7) assigned to MRULE will automatically transfer control to a user supplied subprogram, VCTASK, any time a vehicle initiated task assignment decision is to be made. Like the subprogram WCTASK, VCTASK contains user coded instructions for controlling assignments to vehicles and for selecting a preferred workcenter to assign the vehicle. The syntax for VCTASK is of the form below.

```
      SUBROUTINE VCTASK(IVEH,MC)
      COMMON/SCOM1/ATRIB,.............
      COMMON/EGBELU/NCLNR,............
      .................
C      INITIALIZE THE WORKCENTER SELECTED
      LD=0
      ...............
      ...............
      ...............
c     SET MC EQUAL TO THE INDEX OF THE SELECTED DEPARTMENT.
      MC=LD
      ............
      ............
      ............
      RETURN
      END
```

The subprogram arguments IVEH and MC are the identification numbers of the vehicle to be reassigned and the workcenter selected to receive the vehicle respectively. MC is defined in VCTASK and its definition is according to user coded vehicle assignment instructions. If MC is returned as zero (0), it implies that no workcenter is selected. In such case, the system sets the vehicle idle. MC should be returned as zero if there is no unattended pickup task in the facility.

C.6.3 Comprehensive Example

A shop has the following control strategies for dispatching vehicles for unit load pickup assignments. When a workcenter places a request for a vehicle, the nearest available vehicle within 100.0 feet away from the pickup station of the workcenter is dispatched. Otherwise, the request is not honored. On the other hand, when a vehicle is released and has to be reassigned to another pickup task, the workcenter that has the least average utilization per machine and has an unattended unit load in the outgoing queue is selected. If no unit load pickup task is available, the vehicle is set idle.

The codes presented below under the two user supplied subroutines, WCTASK and VCTASK, contain the dispatching instructions described above. Users are advised to consult their Computer Services Departments for the appropriate Job Control Language (JCL) that will permit them to link their user supplied routine to the simulator.

```
      SUBROUTINE WCTASK(MC,K)
      COMMON/EGBELU/NCLNR,TNOW,XX(100),IACT(19,6),RECORD(40)
      COMMON/ONE/NODCEN(40,2),AJOB(40,3),BOX(10,6),SSETUP(40),NROUTE(40)
     *,VEHICL(30,70),MPARK(10),LOOP(5,20),IROUTE(40,20),INCID(100,3),
     *IDIREC(100,3),CORD(100,2),ISHORT(200,100),FROMTO(100,100),IPATH(80
     *),NODE(100,3),E,F,TEPS,MACHIN(40),PROTIM(40,20),JOBNUM,IQCAP(40,2)
      COMMON/WORK/AAAA(20),AMAP(40,6),IDLVEH(40,2),IFOUR(3,3),BATRIB(20)
      COMMON/VAR/MAXATR,MCENTR,ICMPLE,NUMVEH,IPACH,ICROSS,MRULE,NUMBOX,
     &ICRULE,LSTRAG,LPARK,NUMPAK,NUMLOP,SPEED,VLENGT,NUMJOB,TBLOCK,HTIME
     %,MSCHDL,IBYPAS,IDIST,FACTOR,MIZE,WEIGHT,UDELI(40,2),SEETUP,ISIDE
C
C     SET THE QUEUE POINTER FOR THE EVENTS FILE.
C     MCENTR= NO. OF DEPTS. IN THE SHOP
      IQUEUE=3*(MCENTR+1)
C     LOCATE IDLE VEHICLES IN THE SHOP
      K=0
      FAR=60000000.
C     NUMVEH=TOTAL NUMBER OF VEHICLES IN THE SHOP.
      DO 5 I=1,NUMVEH
C     CHECK THE STATUS OF EACH VEHICLE, MAKE SURE THE VALUES ARE
C     INTEGERIZED.
      L=VEHICL(I,1) + 0.5
      IF(L.GE.3.AND.L.NE.7)GO TO 5
C     VEHICLE I THAT IS QUERRIED IS NOT ENGAGED.
      DISTAN=0.
      IF(L.EQ.1)GO TO 6
C     VEHICLE I IS TRAVELING. LOCATE IT IN THE EVENTS FILE AND
C     CALCULATE ITS DISTANCE AWAY FROM THE PICKUP STATION OF THE CALLING
C     WORKSTATION.
C     SET NA EQUAL TO NO. OF ELEMENTS IN THE EVENTS FILE.
      NA=NNQ(IQUEUE)
      DO 7 II=1,NA
      CALL XEROX(II,IQUEUE,AAAA)
C     CHECK THE EVENT CODE OF THE ENTITY COPIED FROM FILE.
      ICODE=AAAA(12)+0.5
      IF(ICODE.NE.2)GO TO 7
C     THE FILE ENTITY IS A VEHICLE. CHECK THE IDENTIFICATION NUMBER.
      ID=AAAA(4)+0.5
      IF(ID.NE.I)GO TO 7
C     THE REQUIRED VEHICLE HAS BEEN LOCATED IN THE FILE. CALCULATE
C     HOW FAR AWAY IT IS FROM THE NEXT NODE ON ITS PATH BASE ON TIME
C     REMAINING TO ARRIVE AT THE NODE.
C
      TIME=AAAA(13)-TNOW
C     SPEED MULTIPLIED BY REMAINING TIME GIVES REMAINING DISTANCE.
      DISTAN=VEHICL(I,6)*TIME
      GO TO 6
    7 CONTINUE
C     CALCULATE THE TOTAL DISTANCE FROM LOCATION OF VEHICLE NOW TO
C     THE PICKUP POINT OF THE CALLING WORKSTATION.
C
C     NOD1 = NEXT SUCCEEDING NODE ON THE PATH OF VEHICLE OR THE NODE
C     VEHICLE IS CURRENTLY LOCATED.
C     NOD2 = NODE CORRESPONDING TO THE PICKUP POINT OF THE CALLING
C     WORKSTATION.
C
    6 NOD1=VEHICL(I,9)+0.5
      NOD2=NODCEN(MC,2)
      DISTAN=FROMTO(NOD1,NOD2) + DISTAN
C
C     DISPATCH ONLY THE VEHICLE THAT IS WITHIN 100 FEET OF DISTANCE
C     AWAY FROM THE DEMAND POINT AND HAS THE NEAREST DISTANCE AWAY.
      IF(DISTAN.GT.100.)GO TO 5
      IF(DISTAN.GT.FAR)GO TO 5
C     ASSIGN K THE IDENTIFICATION NUMBER OF THE VEHICLE SATISFYING
C     THE DISTANCE CONDITION.
      K=I
      FAR=DISTAN
    5 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE VCTASK(IVEH,MC)
      COMMON/ONE/NODCEN(40,2),AJOB(40,3),BOX(10,6),SSETUP(40),NROUTE(40)
     *,VEHICL(30,70),MPARK(10),LOOP(5,20),IROUTE(40,20),INCID(100,3),
     *IDIREC(100,3),CORD(100,2),ISHORT(200,100),FROMTO(100,100),IPATH(80
     *),NODE(100,3),E,F,TEPS,MACHIN(40),PROTIM(40,20),JOBNUM,IQCAP(40,2)
      COMMON/VAR/MAXATR,MCENTR,ICMPLE,NUMVEH,IPACH,ICROSS,MRULE,NUMBOX,
     &ICRULE,LSTRAG,LPARK,NUMPAK,NUMLOP,SPEED,VLENGT,NUMJOB,TBLOCK,HTIME
     %,MSCHDL,IBYPAS,IDIST,FACTOR,MIZE,WEIGHT,UDELI(40,2),SEETUP,ISIDE
C
C     INITIALIZE THE DEPARTMENT SELECTED TO ZERO.
      MC=0
C     SET COUNTER
      UUTIL=1.0
C     QUERY DEPARTMENTS SEQUENTIALLY (EXCEPT THE LAST) TO IDENTIFY THE
C     QUALIFYING DEPARTMENT.
C     MCENTR=TOTAL NO. OF DEPARTMENTS IN THE SHOP.
      NCENTR=MCENTR-1
      DO 18 K=1,NCENTR
C     SET THE POINTER TO THE OUTGOING UNIT LOAD QUEUE.
      IQUEUE=3*(K-1)+2
C     ANY LOAD IN THE OUTGOING QUEUE?
      IF(NNQ(IQUEUE).LE.0)GO TO 18
C     THERE IS LOAD IN OUTGOING QUEUE.
C     HAVE THEY ALL BEEN ASSIGNED TO VEHICLES FOR PICKUP?
      IF(NROUTE(K).LT.NNQ(IQUEUE))GO TO 17
C     ALL OUTGOING UNIT LOADS IN THIS DEPT. AT THE CURRENT TIME HAVE
C     ASSIGNED TO VEHICLES FOR PICKUP.
      GO TO 18
C     THERE IS AT LEAST ONE UNASSIGNED UNIT LOAD IN THE OUTGOING QUEUE
C     OF THIS DEPT. AT THE CURRENT TIME.
C     CALCULATE THE AVERAGE PER MACHINE UTILIZATION AT THIS DEPARTMENT.
   17 J=NUMVEH + 3*K
      AX=UTIL(J)
      IF(AX.LE.UUTIL)MC=K
      IF(AX.LE.UUTIL)UUTIL=AX
   18 CONTINUE
      RETURN
      END
```

A DESIGN METHODOLOGY FOR OPERATIONAL CONTROL ELEMENTS FOR AUTOMATIC GUIDED VEHICLE BASED MATERIAL HANDLING SYSTEMS

by

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(ABSTRACT)

A methodology for the design of operational control aspects of an Automatic Guided Vehicle (AGV) based material handling system is presented. The methodology, which is composed of an integrated model of an AGV based system, was implemented using simulation technique. The model views a manufacturing function as consisting of machining, queueing, and moving of parts in a shop and that these components of manufacturing must be integrated and co-ordinated if the production objectives of an enterprise are to be realized. A machining center is modeled as a physical region of a plant and it consists of machines for part processing and capacitated queues in which inbound and outbound parts reside, queueing for machining or handling resources.

Automatic guided vehicles provide the transport mechanism required to interface the machining centers. A network approach is employed to represent the layout of the facility, including the location of departments, input and output queues in each department, and the layout of the guidance system on which the AGVs operate. The network approach, along with the co-ordinate system are employed for modeling the actual translation of vehicles and parts through the shop. The

travel time of vehicles and parts between points depends on vehicle speed and the prevailing traffic condition along the path of travel.

Several shop control strategies in the application of AGVs have been modeled, implemented, and their effects on shop performance demonstrated. Among these factors are vehicle dispatching, vehicle routing, unit load size selection, job sequencing, shop loading, queue constraints, and capacity constraints due to vehicles and machines. A job in the shop is considered to consists of one or more parts grouped in portable unit load sizes. Therefore, it is unit loads rather than jobs that make the flow transitions.

The results of the simulation experiments conducted indicated vital control elements in the design of AGV systems. Through a series of output statistics on system performance, the model provides an easy to use tool to analyze, evaluate, and design of AGV based manufacturing system.