

**USE OF SIMULATION-ANIMATION TECHNIQUES IN THE DESIGN
OF AN AUTOMATED GUIDED VEHICLE SYSTEM**

by

Arun Jayaraman

Project submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Master of Engineering

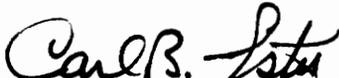
in

Industrial and Systems Engineering

APPROVED:



R.J. Reasor, Ph.D., Chairman



C.B. Estes, Ph.D.



J.D. Tew, Ph.D.

May 6, 1993

Blacksburg, Virginia

C.2

LD
5655
V851
1993
J392
C.2

Use of Simulation-Animation Techniques in the design of an Automated Guided Vehicle System

by

Arun Jayaraman

R.J.Reasor, Ph.D., Chairman

Industrial and Systems Engineering

(ABSTRACT)

Automated Guided Vehicles (AGV) are becoming an increasingly popular system for performing materials handling functions in industry today. The design and implementation of an Automated Guided Vehicle System (AGVS) is a complex issue and involves many aspects. It is highly advisable to design and plan the system prior to its implementation. This project considers some of the key issues and parameters in the initial design phase of an AGVS for a company manufacturing antilock braking systems for automobiles. The design of the AGVS is carried out using simulation-animation techniques. PROMODEL pc, a popular manufacturing simulator is used for developing the simulation models. Different AGVS alternatives are considered. A multi-attribute framework is used for developing and analyzing the AGVS alternatives. The recommended AGVS design alternative is chosen based on economic justification and satisfaction of the company's throughput requirements.

ACKNOWLEDGEMENTS

I would like to thank my adviser Dr.Reasor for his support, advice and guidance over the past two years. Dr.Reasor is one of the nicest persons I've met and it has been a great pleasure working with him. I would also like to thank my committee members Dr.Estes and Dr.Tew for their time and consideration. I would like to thank the staff at Virginia Tech., Lovedia, Nicole, La Vonda and Joni for their help.

I would like to thank my parents Lalitha and V.Jayaraman for their love, support and encouragement over all these years. Special thanks are due to my sister-in-law and my brother, Krithika and Kishore Jayaraman for their love and support and for being there for me. I would like to thank Bala Iyer for his support and advice and Rajendra Auradkar for all his advice. Finally thanks to all my room-mates Sridhar, Shirish, Rajesh, Rajiv and Sharath and all my other friends for their help and for making my life easier over the past two years.

TABLE OF CONTENTS

Chapter 1

Introduction	1
1.1 Overview	1
1.2 Description of an AGVS	2
1.3 Simulation in the design of an AGVS.....	4
1.4 Case Study	7

Chapter 2

Literature Review	9
2.1 Introduction.....	9
2.2 Design of an AGVS	9
2.2.1 Focus of Literature Review.....	11
2.3 AGVS Design factors and tools.....	12
2.3.1 Simulation and Non-simulation Approaches.....	14
2.4 Primary Factors in Initial design of an AGVS.....	22
2.5 Summary	24

Chapter 3

Methodology	25
3.1 Animation	26
3.2 Baseline Model	26
3.3 Primary Design Considerations	27
3.4 Simulation Languages and Simulators.....	31
3.5 PROMODEL pc.....	32
3.6 The Simulation Process and Approach.....	36
3.7 Product Description.....	38
3.7.1 Facility Layout.....	39
3.8 Forecast requirements.....	40
3.9 Final Selection and Justification.....	42
3.10 Summary.....	43

Chapter 4

Data Collection and Experimental Design.....	45
4.1 Data Collection.....	45
4.2 Overview of Simulation Models.....	46
4.2.1 Flow Charts and Operations	
Process Charts.....	48
4.2.2 Description of Facility	
Modeled.....	49
4.2.3 Transporter Path Modeling.....	56
4.3 Small Parts Modeling.....	59
4.4 Assumptions made in Modeling.....	62

4.5	Downtimes Modeled.....	64
4.6	Simulation Parameters.....	64
4.7	Experimental Design.....	65
4.8	List of Models Developed.....	66
4.9	Computer Resources.....	68
4.10	Summary.....	69

Chapter 5

Results and Conclusions.....	70
5.1 Simulation Results.....	70
5.1.1 Baseline Model.....	70
5.1.2 AGVS Models.....	72
5.2 Types of vehicles for the AGVS.....	74
5.3 Cost Estimate and Justification.....	76
5.4 Conclusions and Recommendations.....	78
Bibliography.....	80
Appendix A.....	83
Appendix B.....	89

LIST OF ILLUSTRATIONS

Figure 1 : System Throughput Vs. AGV Fleet Size.....	10
Figure 2 : Layout of Facility used for Modeling.....	41
Figure 3 : Materials handling boxes and cart.....	47
Figure 4 : Flow Chart of Parts for HCU.....	51
Figure 5 : Operations Process Chart for HCU.....	52
Figure 6 : Flow Chart of Parts for TMC.....	53
Figure 7 : Operations Process Chart for TMC.....	54
Figure 8 : Graphic Printout of Facility from Animation.	55

LIST OF TABLES

Table 1 : TMC Production Requirements.....	40
Table 2 : HCU Production Requirements.....	42
Table 3 : List of Models with Parameters.....	68
Table 4 : Results from the Baseline Model.....	73
Table 5 : Results from the AGVS Models.....	74

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

In today's competitive business environment, it is essential for any manufacturing organization to change and adapt itself to technological advances. Rapid advances are being made in automation, including automation of materials handling activities. Materials handling is an important function in any manufacturing situation. Depending on the industry and type of operation, materials handling may account for 30-75% or more of the cost of making a product [Kulwiec, 1985]. Considerable attention should be paid to the design and maintenance of the materials handling system in any industry. With recent advances in computer technology, this area of manufacturing lends itself well to automation.

Automated Guided Vehicle Systems (AGVS) are probably one of the very exciting and dynamic areas of materials handling today [Koff, 1987]. Though the idea has been in existence for a very long time now (over forty years), advances made in the fields of microprocessors and computers has made it an accepted and efficient method for materials handling. Today AGVS is a multi-million dollar industry in

itself. In fact, there are several different types of AGVS' differing from each other in the level of complexity and capability.

1.2 DESCRIPTION OF AN AGVS

Briefly, an AGVS consists of one or more battery operated (usually), driverless, self-guided vehicles carrying or towing materials from one work-place to another. This work-place maybe an individual work-center or a machining center (consisting of a group of work-centers) or even a warehouse. Each vehicle runs at about 2-3 miles/hour. The speeds may be lower when the vehicles are loaded. There are different kinds of AGVS catering to different situations. These vary from towing vehicles which tow a series of carts loaded with materials to unit load vehicles and fork lift vehicles. More recent types include assembly line vehicles and light load AGVS.

These vehicles differ from each other, not only in their load carrying capacities, but also in other factors such as guidance, control and traffic management. Currently, guidance is largely done using wires (electrically) buried in the floor or using reflective tapes (optically) painted on the floor. In the case of wire

guidepaths, the vehicles guide themselves by tracking the amplitude of the signals received from the wires at different sensors located on the vehicle. Any variation in signal amplitude or frequency would indicate deviations from the path and the vehicle corrects its position accordingly. In the case of reflective tapes, the optically reflected signal helps in guiding the vehicle. Again, variations in the reflected intensity would be a measure of the deviations. Recent advances in guidance technology includes wireless vehicle systems and vehicles which run on grids painted on the floor. The vehicles guide themselves by following the patterns on the grid.

The vehicles are usually controlled by means of a central computer. The vehicles are also built-in with a certain degree of on-board controls. The control system is the brain of the AGVS and functions such as vehicle dispatching are carried out by it. Traffic management is another function that prevents the AGV's from running into one another and helps in optimizing the paths taken by the vehicles. Traffic management is done by splitting up the guidepaths into zones and restricting the number of vehicles in a zone or by means of on-board sensing devices. Any design of an AGVS will have to give careful consideration to

all the above functions. But most of these design parameters will enter the picture at the time that the AGVS is to be implemented. Before the physical implementation is made, the feasibility of the AGVS as an alternate materials handling system will have to be evaluated. AGV's offer a flexible and advanced materials handling method. The flexibility of AGV's is largely due to guidepaths they follow. Simply by changing the guidepaths and altering the routing programs in the central computer or microprocessor, any changes in job sequence and schedule can be accommodated. This flexibility can be a great advantage in both job-shop and flow line situations and is the primary reason for the popularity of AGVS' today [Egbelu, 1982]. However, not unlike other automation technologies, an AGVS may or may not be suitable to all kinds of manufacturing systems. Before jumping into the implementation blindly, a careful analysis should be made regarding the feasibility of such a system. This is where digital computer simulation proves to be a boon.

1.3 SIMULATION IN THE DESIGN OF AN AGVS

There has been a dramatic increase in the use of simulation for manufacturing analyses during the past few

years. This has been due to the greater complexity of automated systems, reduced computing costs brought about by microcomputers and engineering workstations, improvements in simulation software which have reduced model development time and the availability of graphical animation which has resulted in greater understanding and use of simulation [Law & Haider, 1989]. Not long ago, simulation was labeled as a "tool of last resort". The technique required significant expenditures of time, capital and resources - both human and computer [Turner, 1986]. Another problem was that engineers could not easily understand and validate the model for accuracy and completeness. The existing simulation software would require from good to complete knowledge of programming and statistical techniques. All these factors reduced the importance of simulation as an effective tool for analysis. But, with the advances in software and computer capabilities mentioned above, computer simulation seems to be an attractive alternative for the dynamic analysis of systems prior to implementation. Today, simulation is an effective tool in all the four phases of the system life cycle, namely

-

- Preliminary design
- Detailed design

- Implementation

- Operation

In particular, simulation would be a valuable tool in the preliminary design phase, where the decision to commit a good deal of the capital is made. This is especially true in cases where the decision is to implement newer technology in a manufacturing situation [Phillips, 1980]. A good example would be the decision to implement an Automated Guided Vehicle System for the materials handling function. In fact, simulation and AGVS installations go hand in hand [Schwind, 1990]. Simulation is the first and best tool for AGVS installations for quite a few good reasons. AGVS and their interfaces are complicated. Several alternative systems with differing capabilities are available. In system design, trade-offs need to be made between guidepaths, vehicle speeds, number of queuing positions etc. Simulating these details can protect from outright system failure. Simulation can demonstrate visually, how a well reasoned solution can work. Awareness of guidepath designs is provided through animation. This can be very helpful in evaluating bids and proposals from different vendors. It is possible to understand if a particular proposal is over or

under-engineered. This is the situation ITT TEVES, North Carolina is faced with.

1.4 CASE STUDY :

ITT Teves manufactures Antilock Braking Systems(ABS). They are experiencing significant growth at their Asheville, North Carolina facility. The expansion of this facility includes plant layout and material handling system improvements to minimize materials flow, reduce cycle times, support JIT deliveries to the point of use, improve quality, etc.. Currently, ABS subassemblies and final assemblies are performed in automated assembly cells within a clean room environment. Much of the materials transfer (components, subassemblies etc.) between these automated assembly cells is performed using manual materials handling methods. Unit loads are transferred in/on bins or carts. This creates congestion, resulting in awkward flow paths and interferes with operator performance. In addition, these unit loads can become very heavy, requiring more than one operator to move. Such movements may result in future lost time injuries to employees. Thus, the purpose of the project is to develop an AGVS design appropriate for transfer of

materials to/from automated assembly cells in this clean room production environment.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter deals primarily with a review on literature associated with the work that has been done in the past on AGVS design considerations. The chapter serves to establish the key design considerations before installing an AGVS and the approaches that have been adopted in the past to analyze these considerations.

2.2 DESIGN OF AN AGVS

There are software and hardware aspects to be considered before installing an AGVS. Long before the actual installation process, it is important to consider all the parameters involved with the AGVS. A key parameter which would deal with factors like meeting throughput requirements, traffic management, congestion etc. would be the number of vehicles needed in the AGVS. Since there is a cost associated with each individual vehicle, it is economical to have as few vehicles as possible. However, this number should not be so low as to sacrifice throughput

for the sake of economy. Determining this parameter is a key element in planning the AGVS. This parameter is affected by other factors such as the track layout for the AGVS, the track capabilities such as unidirectional and bidirectional movement capability, traffic management system, control considerations and many other criteria. Again, while having very few vehicles would lead to ease of controls and traffic management, this could lead to starvation for vehicles and adversely affect the throughput of the manufacturing system. Conversely, having too many vehicles would lead to congestion and would delay the vehicles from reaching their destinations in time. This situation would affect the throughput adversely. In fact the function guiding the relationship between the number of vehicles and the throughput of the system, within a fixed

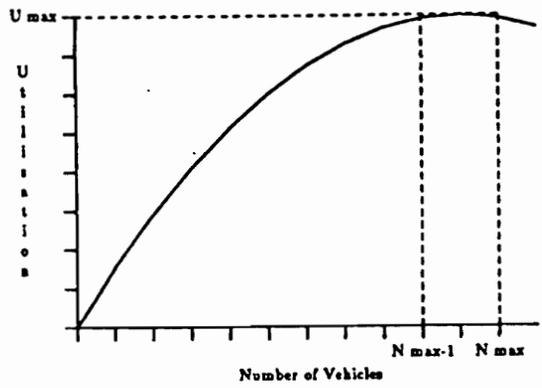


Figure 1 : System Throughput Vs. AGV Fleet Size

interval of time is concave [Sienrich & Tanchoco, 1990]. Figure 1 shows the throughput as a function of the fleet size for a hypothetical system [Ozden, 1988].

2.2.1 FOCUS OF LITERATURE REVIEW

The physical aspects of an AGVS and all the hardware considerations and system factors such as traffic management, system control, load transfer methods, steering guidance etc. are discussed in Koff, G.A.[1985] . The literature discussed here focuses on the factors to be considered during the preliminary design of an AGVS and the methodologies usually employed to develop and analyze design alternatives. Particularly, these design factors address the fleet size in the AGVS, location and number of pickup/delivery points and other factors that directly relate to the feasibility of an AGVS as an alternate materials handling system. This in turn does not mean that factors such as dispatching the vehicles are less important to the performance of the system. It merely means that these factors come into play at the time of actual implementation of the system. Work done in the past to deal with the preliminary design problems can be divided into two major methods, namely -

1. Analytical or non-simulation methods and
2. Simulation methods.

2.3 AGVS DESIGN FACTORS AND TOOLS

Simulation has been used as an extensive tool in the design and analysis of material handling systems for a long time. This has been further enhanced by the advancements in the area of digital computers and microprocessors. Ashayeri, Gelders and Van Looy [1987] discuss the use of micro-computer simulation in the design of Automated Guided Vehicle Systems. The authors establish the importance of using simulation for justification before actually installing an expensive system such as AGVS for materials handling. Several parameters are involved during the design stage of the AGVS. These would include the optimal number of AGV's, route layout, position and capacity of idle stations, position of pickup and delivery points, changing demands, track layout capability (capacity of the vehicles for unidirectional and bidirectional travel), the location of the workcenters and the total plant layout and so on. The authors state that, though a number of the parameters described above can be established using analytical models and/or an intuitive approach, neither considers the dynamics

and integrality of the system. A hypothetical manufacturing system is considered and is simulated using the BASIC programming language. A discrete simulation approach is used to model the system. The authors establish the ease of use and accuracy of results provided by using micro computer simulation for the design and analysis of complex automated systems .

Sale and Stein [1987] emphasize the importance of simulation in modeling an AGVS. Since an AGVS is integral to the larger manufacturing system and directly related to the performance of the total system, it cannot be designed intuitively or through guess-work. It is emphasized that a successful AGVS design must balance fleet size, guide-path layout, input and output queue size and system control considerations. The control software must be designed and tested for a range of operating conditions and contingencies. Simulation modeling lends itself well to meet these requirements.

Davis [1986] addresses some general concepts which can be used to model the design of an AGVS using simulation. Davis points out that AGVS' are particularly sensitive to the interactions among the vehicles in the system and to the level of co-ordination between the AGVS and the entire

manufacturing system. If this dynamic behavior is not properly modeled, it leads to overly optimistic estimates of the AGVS. This is the problem with math programming and queuing theory techniques. Davis highlights vehicle fleet size, track layout and control logic as three characteristics of AGVS' that lend themselves well to simulation analysis. Models developed early in the design process will be more general than those which are created during actual system implementation, since system data is still rough. The utilization of the vehicles and some measure of the AGV blocking are used as performance measures for the hypothetical system modeled. It is emphasized that though factors like variations in vehicle speed between loaded and unloaded conditions, slower speed due to a weak battery condition, acceleration and deceleration are not always modeled, they will have to be taken into consideration, when appropriate.

2.3.1 USE OF SIMULATION AND NON-SIMULATION APPROACHES

In the past, non-simulation methods were used in the estimation of the fleet size and other design parameters. The problem was typically solved as a transportation problem in operations research. Maxwell & Muckstadt [1981] consider

different aspects in the design of an AGVS. In particular, a method to estimate the minimum number of required vehicles and the dispatching rules for these vehicles are discussed. The authors consider time dependent effects such as blocking of vehicles due to congestion and battery charging. However these factors are not considered in the determination of the minimum number of vehicles required. Though the importance of factors such as aisle configuration, proposed position of pickup/delivery points and proposed track layout are highlighted, they are assumed to be known before the optimal fleet size is calculated. The authors present the problem of determining the fleet size as a transportation problem in which the objective is to minimize the unloaded (empty) travel distance of the vehicles. Since dynamic aspects such as the blocking due to congestion and other factors are not considered, the number of vehicles required might be underestimated.

The superiority of simulation techniques over non-simulation techniques is highlighted well in literature. Egbelu[1987,5], describes the use of non-simulation techniques in estimating vehicle requirements in an AGVS. The following are listed as the major factors that affect the vehicle requirements -

1. The system layout.
2. The location of load transfer points.
3. The trip exchanges between workcenters per unit time.
4. The vehicle dispatching strategy.
5. System reliability and
6. Speed of travel.

Setting aside the hardware and vendor related factors, the author narrows down the factors to -

1. The guide-path layout.
2. Location of load transfer points.
3. Vehicle dispatching strategies.

The first two are layout related problems and reduces to the optimality of the guidepath. As the author puts it, there are no exact methodologies to develop the layout and it is done more on a commonsense basis. Thus, with a reasonably good layout and good vehicle dispatching strategies, the number of vehicles required can be minimized. Egbelu describes four analytical or calculation based estimation techniques. All four methods assume that details regarding the manufacturing situation are known. These details include the number of unit loads to be moved, the distance between all workstations in question, travel times of vehicles, loading and unloading time, efficiency of vehicles

and so on. The four methods are compared using a hypothetical system consisting of eight machining centers. The adequacy of the above vehicle requirement estimators is analyzed by using simulation to determine the number of vehicles needed for the same facility. The results of the simulation show that all the four analytical methods underestimate the actual number of vehicles required to meet the throughput. Egbelu suggests that while the analytical methods may provide a good starting point in approximately estimating the number of vehicles, they cannot be used as accurate and conclusive estimators. Simulation will have to follow any of these techniques in order to obtain a good estimate of vehicle requirements.

Tanchoco, Egbelu and Taghaboni[1987, 26] compare the effectiveness of CAN-Q with a simulation based method, for determining the number of vehicles required. CAN-Q stands for Computerized Analysis of Network of Queues and is an analytical model based on queuing theory. It is an approximation model based on the steady-state behavior of the system. CAN-Q has been used extensively in modeling and analyzing manufacturing systems. The simulation analysis is based on AGVSim (Automated Guided Vehicle Simulator) developed by Egbelu and Tanchoco [1982]. The authors

conduct their comparison based on a hypothetical manufacturing system.

The objective is to compare the estimate of the number of vehicles required for this manufacturing system, using CAN-Q and AGVSim. The authors analyze both unidirectional and bi-directional travel configurations for the AGVS. The authors emphasize that the required number of vehicles is affected by several factors including the number of moves, move timing, network layout, product layout and the mutual interference among vehicles which reduces the potential availability of a vehicle over a period of time. The use of mathematical programming optimization approaches are deemed less appropriate, since the dynamic behavior of the system is not captured in the decision making process. CAN-Q, for instance, only provides results from the steady-state performance of the system. Transient behavior is assumed to be unimportant. However the attractive feature of CAN-Q is the minimal data requirements. Simulation and modelling approaches require far more data as input. In both methods proposed by the authors, the number of vehicles required is obtained through an iterative process. Each iteration requires a complete run of the model. Three measures of system performance were used - machine

utilization, mean flow time of products and the system throughput. Each iteration consists of varying the number of vehicles and observing the performance measures. Further, each model is studied for differing values of the cycle ratio 'c', which is defined to be

$$c = \frac{\text{Average operation time per part}}{\text{Average transport time per part}}$$

There is a range of values for 'c' for which the system throughput is constrained by the transportation system. This means that the transportation system is the bottleneck. Beyond this range, the transporter became a non-constraining resource. The bottleneck resource shifted to one of the machining stations. In particular, the manufacturing system is analyzed for two values of 'c' and for both unidirectional and bidirectional AGVS.

It is established that CAN-Q is a good approximating tool for determining the lower bound on vehicle requirement. Though the estimates from CAN-Q are close to the actual requirement as given by the simulation based method (AGVSim), it underestimates the actual number of vehicles

required. Three measures of system performance are used. These are the mean machine utilization, mean flow time and the system throughput. The authors also mention the mean job flow time and the mean queue size as parameters whose values would be of interest in any analysis.

Extending the work on using CAN-Q as a possible vehicle estimator, Egbelu, Wysk, Zhou and Ghosh [1987, 31], evaluate the use of spread sheet analysis for evaluating AGVS. The purpose is to describe a fundamental approach to material handling system planning which emphasizes specific design issues for the use of AGVS in manufacturing. CAN-Q is used to model the AGVS. However the manufacturing system under consideration is not directly modelled using CAN-Q. Instead, Auto-Q is used for the input process. Auto-Q stands for Automatic Input of parameters to CAN-Q. It is a user-friendly software that uses a spread-sheet approach for data entry. Once the data is input to Auto-Q, a data file which is readable by CAN-Q is automatically created. Materials handling calculations (such as the shortest distance between the work-stations) are also automatically done by Auto-Q.

The authors model the manufacturing system in a unique fashion. They divide the sample manufacturing system

into three smaller blocks and model each of these blocks separately. The number of vehicles required for each of these blocks is calculated. The results from each block is added to get the total AGV requirements (fleet size) for the system. Since CAN-Q assumes a steady-state system, the effects of equipment break-downs, peak and low production periods and vehicle blockage and interference are not accounted for in the actual calculations of vehicle requirements. Thus the vehicle requirements would be underestimated.

It is established that though the modelling is made simpler, this method cannot be a complete analysis and design of an AGVS. It only serves as an analysis tool to specify an AGVS. For accuracy, computer simulation would be a necessary element.

Sinreich and Tanchoco [1990] have developed a multi criteria optimization model using the cost and the throughput performance of the manufacturing system to evaluate the effectiveness of an AGVS. The fleet size is thus determined using a goal programming approach. Analytical methods based on the CAN-Q model are combined with simulation to perform the studies. The authors emphasize that economic justification will also have to be

considered while studying the trade-off between the fleet size and the costs incurred.

2.4 PRIMARY FACTORS IN THE INITIAL DESIGN OF AN AGVS

As stated by Egbelu [1987], the three principal factors in consideration in the preliminary stages of the design of an AGVS are,

- The guide-path layout.
- the location and number of the load transfer points.
- the vehicle dispatching strategies.

There is no mathematical formulae involved with arriving at the optimal guidepath layout and the generation of the layout. This part of the design is essentially based on common-sense and a good knowledge of the layout and structural constraints. Similarly, the vehicle dispatching strategies are not typically addressed during the preliminary design stage and is more of an operational aspect. This leaves the location and number of load transfer points (also known as pickup/delivery points) as a primary design criteria.

The other major design issue that will have to be considered in the preliminary design and justification of an AGVS is the track layout capability. This refers to the

capability of the system for bidirectional or unidirectional travel. This design issue directly controls the fleet size and cost of an AGVS. Egbelu and Tanchoco [1986, 7] discuss the potentials for bidirectional guidepath for AGVS'. The authors mention that one of the initial decisions to be made in the design of an AGVS is to determine whether bidirectional or unidirectional flow is appropriate. Simulation techniques lend themselves well in this analysis. Models of bidirectional guidepaths are created for simple layouts and compared with the performance of a corresponding unidirectional guidepath system. Simulation is used to evaluate the systems. The primary criterion used in the comparison of the two flow alternatives is the number of unit loads completed over a period of time. In a bidirectional system, there is a reduction in both the aisle space and guidewire requirements. However the control system becomes more complex and expensive. There is a trade-off and the increased throughput of the system should also be considered in any economic comparison.

One other configuration of AGVS' that has not been investigated in detail are vehicles operating in tandem loops. Bozer and Srinivasan [1989] have investigated the feasibility of a tandem configuration AGVS for a simple

manufacturing system. The tandem configuration is compared with a traditional AGVS with unidirectional motion capability. A tandem configuration is based on partitioning all work-stations into non-overlapping, single vehicle closed loops with additional P/D points provided as an interface between adjacent loops. This system leads to a much simpler control system and reduces congestion. Limitations include a larger fleet size and lesser tolerance for vehicle breakdowns. This configuration generates a load routing problem as opposed to a vehicle routing problem in the case of a traditional AGVS. Again, simulation models were developed to compare the two configurations.

2.5 SUMMARY :

This chapter has reviewed the relevant literature for this project. The major subject that has been covered is the use of digital computer simulation techniques to design and analyze an Automated Guided Vehicle System. The various design parameters involved in the design of an AGVS has been highlighted. The advantages of using simulation techniques over non-simulation techniques to arrive at and analyze these preliminary design parameters has been discussed.

CHAPTER 3

METHODOLOGY

As established in the previous chapter, simulation is the best tool for analyzing and evaluating alternative Automated Guided Vehicle Systems (AGVS) designs. Also, from the First Chapter, it is clear that the objective of this project is to analyze the current materials handling procedures at ITT Teves and suggest a safer, more economic alternative to perform the materials handling function. In particular, the objective was to analyze the feasibility of an AGVS as an alternate materials handling system at ITT Teves. Thus this project was carried out using simulation-modeling techniques. Validation is an important aspect of simulation and in general, with modeling. Validation is the process of confirming that the model is a true representation of reality, or at least close to it. It is very important to validate any model before drawing any conclusions from it. One of the major concerns in simulation has been convincing managers of the model's validity in being close to the real system.

3.1 ANIMATION

This problem is solved if the manager participates closely in the development process. Though this participation is possible in the data collection stage, it is not possible during the modeling and analysis stage. Another means to prove the validity is through the effective use of animation. Graphical animation of simulation output is one of the newest features of many simulation languages. Animation removes many of the "black box" aspects of a simulation model and allows users to see model assumptions in action rather than depending on the modeler's assurance and on long-run statistical output to verify model correctness [Carson, 1986]. Hidden bugs in the model are easily seen and solved through graphical animation [Wang, 1985]. Animation is an important complement to simulation-modeling and does not replace detailed analysis. In this document simulation-animation refers to simulation modeling with animation used as an effective complement.

3.2 BASELINE MODEL

In lieu of the afore mentioned, the first objective of the project was to model the existing system with all the existing parameters. A simple and effective means of

validating the model was to examine the output from the model and compare it with the actual system's output. Coupled with animation, this was a definite step in assuring the modeler as well as the manager of the validity of the simulation process. This is a standard method used in modeling whenever a new system has to be designed [Phillips, 1980].

The current system at ITT Teves uses manual material handling. Accordingly, the system was modeled using the same number of materials handlers currently used by ITT Teves. Once the justification was done and the client was convinced of the validity of the modeling process, alternate material handling equipment which can replace/combine with the manual materials handlers were chosen and the corresponding model was analyzed.

3.3 PRIMARY DESIGN CONSIDERATIONS

Three primary design criteria were considered in the modeling of each AGV system. These are -

1. Travel capability of the vehicles :Unidirectional travel capability for the vehicles or bi-directional travel capabilities for the vehicles or combinations of the two.

2. Unit Load Configurations : Sizes of the unit loads that will be carried by the vehicles in the system. This size was based on the sizes of the unit loads currently being used in the facility. The current unit load size was addressed as the "Full unit load size". These full unit load sizes were used in modeling the current system with the manual materials handling capabilities. This unit load size was used as a starting point so that the compatibility of the existing unit load sizes with the alternate materials handling device could be investigated. For the AGV systems, along with the full unit load sizes, two other sizes were investigated, namely -

Half unit load sizes - all the unit loads in the system were one half of the current unit load sizes used in the system.

Quarter unit load sizes - all the unit loads in the system were one quarter of the current unit load sizes used in the system.

This parameter was addressed as the weight carrying capabilities of the vehicles in the AGVS will be directly affected by the size of the unit loads. This factor, in turn, will affect the type of AGVS chosen.

Thus, a "full unit load size" will require an AGVS with towing type of vehicles, while "half unit load sizes" may require the use of an AGVS using unit load vehicles. This in turn will affect the cost of the AGVS. There are significant differences in the cost of controls and equipment, between towing vehicles and unit load vehicles. Another factor that was affected directly by this parameter was the number of AGV's required by the system. If the unit load was cut down to one-fourth its size, it increased the demand of AGV's to four times the original requirement.

3. Number of P/D Points : The third parameter was the number of pickup and delivery points (P/D points) in the AGVS. These points act as an interface between the vehicles and the assembly cells. The raw materials or any other sub-components to an assembly cell will be delivered at the appropriate "delivery points" by the vehicles. The finished products of each assembly cell will be picked up by the vehicles at the "pick-up points" for subsequent delivery to other work-stations. The number of these P/D points will have a substantial impact on the performance of any AGVS. The congestion and the traffic management in the AGVS was one factor,

that were affected the most, by this parameter. There will have to be guidepaths leading to each P/D points. More P/D points than necessary will lead to wasted space in the facility and expense due to the extra guidepath wires needed. Too few P/D points will lead to blockage of vehicles, overflow of the racks at these points and will adversely affect the throughput of the system. The project investigated the effect of single and/or multiple P/D points at the different assembly cells according to the flow at that center. Each assembly cell however, has at least one input point (for deliveries) and one output point (for pickups). In the case of multiple P/D points, there are multiple pickup and multiple delivery points located around the particular assembly cell.

These three parameters essentially lent direction to the modeling and analysis of the alternate AGVS. The primary design objective, again, was to examine different AGVS designs with particular attention to the number of vehicles needed in the system. The minimum number of vehicles needed to achieve the desired level of throughput was identified.

3.4 SIMULATION LANGUAGES AND SIMULATORS

Currently, simulation modelling is carried out using one of three methods, namely

- Using a general purpose programming language such as C or FORTRAN
- Using a general purpose simulation language such as SLAM, SIMAN, GPSS, etc..
- Using a manufacturing simulator, such as PROMODEL, SIMFACTORY, WITNESS etc..

While general purpose programming languages and general purpose simulation languages can provide a great deal of modelling flexibility, compatibility and debugging capability, the manufacturing simulators in today's market are not far behind [Law & Haider, 1989]. Though the degree of flexibility offered by simulators is not as great as the programming languages, the other advantages offered easily favor one's opinion in choosing a simulator, at least in manufacturing situations. A major factor is the animation capability offered by today's manufacturing simulators. If animation is to be an essential component of the modeling process, then the time required to model using traditional programming languages nearly double and a great deal of

programming expertise is needed. This takes up a lot of time and money. Though special purpose simulation languages like SIMAN and SLAM offer the capability for animation, the animation will have to be developed separately and this factor increases the modeling time. The modeling time is shortened by using a simulator as the animation is developed simultaneously with the modeling. The modeler can spend the time saved, in analyses. For these reasons, a manufacturing simulator was used for the purposes of this project.

There are close to 25 different manufacturing simulators available in the market, today [McComas & Law, 1992]. One of these, PROMODEL pc (referred to as PROMODEL throughout the rest of this report) was chosen for this project. PROMODEL was selected because it was available at Virginia Polytechnic Institute and because it provides a robust modeling environment for AGVS design and analysis.

3.5 PROMODEL pc

PROMODEL provides a modular model building feature with user-friendly pull-down menus. It provides an automatic model building mode which guides the user through an easy model building process. The animation of the model is also developed simultaneously with the model building and

the software provides a variety of icons and symbols. The software provides extensive output statistics and capabilities for generating graphical output of these statistics. The software provides an Interface, using key variables defined in the model which can be changed to perform a quick study of the change. While this might not be an accurate representation of the effect on the actual system, this feature will be helpful in obtaining a direction for future modeling and studies. Thus, for example, it is possible to determine if an increase in the number of vehicles in an AGVS would be a change that might lead to reduced congestion in the system. This decision will have to be substantiated by creating the appropriate models and performing multiple runs of these models. Thus this feature can be very useful in saving the modeling time.

In particular, PROMODEL provides extensive capabilities for modeling AGVS. The guidepaths can be defined as segments. The length of these segments can be varied and are user-defined. The high-point of the software in this respect is that, it incorporates an algorithm that maps the shortest path between all points in the guidepath during compilation time. Thus the algorithm effectively calculates the shortest path for the vehicles to get to one work-center

from another. The modeler is relieved from calculating and mapping all these points. The guidepath is defined as segments and each of these segments connect points on the path. These points are specifically called 'Transporter Points'. These points also serve as pickup/delivery (henceforth referred to as P/D points) points at the different work-centers. Operational aspects of the AGVS can be modeled as well. The vehicles can be defined to have either bi-directional or unidirectional travelling capability or a combination of bi-directional and unidirectional segments. As mentioned in the previous chapter, this was an important parameter in determining the fleet size of the AGVS. The transporter points can be defined to have a 'capacity'. This would be the number of vehicles that can occupy a transporter point at a given time. In practice, this is not done. There are usually some form of pull-off spurs or buffers (or ramps). Defining a capacity for the transporter points would in effect model these buffers. Thus valuable space can be saved on the screen. It is important to have a large portion of the plant layout on the screen so that the manager and the modeler can look at what is going on at different sections of the plant, at the same instant. The software provides

the capability to zoom-in on any portion of the layout for close scrutinization. Icons are provided for representing standard machining centers and also for showing the movement of parts. Materials handling systems such as conveyors, automated guided vehicles, cranes or even people are also provided with icons that represent the actual shape of the respective method very closely. These icons can be painted in different colors. So it is easy to distinguish between the machines and the work-pieces themselves. One distinguishing feature when modelling AGV's and people as materials handlers is that the part being carried is shown very clearly. Coupled with the facts mentioned above about the icons and the colors, it is possible to identify a work-piece being carried by looking at the shape and color of the moving icon. This is a very useful feature when demonstrating the animation to management as they can not only react to the plant layout but also to the actual identity of the parts being moved. This aspect is also important from the modeler's perspective in that the routing of the respective parts to the appropriate workstations can be verified. These factors coupled with several other advantages made PROMODEL the obvious choice for the purposes of this project.

3.6 THE SIMULATION PROCESS AND APPROACH

The simulation process can be broadly categorized into the following steps [Law & Kelton] -

- Definition of objective.
- Data collection.
- Model development.
- Model execution.
- Model output.

Defining the objective is one of the most important steps of a simulation analyses. Failure to have a well defined set of objectives is a common pitfall that leads to an ill-organized project and possibly failure of the entire simulation process [Law & McComas, 1989]. Since the objective of the project was defined on page 24, the next step in the project was to gather data . All the data needed to develop the base model of the existing facility. Since there were no major changes in the production requirements and the system throughput with the alternate material handling system, most of the data gathered at this stage was also useful for the future models. However, this stage of the simulation process needs extra care. Simulation results are extremely sensitive to the data collected [Almodovar, 1988] and wrong data can lead to wrong

results and justifications. The data collected was constantly updated and verified, to make sure that any sudden changes were incorporated.

Following the data collection, the actual model building began. As mentioned earlier, the first model simulated the existing facility with manual materials handlers. The current system uses dedicated materials handlers for the different work-centers. This means that the work-centers will be serviced by the same people over a shift. These materials handlers also perform other duties such as washing and servicing the carts and carriers and other miscellaneous duties. Since the objective was to design an alternate materials handling system, only the materials handling functions of the handlers were captured in the simulation models. Thus, the efficiency of the materials handlers, obtained from the models were reflective of only the materials handling functions. However it was not expected that this fact would have any significant impact on the results of this project. The system throughput requirements were known from the forecast requirements, available from the production planning department of ITT Teves. These figures were important in validating the simulation models and the AGVS. The output from the

simulation had to match the company's throughput requirements for the alternate materials handling system to be effective.

3.7 PRODUCT DESCRIPTION

An antilock braking system (ABS) primarily consists of several hundreds of parts. It has two major mechanical components and other electronic parts. ITT Teves at Asheville, NC does not produce the electronic components. They manufacture and assemble only the mechanical components. The two major mechanical components are -

HCU - Hydraulic Control Unit and

TMC - Tandem Master Cylinder.

These components, in turn are assemblies of several other components. A first level bill of materials for these components is shown below -

HCU-

- Housing
- Valve Block
- Motor
- SG Valve Assembly
- SO Valve Assembly

- Ball Caulk
- Outlet Valve
- Inlet Valve
- Pump Assembly
- Pump Piston

Similarly, the bill of materials for the other component is
TMC

- TMC Housing
- S-Piston Assembly
- D-Piston Assembly

Each of these components consist of several other small components. All of these major and minor components were captured in the models.

3.7.1 FACILITY LAYOUT

A reduced form of the facility layout drawing is shown in Figure 2 . This drawing is not drawn to scale. An enlarged version of this drawing, which was drawn to scale, was used for measurement of distances involved and other related structural data used for modeling purposes.

3.8 FORECAST REQUIREMENTS

ITT Teves manufactures several models of ABS for use by different automobiles. The difference in these ABS stems from different HCU and TMC models. In all, there are eight different HCU models and three different TMC models being assembled. The production requirements for the TMC and HCU are shown in Tables 1 and 2.

Table 1 : TMC Production Requirements

MODEL	PRODUCTION REQUIREMENTS UNITS/MONTH	PRODUCTION REQUIREMENTS UNITS/DAY
TMC 1	34510	1593
TMC 2	5642	261
TMC 3	53400	2465

Table 2 : HCU Production Requirements

MODEL	PRODUCTION REQUIREMENTS UNITS/MONTH	PRODUCTION REQUIREMENTS UNITS/DAY
HCU 1	48400	2234
HCU 2	15148	699
HCU 3	2517	116
HCU 4	3212	148
HCU 5	10650	492
HCU 6	9060	418
HCU 7	420	20
HCU 8	5000	231

3.9 FINAL SELECTION AND JUSTIFICATION

The AGVS was not intended to totally replace the manual materials handlers at the facility. The economic justification was to be achieved by the savings due to the reduction in the material handling staff. The objective was to reduce the material handling staffing in accordance with achieving a three year payback period for the company. These members can be moved to perform other functions in the

company. The calculation of the cost of the AGVS was based on three primary factors -

1. Type of vehicle. This can be -
 - Towing Vehicles.
 - Unit load Vehicles.
 - Fork Style Vehicles.
2. Travel capability of the vehicles. This can be -
 - Unidirectional travel capability or
 - Bi-directional travel capability.
3. Cost of the guidepath wire and system controls for the AGVS.

3.10 SUMMARY :

The problem was to conduct a feasibility study to aid the decision in implementing an Automated Guided Vehicle System at ITT Teves, Asheville, North Carolina. The problem was approached using simulation-animation techniques. The effectiveness of this technique is well highlighted in literature and has been proven to be sound. Due to time constraints and certain inherent advantages that have been discussed previously, a manufacturing simulator was used for the purposes of model building and to carry out the simulation. Of all the manufacturing simulators available

in the market, PROMODEL pc was selected for use. It was decided that the system throughput and animation would be the dominant means of validation. A "first-cut" model and the results from it were shown to the sponsor. This model helped in assuring the user about the validity of the simulation modeling process. This model simulated the existing facility with the existing materials handling methods. Following approval, alternate materials handling systems were investigated, focusing primarily on Automated Guided Vehicle Systems.

CHAPTER 4

DATA COLLECTION AND EXPERIMENTAL DESIGN

4.1 DATA COLLECTION

The first step in any simulation project, after the objective has been properly defined, is to collect the appropriate data. In some projects, the data is directly available from the company's data sheets. In others, the data collection will have to be performed by the simulation modeler/ analyst.

The following data was identified to be most crucial and was used for the initial modeling phase :

- Plant Layout : A detailed version of the plant layout with the distances drawn to scale. A file containing the plant layout in AUTOCAD.
- Detailed drawings of each assembly cell or line with exact locations of operations.
- Forecast requirements of antilock braking systems over a period of six months.
- Bill of Materials showing a detailed listing of all the components and small parts and the numbers of each, in every sub-assembly.

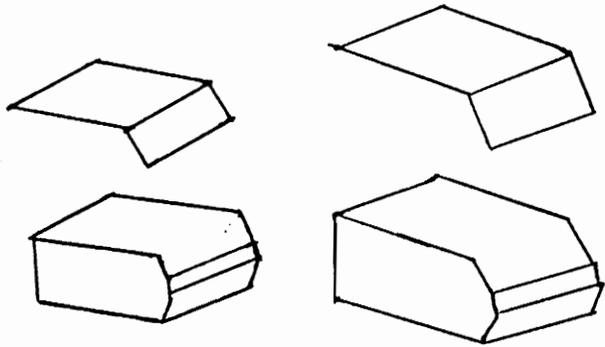
-- Processing times or Cycle-times of all assembly cells and assemblies.

-- Materials handling information. ITT Teves carries their parts around in aluminum boxes of varying sizes. These boxes are, in turn, loaded onto different carts. The carts are moved from one cell to another by the materials handlers. The sizes and capacities of these boxes and carts were gathered as part of the data collection. A rough sketch of the different boxes used is shown in Figure 3 on the following page.

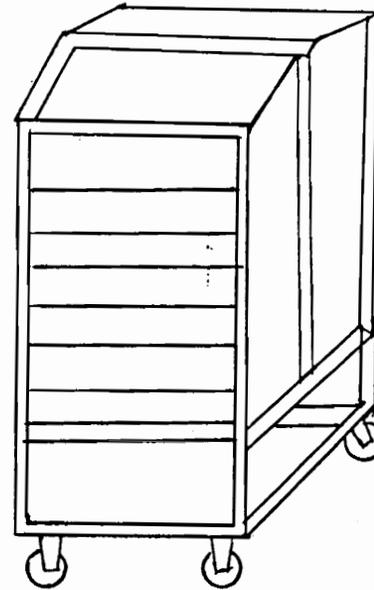
Most of this data was available from past data collections, done in the company. Once the data collection phase was over, the next stage had to do with the actual modeling itself. The modeling was done using the PROMODEL simulator.

4.2 OVERVIEW OF THE SIMULATION MODELS

The base-line model captured the existing facility with manual materials handlers. Ten materials handlers work each shift. Each assembly line has its own dedicated materials handler. ITT Teves operates in a clean-room environment. All parts and components (except electrical items) are



"SHAFFER" Boxes



"CHEVY" Cart

Figure 3 : Materials Handling Boxes and Cart.

washed clean at a staging area, before being routed into the facility.

The raw materials going to each line are stored in an input automated storage and retrieval system (AS/RS). All raw materials, except for the electrical components are taken to the wash area from the input AS/RS. The electrical items are transported directly to the assembly cells. Once the parts have been washed, they are loaded on to aluminum boxes of different sizes. These boxes are then loaded onto carts and the carts are moved to the assembly cells by the respective materials handlers. The carts and the boxes are then re-cycled back to the staging area for subsequent materials handling. The boxes are washed periodically to keep them clean.

4.2.1 FLOW CHARTS & OPERATIONS PROCESS CHARTS

An operation process chart and a flow diagram of the operations is shown in Figures 4, 5, 6 and 7 on the next four pages. The following figures are shown -

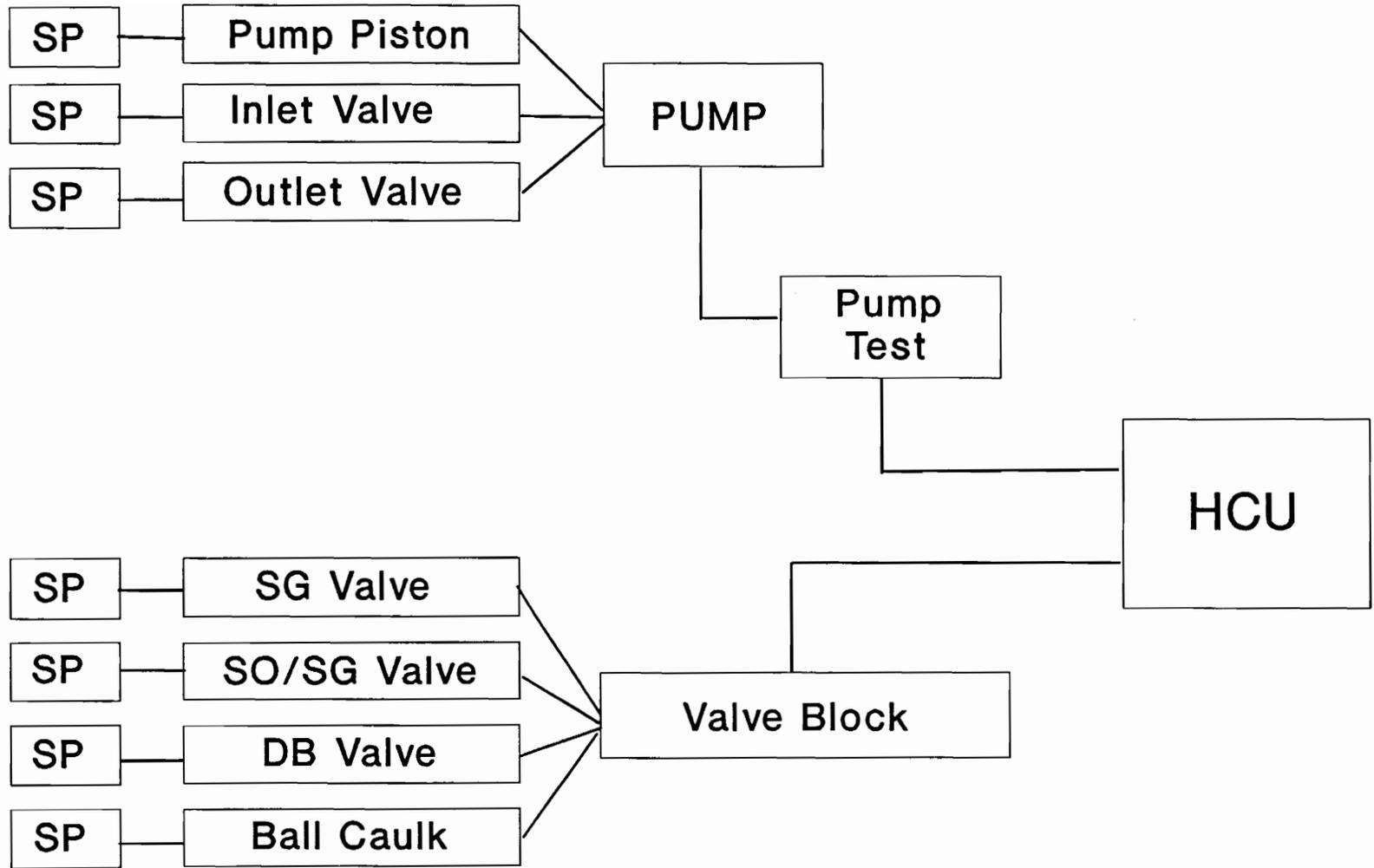
1. A parts flow chart for a HCU.
2. An operations process chart for a HCU.
3. A parts flow chart for a TMC.
4. An operations process chart for a TMC.

The component "small parts" used in the figures refers to an aggregation of small components and raw materials which go into the sub-assemblies and assemblies. These small parts replace the necessity for modeling hundreds upon hundreds of components. The methodology and the logic used for modeling the small parts is explained in detail in a later section, in this chapter. Please refer to Section 4.3 for details.

It is important to note that the figures shown here are representative of the components used for the modeling purposes of this project. The operations process chart used here will only bear a rough, macro-level relationship to the actual operations process chart used by ITT Teves.

4.2.2 DESCRIPTION OF FACILITY MODELED

Each model closely follows the layout of the existing facility. A graphic printout of the layout from one of the alternatives is shown in Figure 8. The dark lines correspond to the structural boundaries in the facility and the lighter lines correspond to the path layout used for the automated guided vehicle system, as used in this model.



SP -- Small Parts

Figure 4 : Flow Chart of Parts for HCU

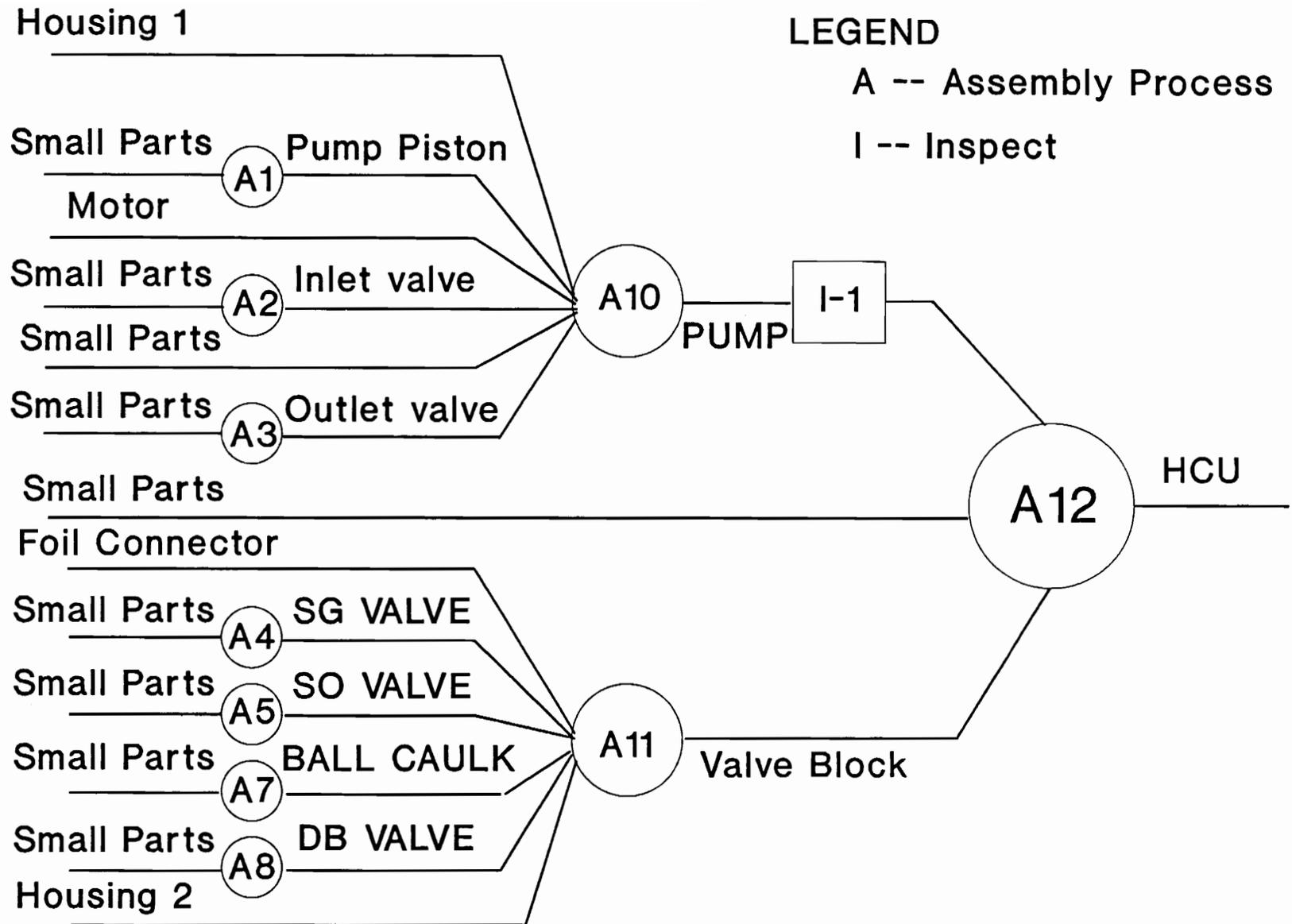


Figure 5 : Operations Process Chart for HCU

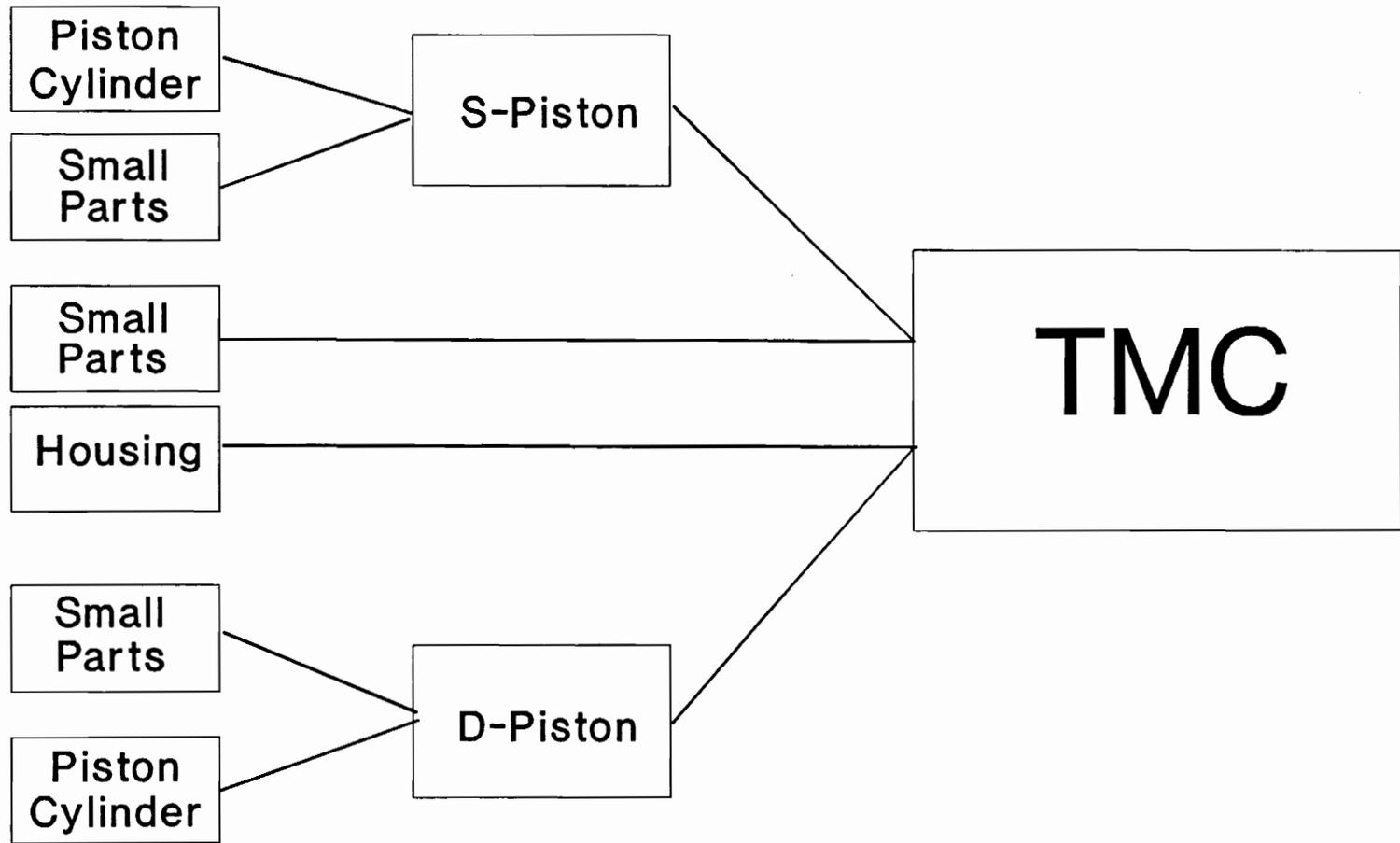


Figure 6 : Flow Chart of Parts for TMC

Graphic printouts of all the models showing the different AGV paths used are not shown here due to the large number of models. The assembly lines, along with the input and output queues, are shown in detail in the figure.

Since the entire project focuses on an alternate means to transport materials, a significant explanation is needed regarding the transporters. The project concentrates on two modes of transportation. One mode uses manual materials handlers, as it is currently being done at ITT. The other uses automated guided vehicles (AGV's) to perform the handling function. The transporters basically carry parts to the different assembly cells from the WASH area and also transport finished sub-assemblies to the areas where final assemblies are performed. The final assemblies are then carried to the finished goods AS/RS. In doing so, the material handling moves are considered at a macro level. In other words, only the material flowing between the machine cells/lines are considered. The flow of materials within the assembly cells are not modeled.

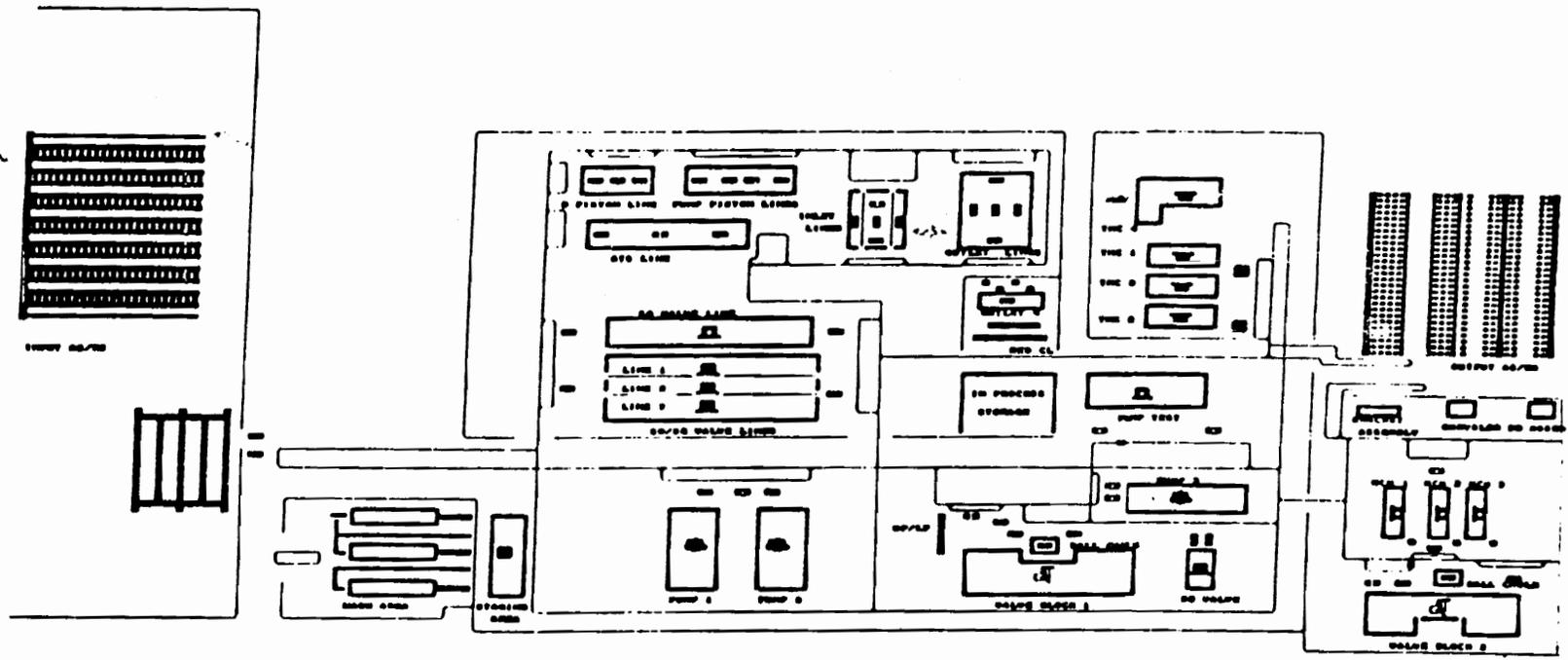


Figure 8 : Graphic Printout of the Facility as Modeled Using
The Animation Provided by PROMODEL

The moves within the assembly cells are not performed by the transporters. They are performed by the person(s) working within the respective cells . Optimization of movements within the assembly cells is not in the scope of this project and is thus not considered. Automated guided vehicles are considered as an alternate way to move the materials between the assembly cells. The movement performed by the operators within the cells will not be performed by the AGV's. The materials handlers or the AGV's deliver parts to the input queues of the respective assembly cells and pick up assemblies or subassemblies from the output queues of the assembly cells. The transporters (people or AGV's) move along the aisles. These aisles will be referred to as transporter paths in the rest of this report.

4.2.3 TRANSPORTER PATH MODELING

In PROMODEL, the transporter path is defined as a series of connected points. The points can be connected along a line or along a diagonal. Transporter paths are laid out taking the structural constraints into account. The transporters are restricted to moving along these lines and between the points. The points are located in the

facility so that the transporters can interface with the input and output queues of the appropriate assembly cells. As mentioned earlier, the materials handlers are being used as dedicated resources and thus service their respective assembly cells.

In the case of the manual materials handlers, the paths are laid out based on the shortest rectilinear distances between the assembly cells involved. It is assumed that the materials handlers will follow these paths. This assumption will be valid, most of the time, because, it is common human tendency to choose the shortest path. Of course, it is natural for the handlers to take an unofficial break or to stop to talk to someone. These aspects are not modeled here. As will be seen later, the handlers are busy moving parts, less than half of the time and thus, any unofficial breaks can easily be accommodated.

There is a difference in the case of the automated guided vehicles. These vehicles are not a dedicated resource and thus service all the machine cells. The vehicles wait for a call to move a part from a particular queue and the closest vehicle moves towards that queue. Thus, it is important for the AGV guidepath to cover all the machine cell areas. Pull-off spurs are provided near the

machine cells so that the vehicles do not block each other, while loading or unloading parts. A point in concern would be the effective travel of the vehicles over the guideway. This relates to the traffic management of the vehicles so that they do not collide with each other over a segment.

All automated guided vehicle systems, today, are provided with controls that take care of traffic management and optimal routing. The vehicles are typically blocked from entering a path already occupied by a vehicle or they are re-routed. These situations would lead to delays in the deliveries and pickup times of the vehicles. It is important to capture the delays due to these situations. Fortunately, a majority of these aspects are taken care of by PROMODEL.

The software calculates the shortest path between all the points at compilation time and stores this information as a map. This information is available to all the vehicles in the system and thus they are able to travel from one point to another through the shortest distance. To handle traffic management, certain points in the transporter path are "blocked" while others are occupied. This blocking mode can be specified along with the definition of the transporter path. The appropriate points are blocked in the

models to handle this aspect. Another way to handle the aspect of traffic management is to define a capacity for the transporter points themselves. Thus it is possible for the vehicles to pass one another at these points. This simulates a ramp at these points. Such ramps are not uncommon in today's automated guided vehicle systems.

The capacities and cycle times of the assembly cells are defined in accordance with the data provided.

4.3 SMALL PARTS MODELING

The most difficult part in the modeling was to capture all the hundreds of small parts that go into different sub-assemblies and assemblies. Attempting to model all these components will clutter up the model and considerably slow down the simulation. In any simulation model, it is important to distinguish between the elements that will significantly affect the results of the model and those that will not. Modeling all the small parts might lend more detail that is not really needed for the purposes of this study.

The problem is simplified by two factors - one, the small parts are grouped together in the aluminum boxes, which in turn are loaded onto carts before movement. The

other factor was evident on interrogating the materials handlers. The small parts to all the lines are replenished only at the end of each shift. The materials handlers check upon the availability of all the parts in their designated machine cells, place an order for the requisite number and move them at the end of each shift.

Thus small parts will have to be delivered only at the end of a shift. The small parts are grouped together and moved in boxes. Effectively, this is equal to a single part being moved to any line, once a shift. Thus instead of modeling all the hundreds of small parts, it would be sufficient to model the movement of carts to the assembly cells, once a shift. This reduces the number of parts to be modeled, dramatically. However, two factors will have to be accounted for by the models -

1. The assembly cells will have to receive their share of parts, periodically. It is important to ensure that the assembly cells are not idle, waiting on parts.
2. The work-load required, on the part of the materials handlers (or the AGV's) to move small parts should not be overlooked. This movement contributes to the

efficiency of the handlers and thus, should be captured.

This method of replenishing small components, spare parts and sub-components, once a shift is common practice in industry. The method is called the **mobile stockroom concept**.

From the Operations process chart for a TMC, we know that the sub-assembly - "D-Piston" goes into the TMC assembly. Let us say that 1500 TMC's are needed every shift. From the bill of materials, it is known that only one D-piston is needed for every TMC assembly. This implies that 1500 D-pistons are needed. Back-tracking, the number of raw materials and small components for each D-piston was calculated from the bill of materials. From the dimensions of the aluminum boxes in which the small parts are carried and from the capacity of the carts in which the boxes are carried, the number of carts that will be needed to supply parts for a shift was determined. Each cart translates to a move by a materials handler.

This modeling technique is the reason behind the simplified parts flow chart and operations process charts shown earlier, in this chapter.

4.4 ASSUMPTIONS MADE IN MODELING

The following is a list of the major assumptions made in this model. These assumptions were justified from the point of view of the objective of the simulation project. Almost any simulation model is based on a few assumptions and it is important to identify and utilize them properly.

1. ITT Teves makes antilock braking systems (ABS) for different automobiles. There are some differences in the components that go into each of these systems. There is some setup downtime that is incurred when changing from one ABS model to another. This downtime will have to be modeled. Fortunately, ITT changes from one ABS model to another at the end of shifts. Thus, the downtime can be incorporated at the end of shifts. It is assumed that there will not be a sudden, unforeseen necessity to change from one ABS model to another, during a shift, over the course of time covered by the simulation.
2. In the ITT Teves facility, all lines have ample storage space around them. Therefore, the queues in front of and following the machine cells are not really constrained. In all the models developed, the queues

(input & output) have a large capacity. The cost of this floor space is not taken into account in this study.

3. Since this project deals with a simulation study to analyze an alternate materials handling system to the one in existence, certain aspects of a manufacturing system are assumed. This particularly refers to the steady availability of all the required components and raw materials. It is assumed that the assembly lines do not shut down due to a lack of inventory. In reality, ITT Teves always holds enough inventory to avoid any stockout situations.

4. Except for the electrical items, all components and raw materials are sent through the washing area before they are routed into the system. Currently, this transfer of materials from the AS/RS to the wash area is not done by the materials handlers considered in this model. A fork truck is used for these purposes. Thus, this transfer of materials from the AS/RS to the wash area is not modeled. The objective of the project was to consider the movement of parts within the clean

room environment. Since the AS/RS containing the raw materials is outside this clean room, the motion of materials from this AS/RS to the WASH area is not modeled.

4.5 DOWNTIMES MODELED

The following downtimes are modeled :

-- All assembly lines, except the valve block line, are down once every four hours. This is the down time for lunch breaks and shift change-over times.

-- At the end of every shift, all lines (cells) experience a downtime due to setup.

-- Once, every three shifts, the TMC and HCU lines undergo a downtime for preventive maintenance.

4.6 SIMULATION PARAMETERS

The simulation model was run for a period of 168 hours (1 week). There is a warm-up period of 24 hours before the simulation statistics are collected. The software automatically flushes the statistics during this period. This warm-up period is incorporated to allow the system to achieve steady state and for the input queues in front of the assembly cells to fill up.

The walking pace for human operators, used for the purposes of modeling was 314 feet/min (or 5.3 TMU's/feet). This data was gathered from the human factors department at Virginia Tech. The speed of the automated guided vehicles was assumed to be 200 feet/min, commensurate with industry standards.

4.7 EXPERIMENTAL DESIGN

The base-line model simulated the existing facility and the existing materials handling method. Subsequent models were developed to investigate the design and feasibility of an Automated Guided Vehicle System (AGVS). The experiment was designed to investigate the following parameters -

- Travel capability of the vehicles in the AGVS - this included unidirectional travel capability and bi-directional travel capability.

- Number of pickup and delivery points and their location around each assembly cell. Two alternatives were investigated. The first one dealt with a single, common pickup and delivery points for each assembly cell. Thus the AGV's will interface with each assembly cell only at two places - one to drop off raw materials and components and the other to pick up output from that cell. Movement of

materials from the AGV drop-off point to the appropriate areas within the cell is done by the operators within the cell.

- Number of vehicles servicing the system. The effect of this parameter on system performance was discussed in detail in Chapter 2. While too few vehicles would lead to starvation for vehicles, too many vehicles will lead to congestion and will adversely affect the throughput of the system. It is important to minimize the number of vehicles for economic considerations as well. The cost of the AGVS increases with the number of vehicles required.

4.8 LIST OF MODELS DEVELOPED

In all, 63 different alternatives were modeled. These alternatives considered different combinations of the key parameters. Effectively, there were four different models. The first model used manual materials handlers. The second model considers AGV's with unidirectional travel capability and single pickup and delivery points at the workstations. The third model considers AGV's with bidirectional travel capability and single pickup and delivery points at the workstations. The fourth model considers AGV's with unidirectional travel capability and multiple pickup and

delivery points at the workstations. By varying the number of vehicles in the system in the second, third and fourth models, sixty-three different alternatives were considered. Table 3, on page 67 gives a list of the AGVS alternatives with the corresponding parameters. The Table can be read as follows : Entry # 1 is a model of the ITT Teves plant with an AGVS serviced by vehicles with unidirectional travel capability, single pickup and delivery points at all assembly lines and the size of all unit loads is one quarter the size of the unit loads currently being used in the facility. This combination of parameters is experimented with 2,3,4,5,6,7 and 8 vehicles in the system, thus leading to seven alternatives in this category. The other entries in the table can be read in the same fashion.

In each of these models, the system throughput (number of HCU's and TMC's) and the utilization of the automated guided vehicles were used as the measures of system performance. A standard was set for the utilization of the vehicles and the throughput was set at the forecast production requirements .

Table 3 : List of Models with corresponding parameters

#	AGV travel capability	P/D Points	Unit Load Size	Number of vehicles in the system	Number of alternatives considered
1.	Unidirectional	Single	Quarter	2,3,4,5,6,7,8	7
2.	Unidirectional	Single	Half	2,3,4,5,6,7,8	7
3.	Unidirectional	Single	Full	2,3,4,5,6,7,8	7
4.	Bi-directional	Single	Quarter	2,3,4,5,6,7,8	7
5.	Bi-directional	Single	Half	2,3,4,5,6,7,8	7
6.	Bi-directional	Single	Full	2,3,4,5,6,7,8	7
7.	Unidirectional	Multiple	Quarter	2,3,4,5,6,7,8	7
8.	Unidirectional	Multiple	Half	2,3,4,5,6,7,8	7
9.	Unidirectional	Multiple	Full	2,3,4,5,6,7,8	7

4.9 COMPUTER RESOURCES

A ZENITH 386, sx/20 pc with 2 Mbyte RAM was used for the purposes of this project. All the simulation models were developed and simulated on this machine. The models were developed using PROMODEL pc.

4.10 SUMMARY

This chapter provides an account of the data collection and experimental design phase of the simulation project. Some of the data was available from the company sheets, while other data had to be collected. In all 63 different alternatives were considered to study the problem of evaluating an alternate materials handling system to the existing one. An automated guided vehicle system was considered as an alternate to the manual materials handlers currently being used by ITT Teves.

The final AGV system design will provide the number of vehicles that will be needed, the sizes of the unit loads that will be carried by the vehicles, the travel capability of the vehicles (unidirectional or bi-directional) and the number and location of pickup and delivery points to be used at the various assembly cells. The results and conclusions are discussed in the next chapter.

CHAPTER 5

RESULTS AND CONCLUSIONS

This chapter discusses the results and conclusions of the simulation study conducted for ITT Teves. As mentioned in the earlier chapters, in each model the throughput of the system and the utilization of the automated guided vehicles were used for evaluating the feasibility of the materials handling system. The number of HCU's and TMC's, the two final assemblies, produced by the system per day was used to assess the system throughput.

5.1 SIMULATION RESULTS

5.1.1 BASE-LINE MODEL

The base-line model, in which the materials handling function was performed manually (using human operators) was primarily developed for the purposes of justification and validation. Currently, ITT Teves uses manual materials handlers. Thus, if the system throughput from the base-line model matches the system throughput from the actual system, then the modeling method would be validated. After

simulating the base-line model, it was observed that the output from the simulation matched the actual system throughput. Along with this result, the simulation model also provided other results, one of which was the utilization of the materials handlers. This information is shown in the following table. The assembly cell serviced by the materials handler and his/her percentage utilization over the period of a shift is shown in Table 4, below. The names are fictitious and bear no resemblance to the actual materials handlers.

From Table 4, it can be seen that the materials handlers are grossly under-utilized. It should be noted that this utilization considers only the tasks associated with movement of materials. The materials handlers perform other duties such as cleaning the shaffer boxes periodically and placing orders for required materials. These tasks have not been captured in the model because they are not directly related to the materials handling moves. If these tasks are considered, then the utilization of the materials handlers will be higher.

5.1.2 AGVS MODELS

The AGVS alternatives were evaluated using the same decision rules used for the base-line model. The decision rule was two-fold. The primary decision rule was obtaining the required system throughput (number of HCU's and TMC's) and the secondary decision rule was the utilization of the automated guided vehicles. Alternatives in which the utilization of the vehicles was too high (greater than 95%) were eliminated and those in which the utilization was too low (less than 70%) were eliminated. The number of vehicles required for satisfying the desired throughput and achieving a desired level of vehicle utilization, from the results of the simulation runs, are shown in Table 5.

The results from all the alternatives developed are tabulated in Appendix A. These tables show the system throughput attained (primary decision rule) and the corresponding utilization of AGV's for all the AGV configurations listed in Table 5 .

Table 4 : Results from the Base-line Model

MATERIALS HANDLER	ASSEMBLY LINE SERVICED	PERCENTAGE UTILIZATION
Joe	DB Valve, Ball caulk, Valve Block	16.72
John	Inlet valve line, Outlet valve line	7.87
Jeff	SO/SG valve lines	2.49
Greg	SO/SG valve lines	1.57
Jim	Valve Block lines	23.38
Anne	Pump Lines	32.88
Mary	HCU lines	19.42
Pete	TMC Lines	18.56
Tim	HCU Lines	0.93
Smith	ATS Line, D-piston, Pump Piston	9.60

Table 5 : Results from the AGVS Models

GUIDEPATH	P/D POINTS PER LINE	UNIT LOAD SIZE	VEHICLES REQUIRED
BIDIRECTIONAL	SINGLE	FULL	3
		HALF	4
		QUARTER	7
UNIDIRECTIONAL	SINGLE	FULL	3
		HALF	4
		QUARTER	7
UNIDIRECTIONAL	MULTIPLE	FULL	4
		HALF	5
		QUARTER	8

5.2 TYPES OF VEHICLES FOR THE AGVS

There are many different kinds of AGVS' available in the market. Along with determining the feasibility of an AGVS as an alternate materials handling system and determining the fleet size, the objective of the project was also to predict the type of AGVS. Given a particular load size, the vehicle scheduling and traffic control aspects of the different types of AGVS' does not differ greatly. The only difference comes with the cost of the individual

vehicles. For instance, fork lift type of AGV's are usually more expensive than unit load carriers, due to better technology. Unless there exists a situation where the loads have to be picked up or dropped off at differing heights, unit load vehicles might serve the purpose as well as fork lift type vehicles. Briefly, the characteristics of the three prominent types of vehicles are as follows :

Towing Vehicles : These vehicles can handle capacities between 2000 and 50,000 lbs. The cost per vehicle ranges between \$10,000 and \$50,000. They have a simple system design and they will involve manual materials handling at the local points of use.

Fork-lift Style Vehicles : These vehicles handle capacities between 1000 and 6000 lbs. The cost per vehicle varies between \$45,000 and \$80,000. The high cost is prohibitive unless the ability to pick-up and deliver at different heights is needed. They usually carry palletized unit loads.

Unit Load Vehicles : These vehicles can handle capacities ranging from 2000 to 4000 lbs, but can handle up to 20,000

lbs with better design. The costs vary significantly, but never exceed \$50,000. Automated or semi-automated materials handling methods can be used at the local point of use of the materials. This automation can lead to a more complicated system design as opposed to towing type of vehicles. In the case of towing vehicles, it is possible for the operators to latch the unit loads to the vehicle and thus the vehicle-P/D point interaction is simplified. However, the fork-lift type of vehicles may involve a more complicated system design as opposed to the unit load vehicles.

5.3 COST ESTIMATE AND JUSTIFICATION

The costs of the automated guided vehicles, system controls and the guidepath were obtained from the information provided by the AGVS product section of the Materials Handling Institute. The total guidepath wire needed was calculated in accordance with the guidepaths defined in the models and the distances were measured from the facility layout of ITT Teves. The total amount of guidepath required was determined to be 2500 Feet. Fork-lift vehicles were eliminated from the consideration for two reasons - one was their relatively high cost and the other

was the lack of a need for transferring loads to different heights. The problem was thus reduced to choosing between towing vehicles and unit load vehicles. Towing vehicles were considered only for "full" unit load sizes. The reason behind this consideration was that the towing vehicles can be utilized to pull the unit loads on the existing carts and thus purchase of new carts can be avoided. On the other hand, for unit load vehicles, only "half" and "quarter" unit load sizes were considered. The reason behind this being that the "full" unit load sizes would lead to the unit load vehicles being "top-heavy" and would cause them to topple over. The cost calculations are shown below.

For a three vehicle system of towing vehicles with Full Unit Load sizes,

3 vehicles at \$30,000 each	\$ 90,000
System control & Guidepath	\$ 250,000
(2500 Ft @ \$100/Ft)	-----
	\$340,000

For a four vehicle system of unit load vehicles carrying Half Unit Load Sizes,

4 vehicles @ \$50,000 each	\$ 200,000
System Control & Guidepath (2500 Ft. @ \$100/Ft)	\$ 250,000

	\$ 450,000

The materials handlers are being paid at the rate of \$13.22/hr. There are 10 material handlers/shift. ITT Teves operates 3 shift/day, 5 days a week. Thus, the cost of a material handler for 1 year would be :

$$\text{cost/year} = \$13.22/\text{hr} * (24*5*52) \text{ hrs/yr} = \$82,493$$

For three years,

$$\text{cost/material handler} = 82493 * 3 = \$ 247,479$$

5.4 CONCLUSIONS AND RECOMMENDATIONS

It is feasible to choose either of the AGV systems discussed above to satisfy the required systems throughput and vehicle utilization. The simulation studies prove this

fact. If the material handlers staffing can be reduced by two persons per shift, it is economically justifiable to spend up to \$500,000 on the AGVS and achieve a three year payback.

The AGV system configuration with the lowest cost is a three vehicle moving "full" unit loads. This means that the existing unit load sizes can be used with the AGVS. Towing type of vehicles will be needed. The throughput is achievable with either bi-directional or unidirectional vehicle travel capability. Unidirectional guidepaths are advised as they simplify system controls.

After reducing the materials handler staffing, there will still be eight materials handlers per shift. It is recommended that each assembly cell have one pickup and one delivery point for interacting with the automated guided vehicles. Once the AGV's drop off the material at these points, the materials handlers will be able to move the materials locally. The operators of the assembly cells who perform this local moving task currently, will be relieved of the task. The materials handlers themselves will only move the materials over very short distances and thus the risk of injuries will be reduced substantially.

BIBLIOGRAPHY

1. Ashayeri, J., Gelders, L.F. and Van Looy, P.M., Micro-computer Simulation in Design of Automated Guided Vehicle Systems. *Material Flow*, Volume 2, 1985, pp. 37-48.
2. Bozer, Y.A. and Srinivasan, M.M, Tandem Configurations for Automated Guided Vehicle Systems Offer Simplicity and Flexibility. *Industrial Engineering*, February 1989, pp. 23-27.
3. Carson, J.S., Convincing Users of Model's Validity is a Challenging Aspect of a Modeler's Job. *Industrial Engineering*, June 1986, pp. 74-85.
4. Davis, D.A., Modeling AGV Systems. *Proceedings of the Winter Simulation Conference*, 1986, pp. 568-573.
5. Egbelu, P.J., The Use of Non-Simulation Approaches in Estimating Vehicle Requirements in an Automated Guided Vehicle Based Transport System, *Material Flow*, Volume 4, 1987 pp. 17-32.
6. Egbelu, P.J., A design Methodology for Operational Control Elements for Automated Guided Vehicle Based Material Handling Systems, Ph.D. Dissertation, V.P.I &S.U.
7. Egbelu, P.J. and Tanchoco, J.M.A., Potentials for Bi-Directional Guidepaths for Automated Guided Vehicle Based Systems, *International Journal of Production Research*, 1986, Volume 24 No. 5, pp. 1075-1097.
8. Erickson, B.E., Electronic Diagnostics for Enhanced Automatic Guided Vehicle Safety and Maintainability. *Material Flow*, Volume 4, 1987, pp. 109-115.
9. Higdon, J., Using Simulation in Planning a New Material Handling System. *Industrial Engineering*, November 1988, pp. 55-59.
10. Harmonosky, C.M. and Sadowski, R.P., A Simulation Model and Analysis : Integrating AGV's With Non-Automated

Materials Handling. proceedings of the Winter Simulation Conference, 1984, pp. 341-347.

11. Koff, G.A., Automatic Guided Vehicle Systems : Applications, Controls and Planning, Material Flow, Volume 4, 1987, pp. 3-16.
12. Law, A.M. and Kelton, D.W., Simulation Modeling and Analysis.
13. Law, A.M. and McComas, M.G., Pitfalls to Avoid in the Simulation of Manufacturing Systems. Industrial Engineering, May 1989, pp. 28-31.
14. Law, A.M. and Haider, S.W., Selecting Simulation Software for Manufacturing Applications : Practical Guidelines and Software Survey. Industrial Engineering, May 1989, pp. 33-46.
15. Law, A.M. and McComas, M.G., How to Select Simulation Software For Manufacturing Applications. Industrial Engineering, July 1992, pp. 29-35.
16. Law, A.M. and McComas, M.G., How simulation Pays Off. Manufacturing Engineering, February 1988, pp. 37-39.
17. Mahadevan, B. and Narendran, T.T., Determination of unit Load Sizes in an AGV Based Material handling System for an FMS, International Journal of Production Research, 1992, Volume 30, No. 4, pp. 909-922.
18. Maxwell, W.L. and Muckstadt, J.A., Design of Automatic Guided Vehicle Systems. IIE Transactions, Volume 14, No. 2, 1982, pp. 114-124.
19. Newton, D., Simulation Model Calculates how Many Automated Guided Vehicles are Needed, Industrial Engineering, February 1985, pp. 68-73.
20. Phillips, D.T., Simulation of Material Handling Systems : When and Which Methodology. Industrial Engineering, September 1980, pp. 65-77.
21. Pritsker, A.A.B., Introduction to Simulation and SLAM-II, John Wiley & Sons, 1984.

22. Ramachandran, J. and Solomon, M.M., Dynamic Scheduling of Automated Guided Vehicles for a Certain Class of Systems. *Journal of Manufacturing Systems*, Volume 9, No. 4, 1990, pp. 315-323.
23. Sale, M.W. and Stein, C.W., Modeling AGV Systems using network Constructs. *proceedings of the Winter Simulation Conference*, 1987, pp. 661-667.
24. Shelton, D and Jones, M.S., A Selection Method for Automated Guided vehicles. *Material Flow*, Volume 4, 1987, pp. 97-107.
25. Sinreich, D and Tanchoco, J.M.A., An Economic Model for Determining AGV Fleet Size. *International Journal of Production Research*, 1992, Volume 30, No. 6, pp. 1255-1268.
26. Tanchoco, J.M.A., Egbelu, P.J. and Taghaboni, F., Determination of Total Number of vehicles in an AGV Based Material Transport System. *Material Flow*, 1987, Volume 4, pp. 33-51.
27. Tompkins, J.A. and White, J.A., *Facilities Planning*. John Wiley & Sons, Inc. 1984.
28. Turner, D.H., Manufacturing Simulation Comes of Age. *CIM Technology*, Fall 1986, Volume 5, No. 3, pp. 16-19.
29. Wang, S.T., Animated graphic Simulation of an Automatic Guided vehicle System. *Proceedings of the Winter simulation conference*, 1985, pp. 252-255.
30. Ward, R.E., Planning, Specifying and Installing an Automatic Guided vehicle System. A Publication of the AGVS Product Section of the Materials handling Institute.
31. Wysk, R.A., Egbelu, P.J., Zhou Chen and Ghosh, B.K., Use of Spread Sheet Analysis for Evaluating AGV Systems. *Material Flow*, Volume 4, 1987, pp. 53-64.

APPENDIX A

The results of the simulation runs are tabulated in this appendix. The first model listed, namely, NEWITT53 refers to the baseline model in which manual materials handlers are used. The rest of the table contains the AGVS models and alternatives. These are the alternatives in which Full Unit Load sizes have been used. The alternatives are numbered in the following fashion -

Consider the alternative ITTAGV32. The first number (3, in this case) refers to the travel capability of the vehicles and the number of P/D points used in the alternative. The notations are :

- 3 - Bi-directional Vehicles with single P/D points at the machining stations.
- 4 - Unidirectional vehicles with single P/D points at the machining stations.
- 5 - Unidirectional Vehicles with Multiple P/D points at the machining stations.

The second number (2, in this case) refers to the number of vehicles used in the system. This means that two vehicles are used in this alternative (ITTAGV32). This number ranges from 2 to 8. As with the table showing the production requirements in Chapter 3, the system throughput

requirements in this table (The HCU's and the TMC's produced per day) are multiplied by the same number in order to protect proprietary information.

MODEL	HCU/DAY	TMC/DAY	AGV UTILIZATION
NEWITT53	3979	4350	-
ITTAGV32	4560	4350	78.73
ITTAGV33	4387	4350	61.7
ITTAGV34	4394	4300	59.69
ITTAGV35	4356	4350	61.37
ITTAGV36	4375	4300	64.78
ITTAGV42	4374	4300	97.47
ITTAGV43	4385	4350	68.8
ITTAGV44	4375	4300	57.38
ITTAGV45	4375	4300	54.3
ITTAGV46	4356	4300	54.48
ITTAGV52	1131	1000	62.49
ITTAGV53	4489	4137	98.1

ITTAGV54	4430	4431	80.1
ITTAGV55	4450	4300	70.11

MODEL	HCU/DAY	TMC/DAY	AGV UTILIZATION
HLFGAV32	1151	1200	65.87
HLFAGV33	4375	4350	89.7
HLFAGV34	4372	4325	79.4
HLFAGV35	4356	4325	76
HLFAGV36	4346	4325	75.16
HLFAGV42	896	4350	99.9
HLFAGV43	4109	4350	100
HLFAGV44	4362	4350	84.5
HLFAGV45	4384	4300	76.76
HLFAGV46	4375	4375	73.67
HLFAGV52	282	250	58.5
HLFAGV53	1034	950	68.8
HLFAGV54	4089	3700	97.1
HLFAGV55	4398	4357	89.8
HLFAGV56	4374	4300	81.1

MODEL	HCU/DAY	TMC/DAY	AGV UTILIZATION
QTRAGV32	298	231	72.91
QTRAGV33	392	348	72.13
QTRAGV34	1383	1429	73.4
QTRAGV35	4053	3666	96.2
QTRAGV36	4190	3767	93.3
QTRAGV37	1575	1541	62.52
QTRAGV38	2569	2311	48.67
QTRAGV42	815	3107	100
QTRAGV43	899	4350	99.8
QTRAGV44	987	4338	97.8
QTRAGV45	1351	4338	92.5
QTRAGV46	4365	4338	99.2
QTRAGV47	4362	4338	95.7
QTRAGV48	4365	4338	93.8
QTRAGV52	490	545	74.34
QTRAGV53	293	298	74.49
QTRAGV54	453	398	74.34

QTRAGV55	1029	907	81.7
QTRAGV56	2046	1864	88.61
QTRAGV57	3885	3492	92.75
QTRAGV58	4233	3853	90.6

APPENDIX B

PROGRAM LISTING

A sample program listing is shown in the following pages. This is a listing of one of the models used for this project. The processing times and the batch sizes used in the original model have been changed in order to protect proprietary information. In all, sixty three different alternatives were developed for the purposes of this project. All these models are different from each other in several ways. It is not possible to list all these models here and only one of them has been shown.

ProModel model: REPORT

*This model has a unidirectional path laid out for the AGVS

ROUTING

Part	Location	Operation (min)	Output part	Next location	Condi- tion Qty	Move time (min)
------	----------	-----------------	-------------	---------------	-----------------	-----------------

*
*All the processing times and batch sizes have been changed from their
*original values to protect proprietary information.

*
*All parts are routed from WASH area to the respective lines.

*
*Route the piston and the small parts to the ATS line.

ATSPT WASH	0		ATSPT STAGE	0	1	0
ATSPT STAGE	UNQUE		ATSPT ATSIQ	0	1	AGV
SPATS WASH	0		SPATS STAGE	0	1	0
SPATS STAGE	UNQUE		SPATS ATSIQ	0	1	AGV

*
*Route the piston and small parts to the D-Piston line.

DLIPT WASH	0		DLIPT STAGE	0	1	0
DLIPT STAGE	UNQUE		DLIPT DPISTIQ	0	1	AGV
SPDLI WASH	0		SPDLI STAGE	0	1	0
SPDLI STAGE	UNQUE		SPDLI DPISTIQ	0	1	AGV

*
*Route the small parts to the PUMP PISTON line.

NPPPT WASH	0		NPPPT STAGE	0	1	0
NPPPT STAGE	ACCUM 2		SPPPT PUMPISIQ	0	1	AGV
	UNQUE					

*
*Route the small parts to the INLET line.

NPILT WASH	0		NPILT STAGE	0	1	0
NPILT STAGE	ACCUM 3		SPILT INLTIQ	0	1	AGV
	UNQUE					

*
*Route the small parts to the outlet line.

NPOLT WASH	0		NPOLT STAGE	0	1	0
NPOLT STAGE	ACCUM 4		SPOLT OUTLTIQ	0	1	AGV
	UNQUE					

*
*Route the small parts to the SOSG LINE.

NPSGV WASH	0		NPSGV STAGE	0	1	0
NPSGV STAGE	ACCUM 3		SPSGV SOSGIQ	0	1	AGV
	UNQUE					

*
*Route the housings and the small parts to the SOSO line.

SPSOV WASH	0		SPSOV STAGE	0	1	0
SPSOV STAGE	UNQUE		SPSOV SOSOIQ	0	1	AGV
HSSOV WASH	0		HSSOV STAGE	0	1	0
HSSOV STAGE	UNQUE		HSSOV SOSOIQ	0	1	AGV

*
*Route the small parts to the DBVALVE LINE

*

SPDBV WASH	ACCUM 2	ASDBV STAGE	0	1	0
ASDBV STAGE	UNQUE	ASDBV DBVALIQ	0	1	AGV

*

*Route the small parts to the BALL CAULK line

*

SPBAC WASH	0	SPBAC STAGE	0	2	0
SPBAC STAGE	UNQUE	SPBAC BACKIQ	TURN 1		AGV
		SPBAC BACK2Q	TURN 0		AGV

*

*Route the valve-block, foil connector and the small parts to the *VALVE BLOCK lines.

*

RAVLB WASH	ACCUM 88	ACVLB STAGE	0	1	0
ACVLB STAGE	UNQUE	ACVLB VLVBIQ	TURN 1		AGV
		ACVLB VLVB2Q	TURN 0		AGV
FOLCN ASRS1	0	FOLCN ASRS1Q	0	1	0
FOLCN ASRS1Q	UNQUE	FOLCN VLVBIQ	TURN 1		AGV
		FOLCN VLVB2Q	TURN 0		AGV
SPVLB WASH	0	SPVLB STAGE	0	1	0
SPVLB STAGE	UNQUE	SPVB1 VLVBIQ	0	1	AGV
		SPVB2 VLVB2Q	0	1	AGV

*

*Route the motor, housings and the small parts to the PUMP lines.

*

MOTOR ASRS	0	MOTOR ASRS2Q	0	1	0
MOTOR ASRS2Q	ACCUM 240	AMOTR ASRS2Q	0	1	0
AMOTR ASRS2Q	0	AMOTR PUMPQ1	TURN 1		AGV
		AMOTR PUMPQ2	TURN 0		AGV
		AMOTR PUMPQ3	TURN 0		AGV
HSPMP WASH	0	HSPMP STAGE	0	1	0
HSPMP STAGE	UNQUE	HSPM1 PUMPQ1	0	1	AGV
		HSPM2 PUMPQ2	0	1	AGV
		HSPM3 PUMPQ3	0	1	AGV
SPPMP WASH	0	SPPMP STAGE	0	1	0
SPPMP STAGE	UNQUE	SPPM1 PUMPQ1	0	1	AGV
		SPPM2 PUMPQ2	0	1	AGV
		SPPM3 PUMPQ3	0	1	AGV

*

*Route the small parts to the HCU lines.

*

SPHCU WASH	0	SPHCU STAGE	0	1	0
SPHCU STAGE	UNQUE	SPHCU HCUIQ	0	1	AGV

*

*Route the small parts and the housings to the TMC LINES.

*

SPTMC WASH	0	SPTMC STAGE	0	1	0
SPTMC STAGE	UNQUE	SPTMC TMCIQ	0	1	AGV
HSTMC WASH	0	HSTMC STAGE	0	1	0
HSTMC STAGE	ACCUM 350	AHTMC TMCIQ	0	1	AGV
	UNQUE				

*

*The ATS line follows

*

ATSPT ATSIQ	USE AGV 3	ATSPT ATSL	0	1	2
SPATS ATSIQ	0	SPATS ATSIQ	0	1	0
ATSPT ATSL	472.68	SPIST ATSOQ	0	1	0
SPATS ATSIQ	USE AGV 3	SPATS EXIT	0	1	0
SPIST ATSOQ	0	SPIST TMCIQ	0	1	AGV

*

*The D-Piston line follows

*							
DLIPT	DPISTIQ	USE AGV 3	DLIPT	DPISTL	0	1	2
SPDLI	DPISTIQ	USE AGV 3	SPDLI	DPISTIQ	0	1	0
SPDLI	DPISTIQ	0	SPDLI	EXIT	0	1	0
DLIPT	DPISTL	716.8	DPIST	DPISTOQ	0	1	0
DPIST	DPISTOQ	0	DPIST	TMCIQ	0	1	AGV

*
* The Pump Piston Line follows
*

SPPPT	PUMPISIQ	USE AGV 3	NPPPT	PUMPISIQ	0	2	0
NPPPT	PUMPISIQ	0	NPPPT	PUMPISL1	TURN	1	.2
			NPPPT	PUMPISL2	TURN	0	.2
NPPPT	PUMPISL1	49.78	PMPPN	PUMPISOQ	0	1	0
NPPPT	PUMPISL2	49.78	PMPPN	PUMPISOQ	0	1	0
PMPPN	PUMPISOQ	ACCUM 2	APMN1	PUMPQ1	0	1	AGV
			APMN2	PUMPQ2	0	1	AGV
			APMN3	PUMPQ3	0	1	AGV

*
*The inlet valve line follows
*

SPILT	INLTIQ	USE AGV 3	SPILT	INLTIQ	0	1	0
SPILT	INLTIQ	0	NPILT	INLTIQ	0	3	0
NPILT	INLTIQ	0	NPILT	INLT1	TURN	1	.1
			NPILT	INLT2	TURN	0	.1
			NPILT	INLT3	TURN	0	.1
NPILT	INLT1	243	DINLT	INLTOQ	0	1	0
NPILT	INLT2	243	DINLT	INLTOQ	0	1	0
NPILT	INLT3	243	DINLT	INLTOQ	0	1	0
DINLT	INLTOQ	0	INLTV	PUMPQ1	TURN	1	AGV
			INLTV	PUMPQ2	TURN	0	AGV
			INLTV	PUMPQ3	TURN	0	AGV

*
*The Outlet Valve line follows
*

SPOLT	OUTLTIQ	USE AGV 3	SPOLT	OUTLTIQ	0	1	0
SPOLT	OUTLTIQ	0	NPOLT	OUTLTIQ	0	4	0
NPOLT	OUTLTIQ	0	NPOLT	OUTLT1	TURN	1	.1
			NPOLT	OUTLT2	TURN	0	.1
			NPOLT	OUTLT3	TURN	0	.1
NPOLT	OUTLT1	136.2	NPOLT	OUTLT4	TURN	0	AGV
NPOLT	OUTLT2	136.2	SOTLT	OUTLTOQ	0	1	0
NPOLT	OUTLT3	136.2	SOTLT	OUTLTOQ	0	1	0
NPOLT	OUTLT4	136.2	SOTLT	OUTLTOQ	0	1	0
SOTLT	OUTLTOQ	0	SOTLT	OUTLTOQ	0	1	4
			OTLTV	PUMPQ1	TURN	1	AGV
			OTLTV	PUMPQ2	TURN	0	AGV
			OTLTV	PUMPQ3	TURN	0	AGV

*
*The SG valve line follows
*

SPSGV	SOSGIQ	USE AGV 3	SPSGV	SOSGIQ	0	1	0
SPSGV	SOSGIQ	0	NPSGV	SOSGIQ	0	3	0
NPSGV	SOSGIQ	0	NPSGV	SOSGL1	TURN	1	.1
			NPSGV	SOSGL2	TURN	0	.1
			NPSGV	SOSGL3	TURN	0	.1
NPSGV	SOSGL1	127.7	S1VAL	EXIT	0	1	0
NPSGV	SOSGL2	127.7	S1VAL	EXIT	0	1	0
NPSGV	SOSGL3	127.7	S1VAL	EXIT	0	1	0
SGVAL	SOSGOQ	0	SGVAL	VLVBIQ	TURN	1	AGV
			SGVAL	VLVB2Q	TURN	0	AGV

*

*The SO Valve line follows

*

SPSOV SOSOIQ	USE AGV 3	SPSOV SOSOIQ	0	1	2
HSSOV SOSOIQ	USE AGV 3	HSSOV SOSOL	0	1	2
SPSOV SOSOIQ	0	SPSOV EXIT	0	1	0
HSSOV SOSOL	383.05	S2VAL EXIT	0	1	0
SOVAL SOSOOQ	0	SOVAL VLVBIQ	TURN	1	AGV
		SOVAL VLVB2Q	TURN	0	AGV

*

*The DB Valve line follows

*

ASDBV DBVALIQ	USE AGV 3	ASDBV DBVALIQ	0	1	0
ASDBV DBVALIQ	0	SPDBV DBVALIQ	0	2	0
SPDBV DBVALIQ	0	SPDBV DBVALL	0	1	2
SPDBV DBVALL	462.3	DBVAL DBVALOQ	0	1	0
DBVAL DBVALOQ	0	DBVAL VLVBIQ	TURN	1	AGV
		DBVAL VLVB2Q	TURN	0	AGV

*

*The Ball Caulk line follows

*

SPBAC BACKIQ	USE AGV 3	SPBAC BACKL	0	1	2
SPBAC BACKL	766.4	BACLK BACKOQ	0	1	0
BACLK BACKOQ	0	BACLK VLVBIQ	0	1	3
SPBAC BACK2Q	USE AGV 3	SPBAC BACKL2	0	1	2
SPBAC BACKL2	766.4	BACK2 VLVB2Q	0	1	3

*

*The Valve Block line follows

*

ACVLB VLVBIQ	USE AGV 3	ACVLB VLVBIQ	0	1	0
ACVLB VLVBIQ	0	RAVLB VLVBIQ	0	88	0
RAVLB VLVBIQ	0	RAVLB VLVBL	0	1	.2
RAVLB VLVBL	.4	VLBLK VLVBOQ	0	1	0
VLBLK VLVBOQ	ACCUM 88	TOVLB VLVBOQ	0	1	0
TOVLB VLVBOQ	0	TOVLB HCUIQ	0	1	AGV
SPVB1 VLVBIQ	USE AGV 3	SPVB1 VLVBIQ	0	1	0
SPVB1 VLVBIQ	0	SPVB1 EXIT	0	1	0
SPVB2 VLVB2Q	USE AGV 3	SPVB2 VLVB2Q	0	1	0
SPVB2 VLVB2Q	0	SPVB2 EXIT	0	1	0
FOLCN VLVBIQ	USE AGV 3	FOLCN EXIT	0	1	0
DBVAL VLVBIQ	USE AGV 3	DBVAL VLVBIQ	0	1	0
DBVAL VLVBIQ	0	DBVAL EXIT	0	1	0
BACLK VLVBIQ	0	BACLK EXIT	0	1	0
SGVAL VLVBIQ	USE AGV 3	SGVAL VLVBIQ	0	1	0
SGVAL VLVBIQ	0	SGVAL EXIT	0	1	0
SOVAL VLVBIQ	USE AGV 3	SOVAL VLVBIQ	0	1	0
SOVAL VLVBIQ	0	SOVAL EXIT	0	1	0
SOVAL VLVB2Q	USE AGV 3	SOVAL EXIT	0	1	0
SGVAL VLVB2Q	USE AGV 3	SGVAL EXIT	0	1	0
DBVAL VLVB2Q	USE AGV 3	DBVAL EXIT	0	1	0
BACK2 VLVB2Q	0	BACK2 EXIT	0	1	0
FOLCN VLVB2Q	USE AGV 3	FOLCN EXIT	0	1	0
ACVLB VLVB2Q	USE AGV 3	ACVLB VLVB2Q	0	1	0
ACVLB VLVB2Q	0	RAVLB VLVB2Q	0	88	0
RAVLB VLVB2Q	0	RAVLB VLVBL2	0	1	.2
RAVLB VLVBL2	.4	VLBLK VLVB2O	0	1	0
VLBLK VLVB2O	ACCUM 88	T1VLB HCUIQ	0	1	AGV

*

*

*The Pump Line follows

*							
APMN1	PUMPQ1	USE AGV 3	APMN1	EXIT	0	1	0
		UNQUE					
APMN2	PUMPQ2	USE AGV 3	APMN2	EXIT	0	1	0
		UNQUE					
APMN3	PUMPQ3	USE AGV 3	APMN3	EXIT	0	1	0
		UNQUE					
INLTV	PUMPQ1	USE AGV 3	INLTV	EXIT	0	1	0
		UNQUE					
INLTV	PUMPQ2	USE AGV 3	INLTV	EXIT	0	1	0
		UNQUE					
INLTV	PUMPQ3	USE AGV 3	INLTV	EXIT	0	1	0
		UNQUE					
OTLTV	PUMPQ1	USE AGV 3	OTLTV	EXIT	0	1	0
		UNQUE					
OTLTV	PUMPQ2	USE AGV 3	OTLTV	EXIT	0	1	0
		UNQUE					
OTLTV	PUMPQ3	USE AGV 3	OTLTV	EXIT	0	1	0
		UNQUE					
HSPM1	PUMPQ1	USE AGV 3	HSPM1	EXIT	0	1	0
		UNQUE					
HSPM2	PUMPQ2	USE AGV 3	HSPM2	EXIT	0	1	0
		UNQUE					
HSPM3	PUMPQ3	USE AGV 3	HSPM3	EXIT	0	1	0
		UNQUE					
SPPM1	PUMPQ1	USE AGV 3	SPPM1	PUMPQ1	0	1	0
		UNQUE					
SPPM1	PUMPQ1	UNQUE	SPPM1	EXIT	0	1	0
SPPM2	PUMPQ2	USE AGV 3	SPPM2	PUMPQ2	0	1	0
		UNQUE					
SPPM2	PUMPQ2	UNQUE	SPPM2	EXIT	0	1	0
SPPM3	PUMPQ3	USE AGV 3	SPPM3	PUMPQ3	0	1	0
		UNQUE					
SPPM3	PUMPQ3	UNQUE	SPPM3	EXIT	0	1	0
AMOTR	PUMPQ1	USE AGV 3	AMOTR	PUMPQ1	0	1	0
		UNQUE					
AMOTR	PUMPQ1	UNQUE	MOTOR	PUMPQ1	0	240	0
MOTOR	PUMPQ1	UNQUE	MOTOR	PUMPL	0	1	.1
AMOTR	PUMPQ2	USE AGV 3	AMOTR	PUMPQ2	0	1	0
		UNQUE					
AMOTR	PUMPQ2	UNQUE	MOTOR	PUMPQ2	0	240	0
AMOTR	PUMPQ3	USE AGV 3	AMOTR	PUMPQ3	0	1	0
		UNQUE					
AMOTR	PUMPQ3	UNQUE	MOTOR	PUMPQ3	0	240	0
MOTOR	PUMPL	.56	PUMP	PUMPO	0	1	0
MOTOR	PUMPQ2	UNQUE	MOTOR	PUMPL2	0	1	0
MOTOR	PUMPL2	.56	PUMP	PUMPO	0	1	.5
MOTOR	PUMPQ3	UNQUE	MOTOR	PUMPL3	0	1	0
MOTOR	PUMPL3	.56	PUMP	PUMP30	0	1	2
PUMP	PUMPO	ACCUM 132	APUMP	PUMPO	0	1	0
APUMP	PUMPO	0	APUMP	PMPTSI	0	1	AGV
PUMP	PUMP30	ACCUM 132	APUMP	PMPTSI	0	1	AGV
APUMP	PMPTSI	USE AGV 3	APUMP	PMPTSI	0	1	0
APUMP	PMPTSI	0	PUMP	PMPTSI	0	132	0
PUMP	PMPTSI	0	PUMP	PUMPTST	0	1	0
PUMP	PUMPTST	.617	TPUMP	PMPTSO	0	1	1
*							
*The Pump Test area							
*							
TPUMP	PMPTSO	ACCUM 132	ATPMP	PMPTSO	0	1	0

ATPMP PMPTSO 0 ATPMP HCUIQ 0 1 AGV

*

*The TMC line follows

*

SPTMC TMCIQ	USE AGV 3	SPTMC TMCIQ	0	1	0
SPTMC TMCIQ	0	SPTMC EXIT	0	1	0
SPIST TMCIQ	USE AGV 3	SPIST TMCIQ	0	1	0
SPIST TMCIQ	0	SPIST EXIT	0	1	0
DPIST TMCIQ	USE AGV 3	DPIST TMCIQ	0	1	0
DPIST TMCIQ	0	DPIST EXIT	0	1	0
AHTMC TMCIQ	USE AGV 3	AHTMC TMCIQ	0	1	0
AHTMC TMCIQ	0	HSTMC TMCIQ	0	350	0
HSTMC TMCIQ	0	HSTMC TMCL1	TURN	1	.1
		HSTMC TMCL2	TURN	0	.1
		HSTMC TMCL3	TURN	0	.1
		HSTMC TMCL4	TURN	0	.1
HSTMC TMCL1	.8387	TMC TMCOQ	0	1	.1
HSTMC TMCL2	.8387	TMC TMCOQ	0	1	.1
HSTMC TMCL3	.8387	TMC TMCOQ	0	1	.1
HSTMC TMCL4	.8387	TMC TMCOQ	0	1	.1
TMC TMCOQ	ACCUM 350	PTMC OUTSTOR2	0	1	4

*

*The HCU lines follow

*

SPHCU HCUIQ	USE AGV 3	SPHCU HCUIQ	0	1	0
	UNQUE				
SPHCU HCUIQ	UNQUE	SPHCU EXIT	0	1	0
ATPMP HCUIQ	USE AGV 3	ATPMP HCUIQ	0	1	0
	UNQUE				
ATPMP HCUIQ	0	TPUMP HCUIQ	0	132	0
	UNQUE				
TPUMP HCUIQ	UNQUE	TPUMP HCUL	TURN	1	.1
		TPUMP HCUL2	TURN	0	.1
		TPUMP HCUL3	TURN	0	.1
TOVLB HCUIQ	USE AGV 3	TOVLB HCUIQ	0	1	0
	UNQUE				
TOVLB HCUIQ	0	VLBLK HCUIQ	0	88	0
	UNQUE				
T1VLB HCUIQ	USE AGV 3	T1VLB HCUIQ	0	1	0
	UNQUE				
T1VLB HCUIQ	0	VLBLK HCUIQ	0	88	0
	UNQUE				
VLBLK HCUIQ	UNQUE	VLBLK HCL1Q	TURN	1	0
		VLBLK HCL2Q	TURN	0	0
		VLBLK HCL3Q	TURN	0	0
VLBLK HCL1Q	UNQUE	VLBLK HCUL	JOIN	1	0
TPUMP HCUL	JOIN 1 VLBLK	HCU HCUOQ	0	1	0
	.6417				
VLBLK HCL2Q	UNQUE	VLBLK HCUL2	JOIN	1	0
TPUMP HCUL2	JOIN 1 VLBLK	HCU HCUOQ	0	1	0
	.6417				
VLBLK HCL3Q	UNQUE	VLBLK HCUL3	JOIN	1	0
TPUMP HCUL3	JOIN 1 VLBLK	HCU HCUOQ	0	1	0
	.6417				
HCU HCUOQ	ACCUM 132	PHCU OUTSTOR1	0	1	4

*

*The following shows the outstorage.

*

PHCU OUTSTOR1	USE AGV 3	PHCU OUTSTOR1	0	1	0
---------------	-----------	---------------	---	---	---

PHCU OUTSTOR1 0
 PTMC OUTSTOR2 USE AGV 3
 PTMC OUTSTOR2 0

HCU EXIT 0 132 0
 PTMC OUTSTOR2 0 1 0
 TMC EXIT 0 350 0

PART SCHEDULING

Part	Location	Qty per arrival	No. of arrivals	Start (min)	Arrival frequency (min)
ATSPT	WASH	1	24	0	480
SPATS	WASH	1	24	0	480
SPDLI	WASH	1	24	0	480
DLIPT	WASH	1	24	0	480
NPPPT	WASH	2	24	0	480
NPILT	WASH	3	24	0	480
NPOLT	WASH	4	24	0	480
NPSGV	WASH	3	24	0	480
SGVAL	SOSGOQ	1	24	279.6	205.71
SPSOV	WASH	2	24	0	480
HSSOV	WASH	1	24	0	480
SOVAL	SOSOOQ	2	24	352.3	288
SPDBV	WASH	2	24	0	1440
SPBAC	WASH	2	24	0	1440
FOLCN	ASRS1	2	24	0	480
RAVLB	WASH	176	216	0	53.33
SPVLB	WASH	1	24	0	480
SPPMP	WASH	1	24	0	480
HSPMP	WASH	1	56	0	205.71
MOTOR	ASRS	240	152	0	79
SPHCU	WASH	1	24	0	480
SPTMC	WASH	1	24	0	480
HSTMC	WASH	350	120	0	116.78

DOWNTIMES

Resource	Basis	Freq(min, cyc) or Setup part	Duration (min)	Start or Lead part	Qty	Maintenance resource
INLT1	CLOCK	240	30	240	1	0
INLT1	CLOCK	480	45	0	1	0
INLT2	CLOCK	240	30	240	1	0
INLT2	CLOCK	480	45	0	1	0
INLT3	CLOCK	240	30	240	1	0
INLT3	CLOCK	480	45	0	1	0
ATSL	CLOCK	240	30	240	1	0
ATSL	CLOCK	480	45	0	1	0
DPISTL	CLOCK	240	30	240	1	0
DPISTL	CLOCK	480	45	0	1	0
PUMPISL1	CLOCK	240	30	240	1	0
PUMPISL1	CLOCK	480	45	0	1	0
PUMPISL2	CLOCK	240	30	240	1	0
PUMPISL2	CLOCK	480	45	0	1	0
OUTLT1	CLOCK	240	30	240	1	0
OUTLT1	CLOCK	480	45	0	1	0
OUTLT2	CLOCK	240	30	240	1	0
OUTLT2	CLOCK	480	45	0	1	0
OUTLT3	CLOCK	240	30	240	1	0
OUTLT3	CLOCK	480	45	0	1	0
SOSGL1	CLOCK	240	30	240	1	0
SOSGL1	CLOCK	480	45	0	1	0
SOSGL2	CLOCK	240	30	240	1	0
SOSGL2	CLOCK	480	45	0	1	0

SOSGL3	CLOCK 240	30	240	1	0
SOSGL3	CLOCK 480	45	0	1	0
SOSOL	CLOCK 240	30	240	1	0
SOSOL	CLOCK 480	45	0	1	0
DBVALL	CLOCK 240	30	240	1	0
DBVALL	CLOCK 480	45	0	1	0
BACKL	CLOCK 240	30	240	1	0
BACKL	CLOCK 480	45	0	1	0
PUMPL	CLOCK 240	30	240	1	0
PUMPL	CLOCK 480	45	0	1	0
PUMPL2	CLOCK 240	30	240	1	0
PUMPL2	CLOCK 480	45	0	1	0
PUMPL3	CLOCK 240	30	240	1	0
PUMPL3	CLOCK 480	45	0	1	0
PUMPTST	CLOCK 240	30	240	1	0
PUMPTST	CLOCK 480	45	0	1	0
TMCL1	CLOCK 240	30	240	1	0
TMCL1	CLOCK 480	45	0	1	0
TMCL1	CLOCK 1440	60	0	1	0
TMCL2	CLOCK 240	30	240	1	0
TMCL2	CLOCK 480	45	0	1	0
TMCL2	CLOCK 1440	60	0	1	0
TMCL3	CLOCK 240	30	240	1	0
TMCL3	CLOCK 480	45	0	1	0
TMCL3	CLOCK 1440	60	0	1	0
TMCL4	CLOCK 240	30	240	1	0
TMCL4	CLOCK 480	45	0	1	0
TMCL4	CLOCK 1440	60	0	1	0
HCUL	CLOCK 240	30	240	1	0
HCUL	CLOCK 480	45	0	1	0
HCUL	CLOCK 1440	80	0	1	0
HCUL2	CLOCK 240	30	240	1	0
HCUL2	CLOCK 480	45	0	1	0
HCUL2	CLOCK 1440	80	0	1	0
HCUL3	CLOCK 240	30	240	1	0
HCUL3	CLOCK 480	45	0	1	0
HCUL3	CLOCK 1440	80	0	1	0
VLVBL	CLOCK 480	45	0	1	0
VLVBL2	CLOCK 480	45	0	1	0

TRANSPORTER SPECIFICATIONS FOR AGV

Speed ft(m)/min	Pickup (sec)	Deposit (sec)	Start position	Search rule	Accel (fpss)	Decel (fpss)
200	10	10	1	OLDEST	1	1

PATH LOGIC FOR AGV

From	To	Block	Speed ft(m)/min	Distance ft(m) or Time(min)
1	2	0	0	43
2	4	0	0	94
4	6	0	0	45
6	8	0	0	50
8	10	0	0	15
10	12	0	0	10
12	14	0	0	20
14	16	0	0	20
16	18	0	0	30
18	20	0	0	10

20	22	0	0	30
22	24	0	0	15
24	26	0	0	30
26	28	0	0	15
28	30	0	0	30
30	32	0	0	45
32	34	0	0	30
34	36	0	0	20
36	38	0	0	30
38	40	0	0	25
40	42	0	0	15
42	44	0	0	60
44	46	0	0	20
46	48	0	0	30
48	50	0	0	70
2	52	0	0	45
52	54	0	0	45
54	50	0	0	15
50	56	0	0	45
56	60	0	0	105
60	1	0	0	45
50	62	0	0	15
62	64	0	0	45
64	66	0	0	45
66	68	0	0	128
68	70	0	0	25
70	72	0	0	40
72	74	0	0	10
74	46	0	0	50
62	76	0	0	25
76	78	0	0	25
78	80	0	0	20
80	64	0	0	25
78	79	0	0	15
79	80	0	0	15
79	82	0	0	40
82	84	0	0	20
66	86	0	0	15
86	90	0	0	25
90	92	0	0	35
92	94	0	0	15
94	96	0	0	25
96	98	0	0	30
98	81	0	0	40
81	83	0	0	70
83	85	0	0	40
85	87	0	0	30
87	89	0	0	30
89	90	0	0	35
90	86	0	0	15
84	86	0	0	B15
84	71	0	0	56
71	56	0	0	105
94	95	0	0	15
95	96	0	0	15
98	99	0	0	25
99	81	0	0	25
52	A	0	0	25
A	A1	0	0	20
A1	54	0	0	20

76	B	0	0	15
B	78	0	0	15
80	C	0	0	15
C	64	0	0	15
64	D	0	0	15
D	E	0	0	35
E	66	0	0	15
4	F	0	0	5
F	G	0	0	5
G	6	0	0	5
8	H	0	0	5
H	10	0	0	5
12	I	0	0	15
I	14	0	0	15
16	J	0	0	15
J	18	0	0	17
20	K	0	0	16
K	22	0	0	16
24	L	0	0	20
L	26	0	0	20
28	M	0	0	16
M	30	0	0	17
32	N	0	0	15
N	34	0	0	16
36	O	0	0	16
O	38	0	0	16
40	P	0	0	20
P	42	0	0	20
44	Q	0	0	15
Q	R	0	0	25
R	48	0	0	20
96	97	0	0	17
97	98	0	0	18
70	S	0	0	10
S	T	0	0	35
T	72	0	0	10
85	U	0	0	18
U	87	0	0	16
2	3	0	0	48
3	5	0	0	25
5	7	0	0	48
7	2	0	0	54
89	Z3	0	0	55
Z3	Z2	0	0	25
Z2	89	0	0	35
72	Z4	68	0	20
Z4	Z5	0	0	40
Z5	Z6	0	0	45
Z6	74	68	0	20

LOCATION INTERFACES FOR AGV

Location	Point	Location	Point	Location	Point	Location	Point
ASRS1Q	3	OUTSTOR1	Z3	OUTSTOR2	Z5	ASRS2Q	5
ATSIQ	H	ATSOQ	P	BACK2Q	95	BACKIQ	79
DVALIQ	82	DBVALOQ	82	DPISTIQ	I	DPISTOQ	J
HCUIQ	97	INLTIQ	O	INLTOQ	M	OUTLT4	N
OUTLTIQ	N	OUTLTOQ	M	PMPTSI	D	PMPTSO	E
PUMP3O	C	PUMPISIQ	K	PUMPISOQ	K	PUMPO	A1
PUMPQ1	A	PUMPQ2	A1	PUMPQ3	C	SOSGIQ	F

SOSGOQ	R	SOSOIQ	G	SOSOOQ	Q	STAGE	1
TMCIQ	T	VLVB2O	99	VLVB2Q	95	VLVBIQ	B
VLVBOQ	B						

CAPACITIES

Resource	Qty	Resource	Qty	Resource	Qty	Resource	Qty	Resource	Qty
AGV	4	ASRS	2000	ASRS1	2000	ASRS1Q	2000	ASRS2Q	2000
ATSIQ	2000	ATSL	1	ATSOQ	2000	BACK2Q	100	BACKIQ	2000
BACKL	1	BACKL2	1	BACKOQ	2000	DBVALIQ	2000	DBVALL	1
DBVALOQ	2000	DPISTIQ	2000	DPISTL	1	DPISTOQ	2000	HCL1Q	2000
HCL2Q	2000	HCL3Q	2000	HCUIQ	4000	HCUL	1	HCUL2	1
HCUL3	1	HCUIQ	2000	INLT1	1	INLT2	1	INLT3	1
INLTIQ	2000	INLTOQ	2000	OUTLT1	1	OUTLT2	1	OUTLT3	1
OUTLT4	1	OUTLTIQ	2000	OUTLTOQ	2000	OUTSTOR	5000	OUTSTOR1	1000
OUTSTOR2	1000	OUTSTR1	5000	OUTSTR2	5000	PMPTSI	2000	PMPTSL	1
PMPTSO	2000	PUMP3O	1000	PUMPISIQ	2000	PUMPISL1	1	PUMPISL2	1
PUMPISOQ	2000	PUMPL	1	PUMPL2	1	PUMPL3	1	PUMPO	2000
PUMPQ1	2000	PUMPQ2	2000	PUMPQ3	2000	PUMPTST	4	SOSGIQ	2000
SOSGL1	1	SOSGL2	1	SOSGL3	1	SOSGOQ	2000	SOSOIQ	2000
SOSOL	1	SOSOOQ	2000	STAGE	10000	TMCIQ	5000	TMCL1	1
TMCL2	1	TMCL3	1	TMCL4	1	TMCOQ	1000	VLVB2O	1500
VLVB2Q	2000	VLVBIQ	2000	VLVBL	1	VLVBL2	1	VLVBOQ	5000
WASH	20000	1	5	2	5	3	5	4	5
6	5	7	5	8	5	10	5	12	5
14	5	16	5	18	5	20	5	22	5
24	5	26	5	28	5	30	5	32	5
34	5	36	5	38	5	40	5	42	5
44	5	46	5	48	5	50	5	52	5
54	5	56	5	62	5	64	5	66	5
68	5	70	5	72	5	A	1	B	1
C	1	D	1	E	1	F	1	G	1
H	1	I	1	J	1	K	1	L	1
M	1	N	1	O	1	P	1	R	1
T	1	U	1	74	5	A1	1	76	5
78	5	80	5	82	5	84	5	86	5
90	5	92	5	94	5	96	5	98	5
81	5	83	5	85	5	87	5	89	5
71	5	95	1	97	1	99	1	5	5

SIMULATION PARAMETERS

Run	Startup	Rept	Resource	Seed
(hrs)	(hrs)	code	to track	
168	24	5	0	0

GRAPHIC OPTIONS

Graph	Max	Max	Scr	Fig	Icon
mode	row	col	clr	clr	file
3	133	240	D	M	PM.LIB

STATIC SYMBOLS

ID	Sym	Clr	Row	Col	ID	Sym	Clr	Row	Col	ID	Sym	Clr	Row	Col
ATSIQ	B	M	57	88	PUMP3O	B	1	100	158	STAGE	2	4	109	76
HCL1Q	1	6	107	199	HCL2Q	1	6	107	205	HCL3Q	1	6	107	210
PUMPQ1	B	M	99	103	OUTLT1	A	2	53	138	INLT2	A	2	55	125
INLT3	A	2	55	128	PUMPQ2	B	M	99	112	PUMPQ3	B	M	98	158
BACKL	B	2	108	149	SOSOIQ	B	M	73	84	ASRS2Q	B	5	90	42
ASRS1Q	B	5	93	42	ATSL	B	5	57	96	ATSOQ	B	1	57	104
DPISTIQ	B	M	48	87	DPISTL	B	5	48	90	DPISTOQ	B	1	48	93
PUMPISIQ	B	M	48	101	PUMPISL1	B	2	48	105	PUMPISL2	B	2	48	108
PUMPISOQ	B	1	48	112	OUTLTIQ	B	M	58	141	OUTLT2	A	2	53	141
OUTLT3	A	2	53	144	OUTLTOQ	B	1	48	141	OUTLT4	B	2	68	143
INLTIQ	B	M	58	125	INLTOQ	B	1	52	125	SOSGIQ	B	M	82	84

SOSGL2	I	2	82	103	SOSGL3	I	2	79	103	SOSGOQ	B	1	83	120
DBVALIQ	A	M	107	170	DBVALL	I	2	112	171	BACK2Q	B	M	114	198
BACKL2	B	2	113	204	DBVALOQ	A	1	107	172	PUMPL	a	2	108	102
PUMPL2	a	2	108	113	PUMPO	B	1	99	108	PUMPL3	a	2	100	168
VLVBIQ	B	M	103	139	VLVBL	g	2	113	149	VLVBL2	g	2	118	203
VLVB2Q	B	M	114	194	VLVB20	B	1	113	213	VLVBOQ	B	1	104	143
TMCIQ	2	M	72	175	TMCL1	4	5	71	167	TMCL2	4	5	66	167
TMCL3	4	5	61	167	TMCL4	4	5	51	167	TMCOQ	2	1	63	175
HCUIQ	B	M	108	202	HCUL	6	2	102	197	HCUL2	6	2	102	203
HCUL3	6	2	102	208	HCUOQ	B	1	95	202	OUTSTOR	1	5	64	201
WASH	WB	4	110	46	OUTSTR1	1	4	63	201	OUTSTR2	1	4	63	208
PMPTSI	B	M	89	156	PMPTSL	d	B	82	162	PMPTSO	B	1	89	172
SOSOOQ	B	1	73	120	ASRS1	1	B	94	35	ASRS	1	G	94	29
SOSOL	I	2	73	103	BACKIQ	B	M	106	145	BACKOQ	B	1	106	153
PUMPTST	I	2	83	162	INLT1	A	2	55	122	SOSGL1	I	2	85	103
SOSGL3	I	2	79	103	OUTSTOR1	1	C	63	201	OUTSTOR2	1	C	63	208

DYNAMIC SYMBOLS

ID	Sym	Clr									
ACVLB	.	B	AGV	AC	5	AHTMC	.	C	AMOTR	.	G
APMN1	,	O	APMN2	,	O	APMN3	,	O	APUMP	.	M
ASDBV	.	B	ATPMP	.	M	ATSPT	,	1	BACK2	"	O
BACLK	,	2	DBVAL	,	3	DINLT	"	8	DLIPT	/	3
DPIST	<	4	FOLCN	>	6	HCU	.	B	HSPM1	.	2
HSPM2	.	2	HSPM3	.	2	HSPMP	,	G	HSSOV	.	C
HSTMC	.	G	INLTV	"	5	MOTOR	.	B	NPILT	"	5
NPOLT	"	4	NPPPT	"	6	NPSGV	"	8	OTLTV	<	3
PHCU	;	R	PMPPN	/	3	PTMC	;	B	PUMP	.	7
RAVLB	,	M	SIVAL	/	8	S2VAL	/	8	SGVAL	/	O
SOTLT	"	C	SOVAL	/	8	SPATS	/	3	SPBAC	/	3
SPDBV	/	3	SPDLI	/	3	SPHCU	/	3	SPILT	/	3
SPIST	"	6	SPOLT	/	3	SPPM1	/	R	SPPM2	/	R
SPPM3	/	R	SPMP	/	3	SPPPT	/	3	SPSGV	/	3
SPSOV	/	3	SPTMC	/	3	SPVB1	/	R	SPVB2	/	R
SPVLB	/	3	T1VLB	.	M	TMC	;	G	TOVLB	.	B
TPUMP	.	R	VLBLK	/	W						

TRANSPORTER POINTS

Point	Row	Col												
1	108	80	2	95	80	3	95	45	4	85	80	A	97	104
6	71	80	8	59	80	10	53	80	B	102	139	12	50	80
C	98	156	D	91	159	14	43	80	16	43	86	18	43	95
20	43	100	22	43	114	24	43	121	26	43	130	28	43	135
30	43	146	32	62	146	34	62	137	36	62	129	38	62	121
40	62	113	42	62	108	44	71	126	46	77	126	48	86	126
50	95	126	52	95	97	54	95	117	56	119	126	62	95	134
64	95	155	66	95	181	68	55	181	70	61	179	72	75	179
7	92	80	E	91	172	F	82	82	G	73	82	H	57	83
I	47	83	J	44	90	K	44	107	L	48	125	M	45	141
N	61	141	O	61	125	P	57	109	R	83	123	T	72	177
U	93	202	74	77	179	60	119	80	76	101	134	78	101	146
80	101	155	79	104	150	82	104	170	84	104	181	86	100	181
90	100	190	92	110	190	94	110	193	96	110	199	98	110	205
81	110	220	83	90	220	85	90	206	87	90	198	89	90	190
71	119	181	95	112	196	99	111	212	Q	73	123	97	109	202
S	63	177	5	92	45	A1	97	112	Z3	81	200	Z2	81	187
Z4	75	188	Z5	77	198	Z6	77	186						

TRANSPORTER PATH LAYOUT

From	To	Layout
1	2	U13
2	4	U10
4	6	U14
6	8	U12
8	10	U6
10	12	U3
12	14	U7
14	16	R6
16	18	R9
18	20	R5
20	22	R14
22	24	R7
24	26	R9
26	28	R5
28	30	R11
30	32	R2 D19 L2
32	34	L9
34	36	L8
36	38	L8
38	40	L8
40	42	L5
42	44	D6 R18 D3
44	46	D6
46	48	D9
48	50	D9
2	52	R17
52	54	R20
54	50	R9
50	56	D24
56	60	L46
60	1	U11
50	62	R8
62	64	R21
64	66	R26
66	68	U40
68	70	L2 D6
70	72	D14
72	74	D2
74	46	L53
62	76	D6
76	78	R12
78	80	R9
80	64	U6
78	79	D3 R4
79	80	R5 U3
79	82	R20
82	84	R11
66	86	D5
86	90	R9
90	92	D10
92	94	R3
94	96	R6
96	98	R6
98	81	R15
81	83	U20
83	85	L14
85	87	L8

87	89	L8
89	90	D10
90	86	L9
84	86	BU4
84	71	D15
71	56	L55
94	95	D2 R3
95	96	R3 U2
98	99	R3 D1 R4
99	81	R5 U1 R3
52	A	D2 R7
A	A1	R8
A1	54	R5 U2
76	B	R2 D1 R3
B	78	R4 U1 R3
80	C	R1 U3
C	64	U2 L1 U1
64	D	U4 R4
D	E	R13
E	66	R5 D4 R4
4	F	R2 U3
F	G	U9
G	6	U2 L2
8	H	R3 U2
H	10	U4 L3
12	I	R3 U3
I	14	U2 L3 U2
16	J	D1 R4
J	18	R5 U1
20	K	D1 R7
K	22	R7 U1
24	L	D5 R4
L	26	R5 U5
28	M	D2 R6
M	30	R5 U2
32	N	U1 L5
N	34	L4 D1
36	O	U1 L4
O	38	L4 D1
40	P	U5 L4
P	42	D4 L1 D1
44	Q	L3 D2
Q	R	D10
R	48	D3 R3
96	97	U1 R3
97	98	R3 D1
70	S	L2 D2
S	T	D9
T	72	D2 R2 D1
85	U	D3 L4
U	87	L4 U3
2	3	L35
3	5	U3
5	7	R35
7	2	D3
89	Z3	L1 U8 R11 U1
Z3	Z2	L13
Z2	89	D9 R3
72	Z4	R9
Z4	Z5	D2 R10

VITA

Arun Jayaraman was born on December 6, 1968 in Madras, India, to Mrs. and Mr. V. Jayaraman. Mr. Jayaraman completed his Bachelor of Engineering Degree in Mechanical and Production Engineering from Annamalai University, Tamilnadu, India in June 1990. Mr. Jayaraman completed his Master of Engineering degree in May 1993 from Virginia Polytechnic Institute and State University.

Mr. Jayaraman's work experience includes the position of a Graduate Engineer trainee at T.I. Cycles of India Ltd. and as a graduate intern at Telebrands, Roanoke Virginia. Mr. Jayaraman was a Graduate Research Assistant for two semesters and a Graduate Teaching Assistant for two semesters at Virginia Polytechnic Institute and State University, Virginia.

J. Jayaraman