EFFECT OF CONTROL ARCHITECTURES ON AUTOMATED GUIDED VEHICLE SYSTEMS

by

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Thesis submitted to the faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree

of

MASTER OF SCIENCE

in

Industrial and Systems Engineering

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February, 1995

Blacksburg, Virginia

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(ABSTRACT)

Automated Guided Vehicle Systems (AGVSs) have been widely adopted by many low to medium manufacturing operations, particularly in Flexible Manufacturing Systems (FMS). The high degree of flexibility and control offered in vehicle routing has made AGVS a proven and viable material handling technology in today's manufacturing systems *[Bozer91].* An important aspect in maintaining flexibility in an AGVS is its control architecture.

A control architecture provides the backbone of the physical and the informational infrastructure of a system. This research has identified three types of control architectures. They are the centralized, hierarchical, and heterarchical control architectures. When designing an AGVS, most designers do not consider control architecture as a design factor, and do not analyze its effect on the system's performance. The objective of this research is to analyze the effect of control architectures on the relative performance of the AGVS.

This research uses simulation to study the effect of control architectures on the AGVS. The simulation model for each control architecture contains two parts -- an AGV controller and a shop floor controller. Both models are programmed in C language. The AGV controller consists of three basic components -- vehicle

scheduling, vehicle routing, and traffic control. Each of these three components is modeled according to the nature and characteristics of the corresponding control architecture. Two different flow path layouts are considered for the shop floor model. The two layouts are different in size and number of work stations. Performance measures chosen for this study are intended to reflect the responsiveness of the system and the overall system performance under the impact of different control architectures.

ACKNOWLEDGMENTS

I wish to thank Dr. Roderick Reasor for his guidance and support. He has provided continual patience and persistence that were integral to my accomplishments. I wish also thank my committee members, Dr. William Schimdt and Dr. Bevlee Watford, for their involvement in my research and for accommodating my defense schedule under such short notice.

I would like to thank my parents for their faith in my ability and their financial support. Furthermore, I would like to express my gratitude to Charles Chiang for providing me his computer facilities and for being there whenever I need him.

Table of Contents

List of Illustrations

List of Tables

CHAPTER I

INTRODUCTION

1.1 Introduction

The increasing demand for higher flexibility in manufacturing systems has caused Automated Guided Vehicle Systems (AGVSs) to receive significant attention in recent years. Consequently, a great deal of work has been conducted in designing and developing AGVS. Since the 1950s, the AGVs have changed from vacuum tube based technology to today's microprocessor based intelligent vehicle *[Hammond86].* Today's vehicles are no longer restricted to ground facilities, and advanced wireless vehicles have been developed using ultrasound, image processing, laser or radio technologies *[Boegli84]*. The improvement of computer and communication technology plays a vital role in the success of AGVS development. As technologies improve, with corresponding cost reductions, more intelligent AGVs with higher level decision-making capabilities are being built.

Corresponding to the revolutionary developments in the vehicle design and the manufacturing technology, a number of manufacturing control architectures have been identified in this research. Each control architecture has its own potential benefits according to the nature and functions of the system. The AGVS and the various AGVS design problems are described in the following sections, followed by the problem statement and the objective of this research work.

1.2 AGVS

An AGVS is an advanced material handling system that involves one or more driverless vehicles (AGVs). Major components of an AGVS are the vehicle, the flow path, the load transfer system, and the control system. The vehicles or AGVs are powered by battery with re-programmable capabilities for path selection, and positioning *[Hammond86]*. An AGV can be dynamically controlled by a central computer or by an on-board micro-processor *[Vosniakos90]*. A guide wire embedded in the floor and strips of reflective materials taped on the floor are among the methods used to direct the paths of the AGVs. Many types of load transfer systems have been developed, such as manual load transfer, automatic couple and uncouple, power roller/belt/chain, power lift/lower, and power push/pull, that are used to accommodate the different needs in the manufacturing environment.

The objective of the AGV control system is to manage, monitor, communicate and control the AGVs and other supporting devices. It also works jointly with other functions in the system for effective material handling management. There are three major functions in the AGV control system: (1) dispatching, (2) routing, and (3) traffic management. The dispatching function makes task assignment to an AGV. The routing function assigns path instructions to a vehicle. The traffic management function monitors and controls the traffic flow on the factory floor.

A conventional AGV controller first draws an incoming job and assigns a vehicle from a fleet of idle vehicles to pick-up the job using the selected dispatching rule. There are generally two categories of AGV dispatching rules: (1) work center initiated dispatching rules, and (2) vehicle initiated dispatching rules *[Egbelu84, Dalal91]*. The work center initiated dispatching rules involve one work center and multiple vehicles. The work center picks the vehicle that favors its conditions most. The vehicle initiated dispatching rules involve a vehicle which has just been idled, and there are a number of jobs requesting pick-up.

AGV routing is usually accomplished either by the frequency select method or by the path-switch select method *[Koff85&87]*. In the frequency select method, each assigned route has a specific frequency. The frequency is broadcasted to different decision points. According to the route assignment of the vehicle, it selects the appropriate frequency, and the routing is automatically accomplished. In the path-switch select method, the vehicle approaches a decision point and passes an activated device that causes one path to be turned on while the other paths at the decision point are turned off. The vehicle has only one live path to follow and the routing is accomplished.

When there are multiple vehicles in the system, traffic management is essential. Traffic control and collision avoidance are usually performed using one of the three traffic management techniques: (1) zone control, (2) forward sensing, and (3) combination control. Zone control segments the AGV guide path layout into separate zones, and only one vehicle is permitted in a given zone at a time. Forward sensing uses a sensing system on-board the vehicle to detect the presence of another vehicle or obstacle. Combination control combines the zone control and the forward sensing technique, hoping to benefit from both traffic control methods.

1.3 AGVS Design

Development in AGVS design has evolved into two areas of research: (1) system design problems, and (2) system control problems. System design problems are associated with selecting AGV equipment, designing guide path, determining number of vehicles needed in the AGVS and interfacing with manufacturing and storage systems *[Kusiak85]*. Research relevant to the system design problems such as Maxwell and Muckstadt's (1982) analytical approach to solve for the minimum number of vehicles needed in an AGVS, and Bozer and Srinivasan's (1989) tandem network. System control problems include optimal routing and scheduling of the vehicles *[Kusiak84]*. Research relevant to the system control problems such as Egbelu and Tanchoco's (1984) simulation study to analyze workcenter-initiated and vehicle-initiated dispatching rules, and Hodgson et al. 's (1987) AGVS control rules using Markov decision processes. An extensive review of vehicle routing that is not specific to AGVS is contained in Golden and Assad (1986).

1.4 Problem Statement

Existing AGVS research often focuses on sub-optimizing AGVS components; for example, determining the optimum AGV fleet size, finding the most effective AGV dispatching rules, and optimizing the AGV guide path. Instead, it is more important to select the most appropriate control architecture early in the design stage. The purpose of a control architecture is to provide a backbone to the physical and the informational infrastructure of a system. It also determines the co-relationship between system components, and establishes limitations or possibilities for changes in the future. Recent literature review indicates that no research has been proposed to consider the control architecture as a factor in the AGVS design. Furthermore, limited research has been directed towards understanding the effect of control architecture on AGVS performance.

1.5 Research Objective

The primary objective of this research is to use simulation experimentation to study the performance of the AGVS under the impact of different types of control architecture. This research has identified three basic types of control architecture: (1) centralized, (2) hierarchical, and (3) heterarchical (decentralized or distributed). The simulation model describes three types of control architecture with each model consisting of two parts: (1) AGV controller, and (2) shop floor controller. Both controllers are programmed in C language. The AGV controller is comprised of three basic components: (1) vehicle dispatching, (2) vehicle routing and (3) traffic management. The structure of the three components in each model reflects the nature and characteristics of the corresponding control architecture.

1.6 Document Outline

Chapter 2 provides a literature review of all the relevant material. Chapter 3 details the development of the simulation models. It defines the problem and system definitions of the simulation study. It also describes the experimental procedures and measures used in evaluating the AGVS performance. Chapter 4 reports the results of the simulation study. Chapter 5 concludes with a summary of this research and discusses future research.

CHAPTER II
LITERATURE REVIEW

2.1 Introduction

This chapter reviews the literature relevant to this research and is divided into three sections to cover the following areas:

1. General Control Architecture
2. AGVS Control Architecture
3. Simulation in Manufacturing

2.2 Control Architecture

Control architecture is the infrastructure of control systems. Figure 1 illustrates three types of control architectures: (1) centralized, (2) hierarchical, and (3) heterarchical (decentralized or distributed). A centralized control architecture employs a central computer to perform all the planning and processing tasks. A hierarchical control architecture employs "levels of control" and master/slave relationship. Commands input at the highest level are filtered, and more detail is added as they pass on to the next level in the hierarchy. Modules at each level make decisions based on commands received from the level above, and feedbacks received from the level below. A heterarchical control architecture is built upon locally autonomous entities. It relies on peer-to-peer communication

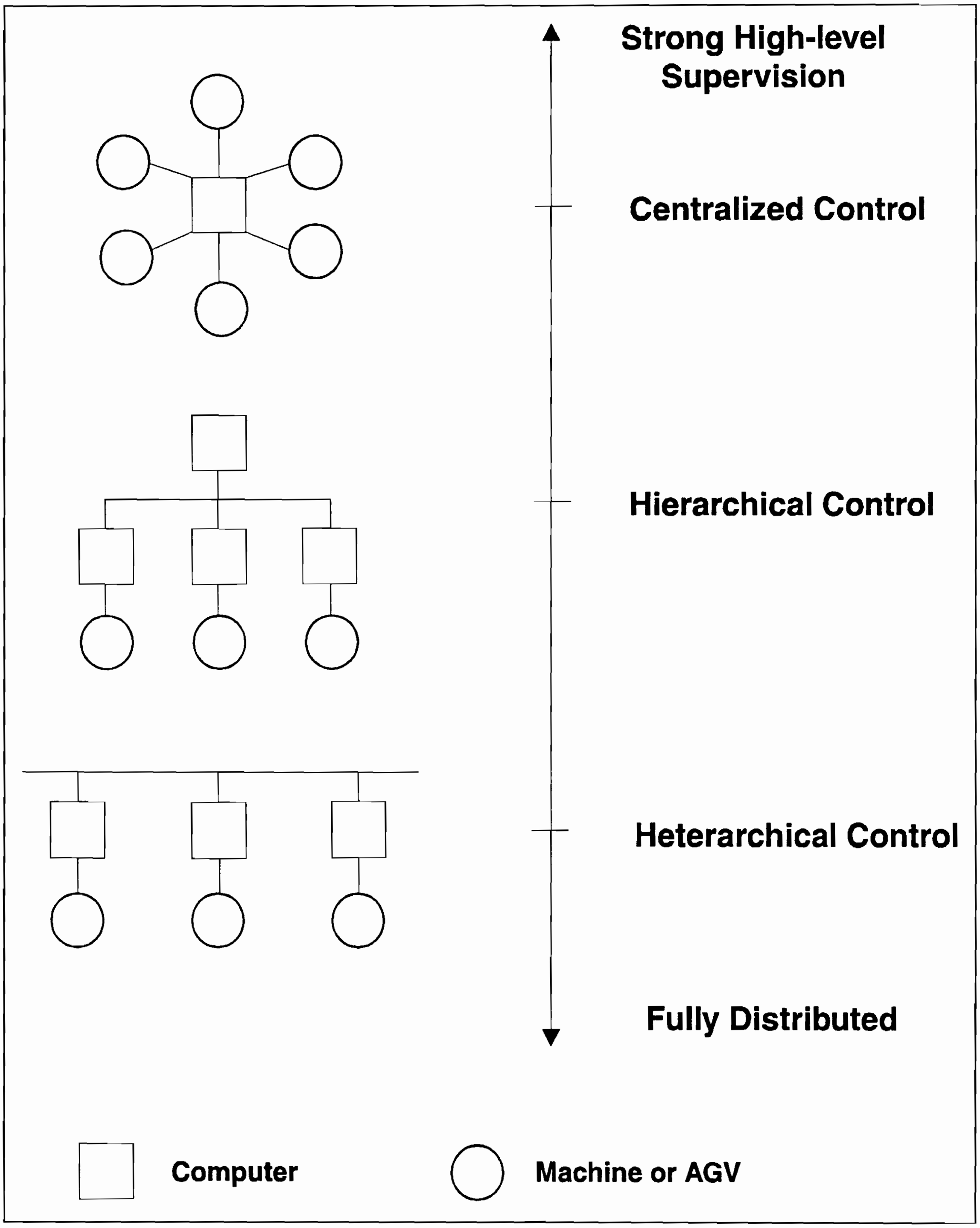


Figure 1. Spectrum of Manufacturing Systems Control Architecture

to control and process decisions *[Boyd91]*.

The majority of the studies in control architecture have been performed in the area of Computer-Integrated Manufacturing (CIM) and Flexible Manufacturing Systems (FMS). The Automated Manufacturing Research Facility (AMRF) constructed at the National Bureau of Standards is a small, integrated, flexible manufacturing system. It serves as an experimental test bed to develop a generic architecture for real-time production control and to propose solutions to system integration problems. The AMRF uses a five layer hierarchical production control model to manage multiple factories. The five levels of control hierarchy are: facility, shop, cell, workstation, and equipment. Each level is driven by data from adjacent layers, and can be expanded to yield a more traditional tree-like hierarchy as depicted in Figure 2. This control structure provides a mechanism for partitioning the functions and databases needed to meet the manufacturing requirements *[Jones86]*. Unfortunately, the research does not enforce a uniform method of implementation within the control modules. In fact, utilization of different techniques and programming languages in the design of the existing control modules would further complicate the system integration problems.

An experimental heterarchically controlled FMS has been developed by Duffie, et al. It uses "intelligent manufactured parts" which act as the active entities and participate in the decision making process of the simulated model. The system is comprised of independent robot, part processing, manufactured part, and human entities that cooperatively control the system through messages exchanged on a communication network. The new system architecture and design philiosophies result in reduced complexity, higher fault tolerance, shorter

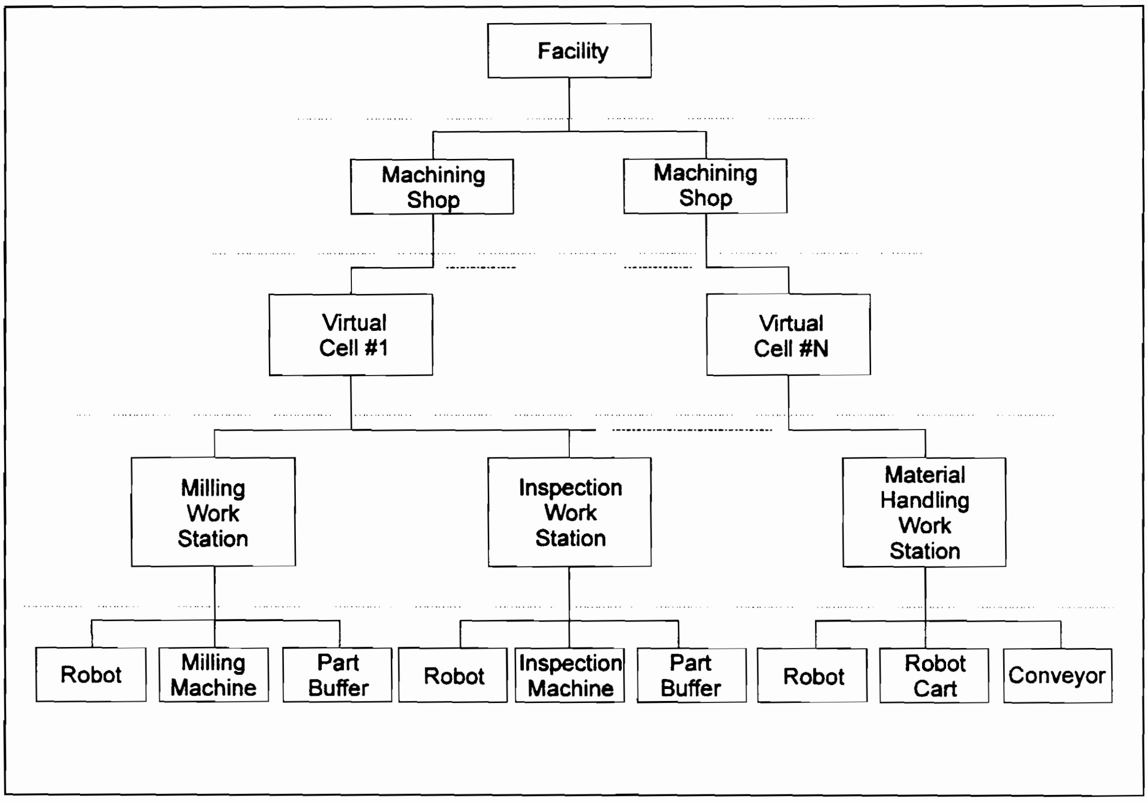


Figure 2. Expanded Automated Manufacturing Research Facility Control Hierarchy

development times, and lower development costs *[Duffie86-91]*. However, this research failed to address the issues of quantitative performance measurement and evaluation procedures needed in comparing the various architectures and philosophies.

Jones and Saleh (1990) presented a multi-level/multi-layer control architecture to manage shop floor activities of CIM. The approach is based on techniques from control theory and operations research. Each module in the architecture performs three functions: (1) adaptation, (2) optimization, and (3) regulation. Adaptation is responsible for generating and updating plans for executing assigned tasks. Optimization is responsible for evaluating proposed plans, and generating and updating schedules. Regulation is responsible for interfacing with subordinates and monitoring execution of assigned tasks. Figure 3 shows the multi-level/multi-layer control scheme. This control architecture combines the best features of the hierarchical and the heterarchical systems. These are the major features of the architecture: (1) it separates control, data management, and communications management; (2) it distributes both decision-making and control; (3) it requires each module to work on many jobs simultaneously; and (4) it provides for limited negotiations between a supervisor and its subordinates *[Jones90]*. This research has initiated the model development, and more work is needed before the actual implementation.

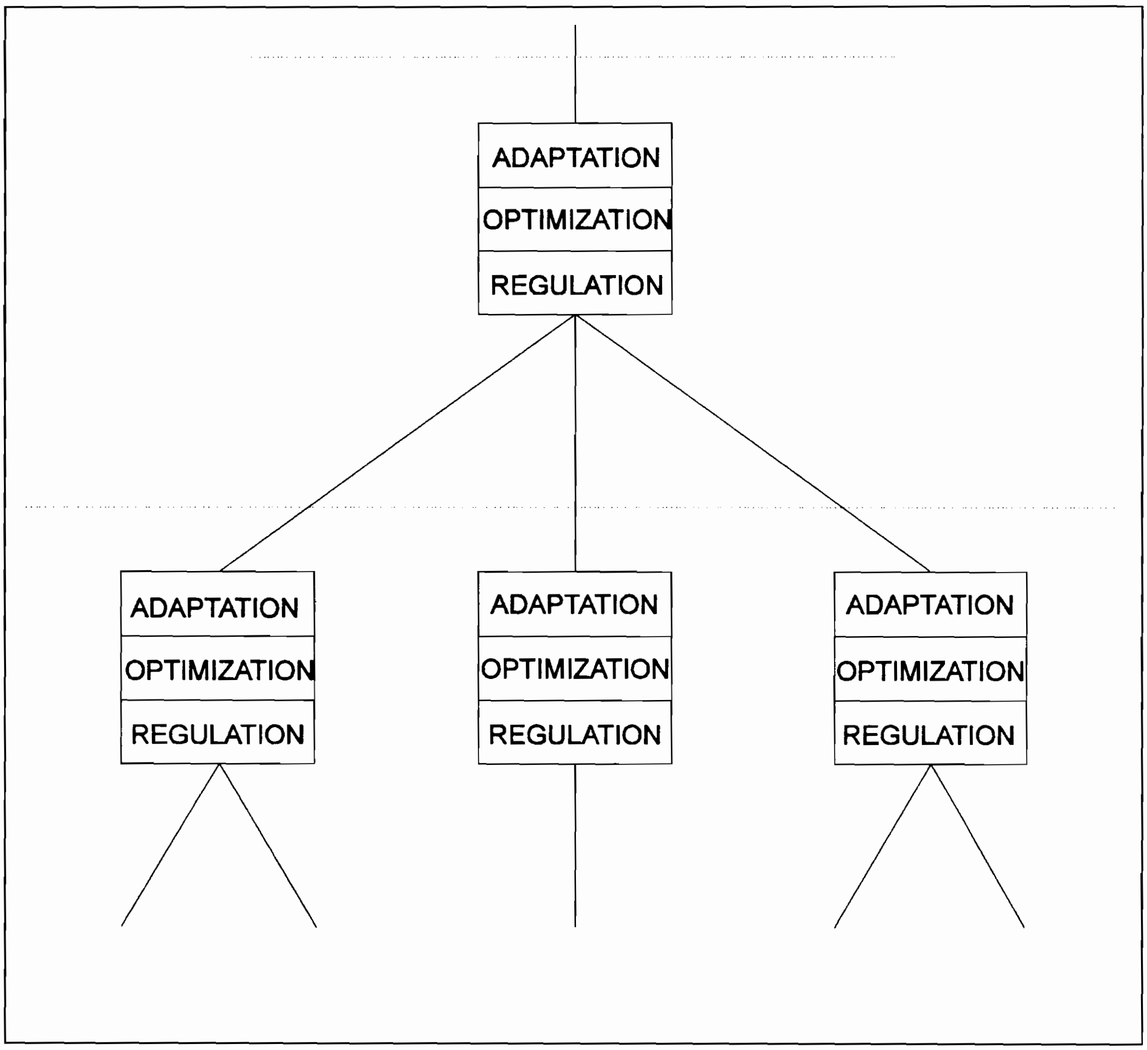


Figure 3. Multi-level/Multi-layer Control Architecture

2.3 AGVS Control Architecture

Most studies related to the design of AGVS do not address the issue of AGVS control architecture, such as network design *[Egbelu86&90]*, vehicle dispatching *[Egbelu84]*, vehicle routing *[Blair84]*, system control strategies, and optimal vehicle fleet size *[Egbelu87]*. The following section reviews papers that speak of the AGV control architecture.

Hammond describes a central processing scheme used in the material handling and AGV system. The centralized system uses a single control unit to schedule, monitor, manage, and control all material handling devices *[Hammond86]*. Figure 4 shows the central processing scheme. A similar system has also been reported by Mullins (1984). The centralized AGVS was implemented at Ford's Karmann German plant, in 1984. The plant employed fourteen centralized control AGVs in its mixed model assembly lines. Instead of pre-programming the AGVs in a fixed path, the vehicles are directed from one point to the next depending on the traffic conditions. At each successive point, the AGV receives its next set of instructions from the central computer *[Mullins84]*. The simplistic nature of the centralized control architecture provides a single and global information source for easy retrieval and optimization. However, as the system grows, the system's speed of response tends to become slower and inconsistent. Its strong reliance on one central computer also directly affects the system's fault-tolerance. If the central unit fails, the entire system will no longer function *[Hammond86, Boyd91]*.

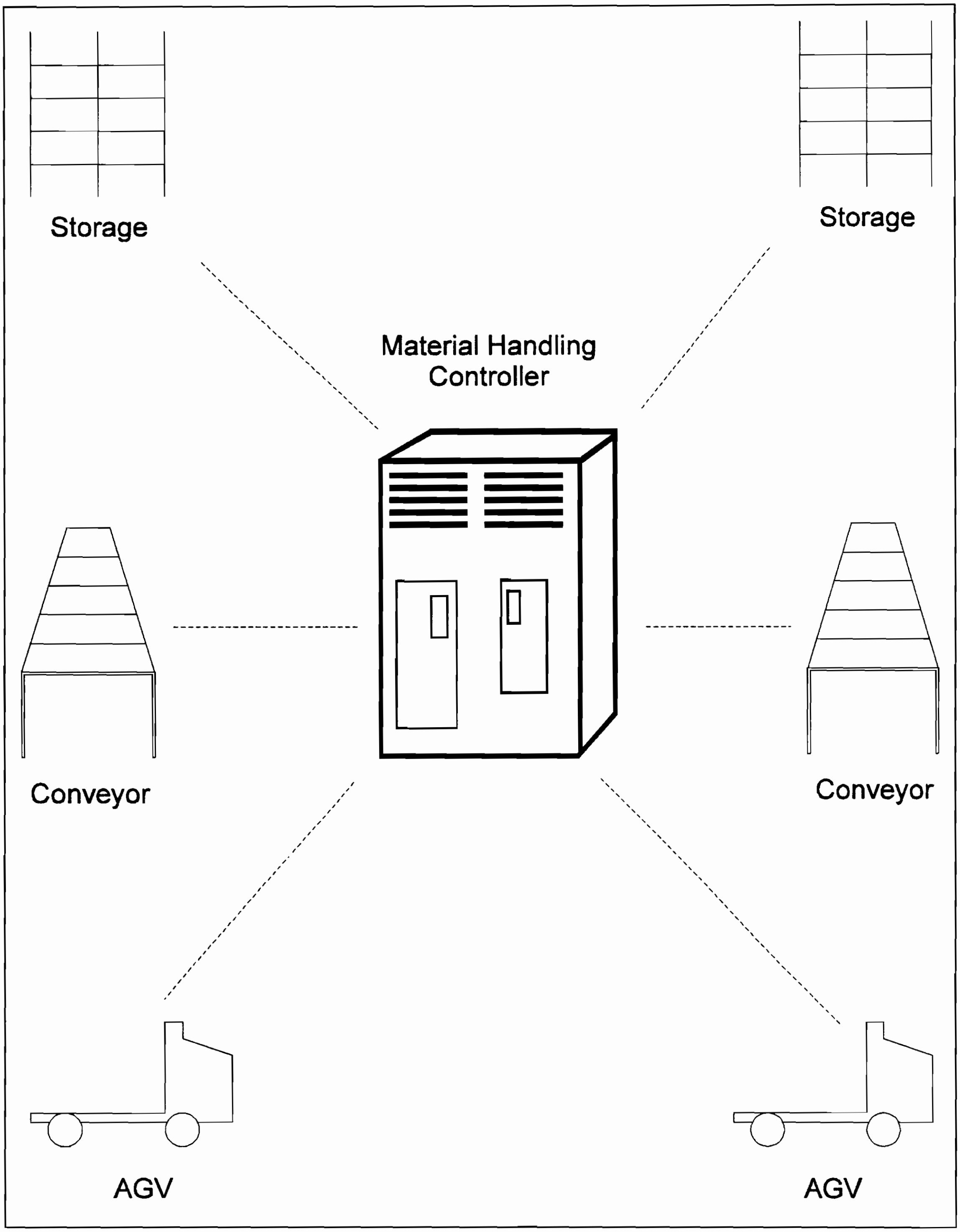


Figure 4. Centralized Processing Scheme of Material Handling System

Drawbacks of the central control led to the consideration of the hierarchical control architecture. Both Hammond and Lingren presented a similar hierarchical AGV control system model. The hierarchical control model has three levels: (1) central control, (2) floor control, and (3) vehicle on-board processor control. The central control unit serves four main functions: (i) communication, (ii) monitoring, (iii) assignment, and (iv) user interface. Communication between the central control unit and its immediate subordinates is maintained on a continuous basis in order to monitor traffic conditions, to make appropriate assignments and to generate system statistics. The floor control communicates directly with the AGVs, and other devices, such as conveyors, Automatic Storage and Retrieval System, and sensors. Other tasks at this level include assigning instructions to the vehicles, sending destination, build time and lift/low height information to the vehicles, scheduling routings, and providing collision avoidance information. It also communicates to its immediate superior, the facility's host computer, to provide feedback from the AGVs. The vehicle on-board processor control keeps track of the vehicle location, interprets commands received from the floor control (second level of control), and monitors the on-board safety devices. It also provides continuous communication with the floor control concerning whether the vehicle should continue its path. This continuous communication is designed to eliminate the risk of vehicle' collisions at crossings. Other tasks include guidance or tracking the guide-path, positioning at pick-up/delivery stations, accelerate/decelerate sequences, load detection, battery condition, and bar code reading *[Hammond86, Lindgren87]*.

Similar to Hammond and Lingren's three-level hierarchical approach, Rouse presented a four-level approach. Rouse has extracted the communication function from the central control and created a superior level above it called "the connection of the factory host" which is generally a connection to a Local Area Network (LAN). In most cases, the AGVS typically has three levels of control;

however, when the AGVS is implemented into an integrated factory, an extra level will provide a higher transparency and modularity to the system design.

Division of control in the hierarchical structure greatly limits the size and complexity of any system to manageable levels. Each level of control can operate at different time scales and be responsible for different control decisions. This allows the system to handle an enormous amount of static and dynamic data *[Boyd91]*. Division of control also decreases the planning horizon as the instructions pass down the hierarchy. Thus, it allows the lower level of the hierarchy to be more responsive and approaches real-time performance. Other significant advantages include gradual implementation, redundancy, and reduced software development. Hierarchical control architecture does not commit itself to a single, expensive cental unit; depending on the current control requirements, other layers of control can be added to the architecture incrementally *[Albus81, Groover87, Duffie88]*.

Some practical design constraints with the hierarchical control approach are computational limitations of local controllers and inter-level communication links failure. In case of inter-level communication links failure such as, local controllers cut-off from directing supervisor, which will result in a virtual and almost immediate shut-down of the system. The higher up the link failure, the greater the number of lower level controllers that will be disabled. The structure of a hierarchical control system also constrains the flow of information from one level to another and causes delays between levels of control. Therefore, control strategies are left with some insufficient, out-dated or estimated data *[Cassandras86]*. Furthermore, the hierarchical control system design is usually fixed in the early stages. For instance, when establishing relationships between levels of control, substantial knowledge among neighboring modules is required.

This module interdependence has made modification, debugging, testing, and maintenance difficult *[Duffie86-88].*

Innovations in distributed computing and communication networks have brought along a new type of control structure called heterarchical control or distributed control.

In 1986, Duffie and Piper first presented a heterarchical manufacturing cell control with dynamic part-oriented scheduling. As described in section 2.2, the heterarchical system uses intelligent manufactured parts. Part entities have knowledge about the processing that they require, while machine entities have knowledge about the processes that they can perform. Part entities broadcast the processing requirements through the system network, while machine entities simply broadcast the processing availability. When a match is found, the part entity will negotiate with the machine to establish an agreement. The part is then transported to the machine and processing begins. This research uses an open approach when integrating a material handling device into the cell control. Each material handling device, such as a robot or an AGV, is modeled as an individual system entity that participates in the negotiation/reservation process. Figure 5 shows an example of the reservation process.

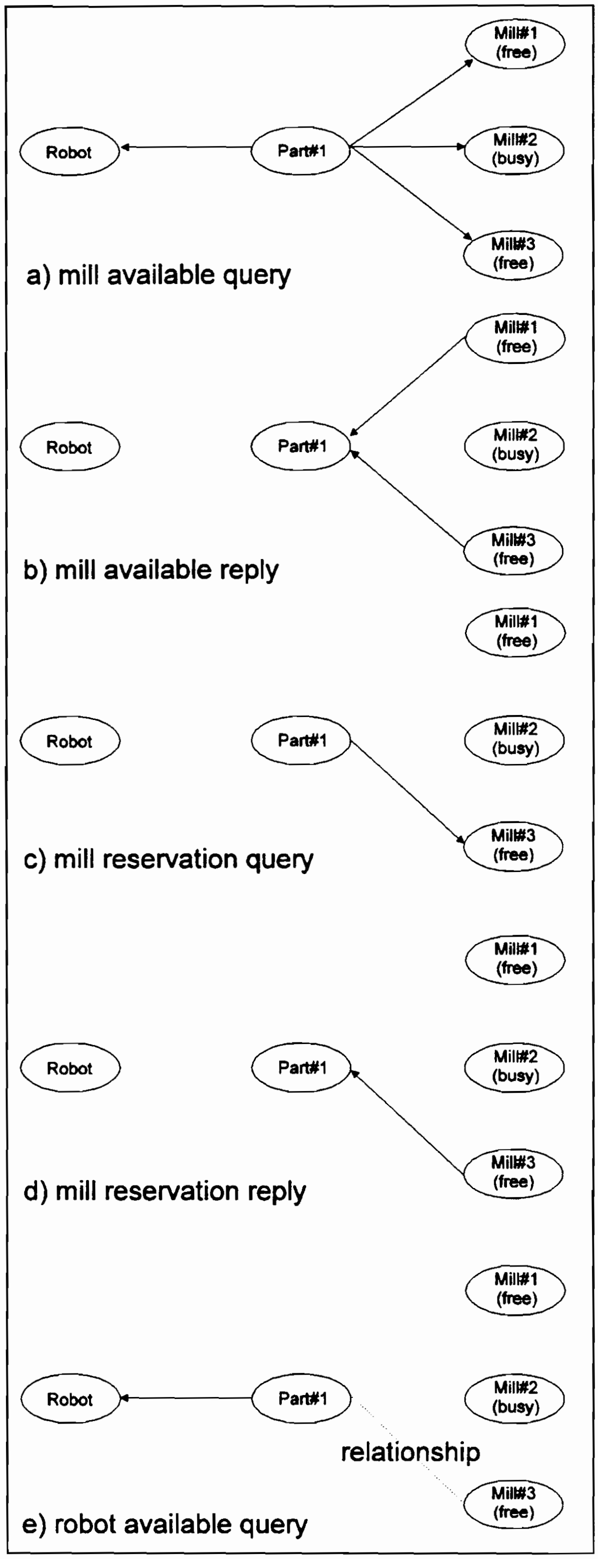


Figure 5. Reservation of a Part Processing Entity by a Manufactured Entity

Based on Duffie and Piper's approach, Maley (1980) developed a system called CADENCE (Computer Automated Distributed Environment for Network Coordination and Execution), which uses distributed decision making in managing the flow of individual intelligent parts. The purpose of the developed system is to permit fast turn around of orders for replacement parts of the company's machining equipment. In Maley's approach, an intelligent entity (part or workstation) is a dynamic information storage and processing unit. For instance, each intelligent part maintains its own quality control history, performance measures, due dates, operation requirements, and a variable process plan; whereas, an intelligent workstation stores its own NC programs, processing capabilities, historical production capacity, maintenance records and tooling management. The domain of Maley's approach is the negotiation procedure. Negotiation between parts and workstations are performed similar to an auction. However, unlike a centralized auction with a single auctioneer selling an object, the negotiation is more like auctioning multiple objects simultaneously. It is based on the contract negotiation scheme developed by Smith (1980) and a task bidding approach developed by Shaw and Whinston (1985). Maley orchestrated his own part negotiation algorithm. The algorithm has four phases: (i) posting, (ii) workstation evaluation and bid generation, (iii) part evaluation of bids, and (iv) acceptance and commitment. Through a message passing communication framework, the material transport system is integrated into the whole process. Although no conclusive evidence has proven that Maley's approach is any better than any centralized or hierarchical control scheme, there is no doubt that this negotiation algorithm has demonstrated a robust management of dynamic system operations for future distributed systems.

The only paper that this research is aware of, that explicitly compares the heterarchical system approach to the others is the one by Duffie and Piper

(1987). They found that the heterarchical approach required substantially fewer lines of code than the hierarchical or centralized approaches. This was used as a complexity indicator, and the heterarchical approach was found to be relatively less complex than the other two. The practice of full local autonomy also increases the system's fault-tolerance, because if one or more components malfunction, the rest of the autonomously functioning components should not fail. The nature of flat architecture of the approach allows easy modification and addition of new components into the system.

However, distributed control also poses a number of restrictions and problems. When a variety of peer control component computers are employed, hardware and software incompatibility issues arise. They include differences in internal formatting, differences in communication protocols, and incompatibilities in operating systems, file servers, and database systems *[Stanvokic84]* . Other potential problems are network capacity, response requirements, availability of commercial software, and operating systems to support the multi-tasking and cooperative environment.

Every control architecture has its own pros and cons. There is a need to develop some guidelines for choosing a control architecure. More research should also be directed at comparing and analyzing the performance of each control architecture in terms of the actual system outputs, such as throughput, job flow time and utilization.

2.4 Simulation in Manufacturing

Computer simulation is widely used in studying AGVS network design *[Anderson85, Gaskins87]*, minimizing vehicle fleet size *[Maxwell82]*, scheduling *[Egbelu84, Stankovic84, Wu89]*, and system control logic *[Gaskins89]*. It allows the construction of complex and realistic representations of actual systems. Through statistics-collection or real-time observation, great insight can be gained into the operation of the actual system *[Benjaafar92]*.

Simulation studies are usually done using a high level programming language, a general purpose simulation language or a simulator. General purpose simulation languages such as SLAM *[Pegden86]*, GPSS *[Schriber74]*, SIMAN *[Pegden82]* and SIMscript *[Russell83]* are used to model most manufacturing systems and generally include features for specific manufacturing characteristics; whereas a manufacturing simulator is a computer software package created using a general purpose simulation language, designed to simulate a system contained in a specific class of manufacturing systems with little or no programming. In general, manufacturing simulators are usually used for one of the two purposes: (I) to evaluate the impact of a modification to the manufacturing system such as the addition or deletion of a machine tool and (II) to study how a given control strategy affects the performance of the system *[Chry88]*. The commercial simulators are probably the easiest to use and yield fastest results, but they are least flexible and unable to model complex systems. A review of an exhaustive list of nineteen simulation packages based on various general purpose programming languages can be found in Khan (1991).

Recent researchers have also turned to artificial intelligence techniques to deal with hueristic-based and complex manufacturing problems. Examples of these general purpose intelligent simulation systems are ROSS *[Faught80]*, KBS *[Husain89]*, and FACTOR *[Peterson89]*. A number of researchers, Floss and Talavage (1990), Shodhan (1989), and Mellicamp and Wahab (1987), have also proposed some domain-specific systems that are developed in the area of manufacturing systems (mainly in FMS) design and control *[Benjaafar92]*. Instead of using developed simulation systems, there are also some artificial intelligence languages available, particularly Object-Oriented Programming (O-OP) language. Examples of O-OP languages are SIMULA *[Birtwisle87]*, SMALLTALK *[Goldberg84]*, and C++.

This simulation study emphasizes modeling the interactions among the decision-making functions of the AGVS controller. It is much easier to model the system in a high level programming language than a general purpose simulation language. Most general purpose simulation languages focus upon modeling the job-related entity flow through enhanced stochastic queueing networks *[Davis93]*. This study is more interested in modeling the decision flow within the control system. Performance of the job-related entites is an effect of the decision-making properties of the control system.

2.5 Summary

Control architecture is the infrastructure of control systems. The majority of the studies in control architecture have been performed in the area of Computer-Integrated Manufacturing (CIM) and Flexible Manufacturing Systems (FMS). There are three types of control architectures: (1) centralized, (2) hierarchical, and (3) heterarchical (decentralized or distributed).

Most studies on AGVS design do not address the issue of AGVS control architecture. There has only been one published research article that compares the heterarchical approach to the centralized and the hierarchical *approach [Duffie87]* . There is a need to develop some guidelines for choosing a control architecture. More research should also be directed at comparing and analyzing the performance of each control architecture in terms of the actual system outputs, such as throughput, job flow time or utilization.

Simulation in manufacturing can be accomplished through existing simulation languages such as SIMAN and SLAM, or artificial intelligence languages such as LISP, or high level programming languages such as Fortran and C. Depending on the objective of the simulation, different approaches can be used. This simulation study is interested in modeling the decision flow of the system rather than the job-related entity flow. Therefore, it is much simplier to model the system using a general purpose programming language than using a simulation language.

CHAPTER III
SIMULATION STUDY AND EXPERIMENTAL PROCEDURES

3.1 Problem Definition

The purpose of the simulation study is to characterize the behavior of the AGVS under the impact of different types of control architecture. Three simulation models have been constructed. They are: (1) centralized AGV control system model, (2) hierarchical AGV control system model, and (3) heterarchical AGV control system model.

3.2 System Definition

The models of the AGV control system have been kept fairly simple to help focus on the problems under consideration and reduce the possibility of "noise" in the experimental results. Each simulation model contains two major parts: (I) AGVS controller and (II) shop floor controller. The following sections describe the two controllers, and Figure 6 shows the basic representation of the simulation models.

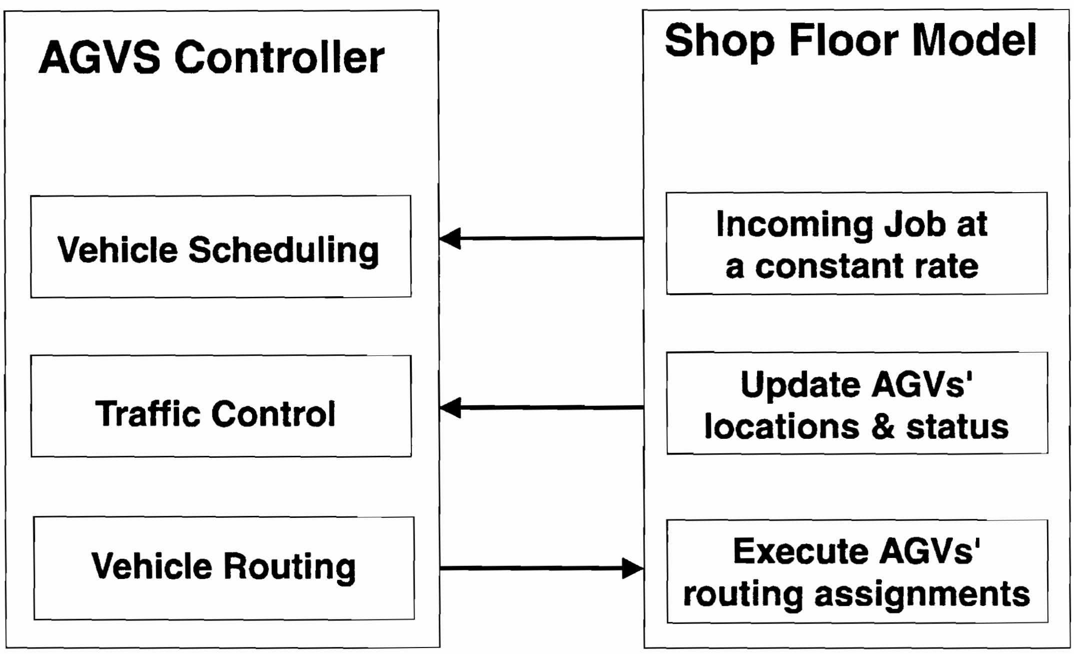


Figure 6. Representation Scheme for the AGVS simulation models.

3.3 AGVS Controller

The AGVS controller provides three basic AGVS functions. They are (i) vehicle scheduling, (ii) vehicle routing, and (iii) traffic management. The three functions are constructed to interact according to the nature and characteristics of each control architecture.

The AGV controller uses a set of two dispatching rules to accomplish the vehicle dispatching requirements of an AGV based material handling system *[Egbelu84b]*. This study employs the modified first-come-first-serve dispatching rule, and the nearest vehicle rule throughout the three simulation models.

The traffic management module monitors the traffic conditions on the shop floor, and maintains a collision-free traffic flow in the system. It communicates with the shop floor controller continuously at regular intervals to update the locations and the states of the vehicles. The shop floor controller implements a zone traffic control technique. Based on the traffic information collected by the traffic management system, the routing module issues the shortest path for the vehicle to deliver its service.

3.4 Shop Floor Controller

All three models use two identical floor plans in the simulation study. The floor plans are comprised of non-identical workstations, a station for pallet loading and unloading, and a vehicle docking area. The small configuration layout has four work stations, while the large configuration layout has twelve work stations. The work stations are served by a fleet of identical AGVs. The floor layouts are designed such that AGVs are only permitted to travel in a single direction, except for the drop-off and pick-up sections. The objective of using two distinctly different (number of workstations) floor plans is to examine the performance of different control architectures as the system's size increases. Figures 7 and 8 show the two floor plans.

Jobs arrive at the system at a constant rate. They enter into an input queue accordingly and wait at the load/unload station. The jobs in the queue are served on a first-come-first-serve basis. Each job has its own process plan. For example, job 1 is to be processed by machine 1, and 2 sequentially. When job 1 enters into the system, an AGV is requested to travel to the input queue and transport the job to machine 1. If exactly one AGV is available, it is assigned to the job immediately. However, if more than one vehicle is qualified for the job, the vehicle scheduler selects the nearest vehicle (shortest travel distance) for the task. If no AGV is available, the job remains in the input queue and waits for the next available AGV. If no job is waiting in the queue, the idle AGVs travel empty back to the docking station.

When a job is delivered to the machine, it first enters into the work station's input buffer. If the machine is ready to process a new part, the job proceeds for processing. Otherwise, the job remains at the input buffer until the machine is ready. Following processing at the first machine, the job moves to the output buffer of the work station and signals the system control for the next machine availability. When processing at the first machine is completed and the second machine is free, the job requests an AGV. Otherwise, the job remains at the output buffer and waits until the next machine is available. The procedures continue in the same manner, until all processes are completed, and the finished part returns to the load and unload station. The routing and processing times of

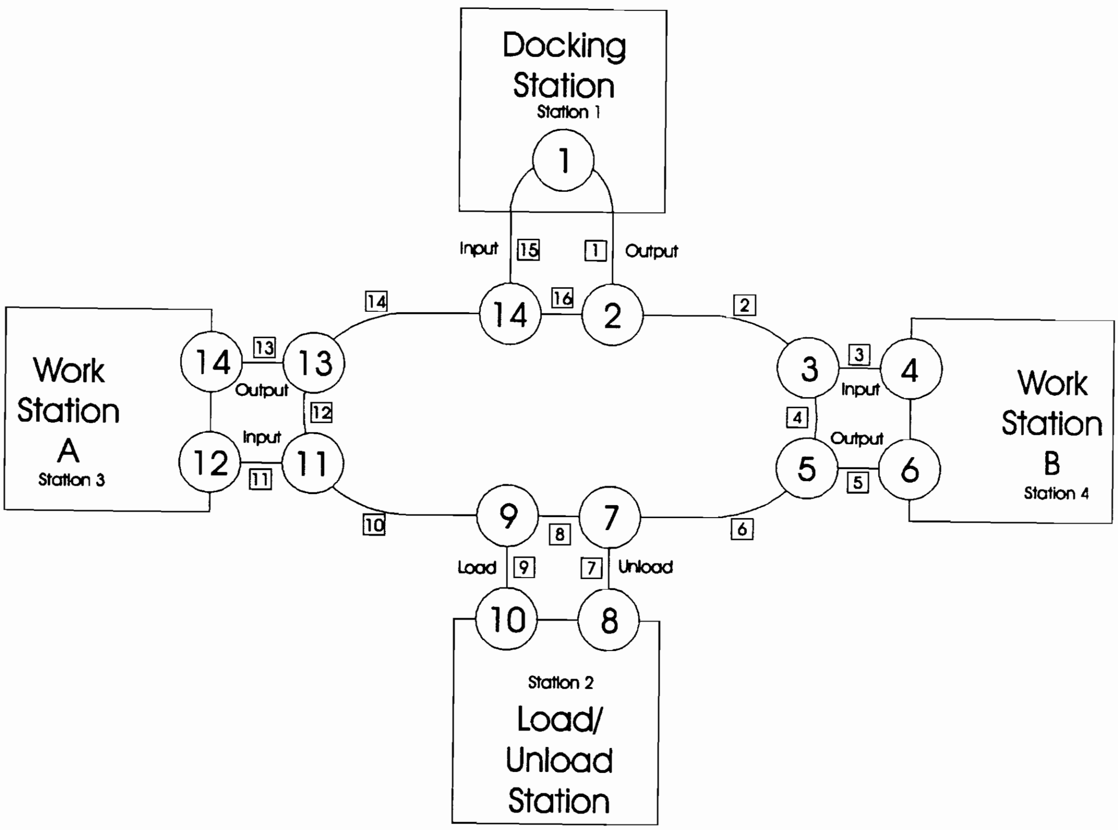


Figure 7. Shop Floor Layout -- Small Configuration

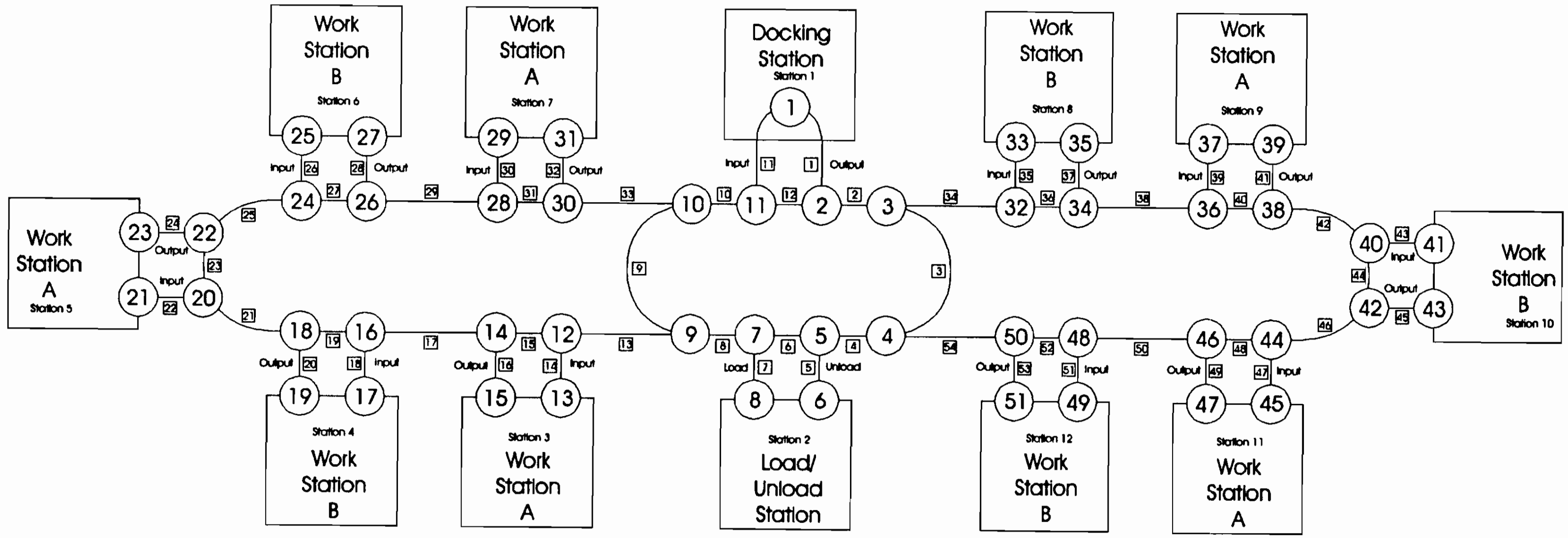


Figure 8. Shop Floor Layout -- Large Configuration

each job type are predetermined. Table 1 shows the routing matrix used in the two shop floor layouts. Tables 2 and 3 show the distance matrices used in the models.

Other important assumptions used in the simulation models:

1. Each job that enters the system is composed of only one part.
2. Each job type has a unique route defined by its technological requirements. All jobs belonging to the same type follow identical routes.
3. Vehicles in the system are a single unit load carriers, and each job requires one vehicle.
4. Jobs entering to the system are instantly released into an input queue at the load/unload station.
5. Jobs arriving at the work station are released to the machine input queue and are processed in a FCFS order.
6. Finished processing jobs are released to the output queue for the vehicle to pickup.
7. Vehicles are moving at a constant speed, no acceleration or deceleration is allowed.
8. Fixtures, pallets, tools, and load / unload stations are not limited resources.

Table 1. Routing Matrix for both shop floor configurations.

	Routing Sequences	
Job Type	Station #	Station #
1	3	Load/Unload Station
2	4	Load/Unload Station
3	5	Load/Unload Station
• • •	• • •	• • •
8	10	Load/Unload Station
9	11	Load/Unload Station
10	12	Load/Unload Station

Note: Each job type is processed by one work station and then returned to the Load/Unload station. The small system configuration uses job types 1 and 2. The large system configuration uses job types 1 through 10.

Table 2. Distance (feet) Matrix for the Small Shop Floor Configuration.

	Docking Station	L/U Station	Station A	Station B
Docking Station	0	10	50	100
L/U Station	110	0	40	90
Station A	65	75	0	45
Station B	30	40	45	0

Table 3. Distance (feet) Matrix for the Large Shop Floor Configuration

Station #	Dock	L/U	3	4	5	6	7	8	9	10	11	12
Dock	0	30	50	65	75	85	100	25	40	50	60	75
L/U	30	0	25	40	50	60	75	50	65	75	85	100
3	75	100	0	20	30	40	55	95	110	120	130	145
4	60	85	105	0	15	25	40	80	95	105	115	130
5	50	75	95	110	0	15	30	70	85	95	105	120
6	40	65	85	100	110	0	20	60	75	85	95	110
7	25	50	70	85	95	105	0	45	60	70	80	95
8	100	75	95	110	120	130	145	0	20	30	40	55
9	85	60	80	95	105	115	130	105	0	15	25	40
10	75	50	70	85	95	105	120	95	110	0	15	30
11	65	40	60	75	85	95	110	85	100	110	0	20
12	50	25	45	60	70	80	95	70	85	95	105	0

3.5 Model 1 -- Centralized AGV Control System

Model 1 represents a typical centralized control AGVS. It is designed to retain the inherent single and complete centralized information and decision making properties of the centralized control architecture. The model has a central controller that is responsible for vehicle dispatching, routing, and traffic control. The vehicles receive and execute all routing instructions from the central control unit. The master/slave relationship is simulated by limiting the message passing only between the central control unit and the AGV. No peer-to-peer (vehicle to vehicle) messaging is allowed. Inputs into the central controller are job requests, vehicle locations and vehicle states. Outputs to the vehicles are assigned destination, route information, and traffic control instruction. Figure 9 shows a representation of the proposed centralized AGV control system. Figure 10-13 shows the information flow among the functions of the model.

Incoming jobs, local transportation requests, vehicle locations and vehicle status are input into the central controller at a regular interval. Job requests generated from the shop floor model enter into an input queue and wait for the controller to schedule the next available vehicle for service. The vehicle scheduler uses a first-come-first-serve strategy to draw the first job at the input queue. Then it schedules the job to the next available vehicle based on the shortest travel distance rule. The vehicle's information (location and status) is updated to the traffic control bulletin board to provide the necessary information for the routing module to allocate an appropriate path or the shortest path for the vehicle. After the appropriate route has been determined, the central controller sends the dispatching information (destination and route instructions) to the assigned vehicle.

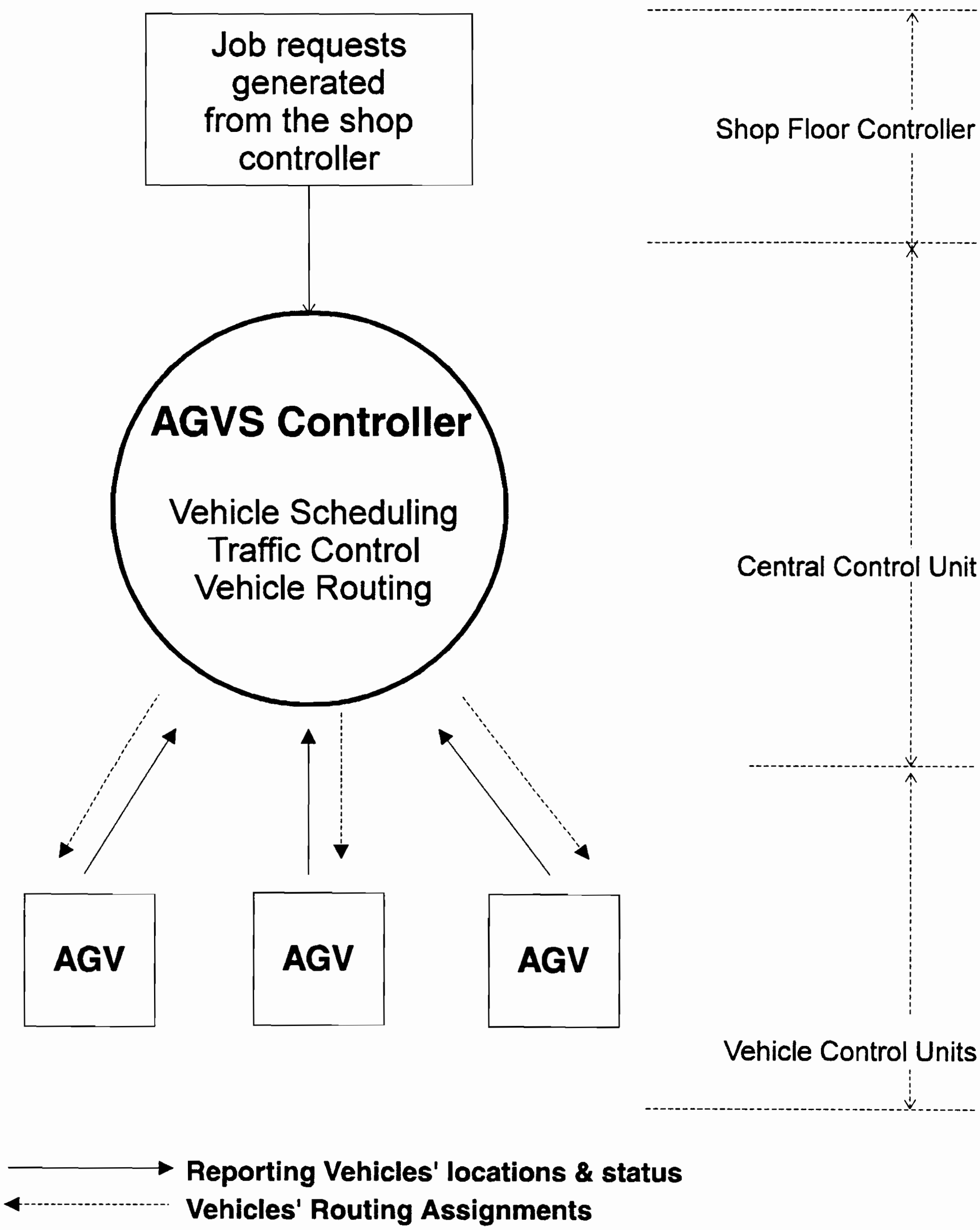


Figure 9. Model 1 -- Centralized AGV Control System.

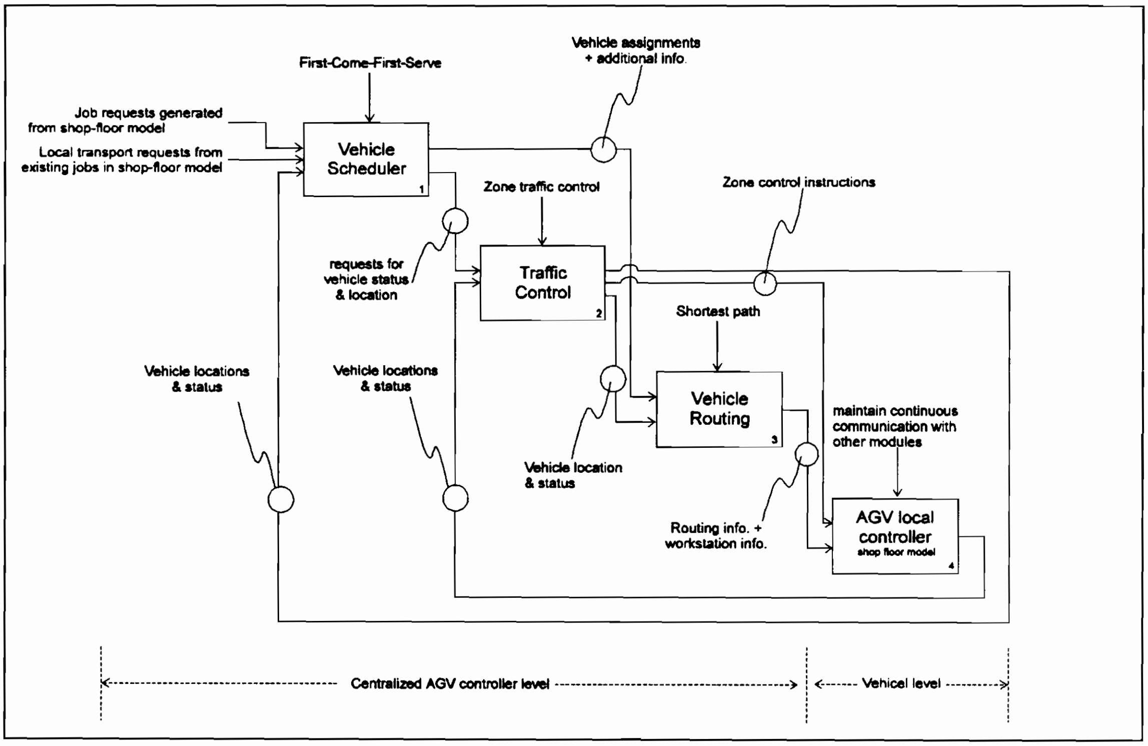


Figure 10. Information flow diagram 1 of the centralized AGVS model.

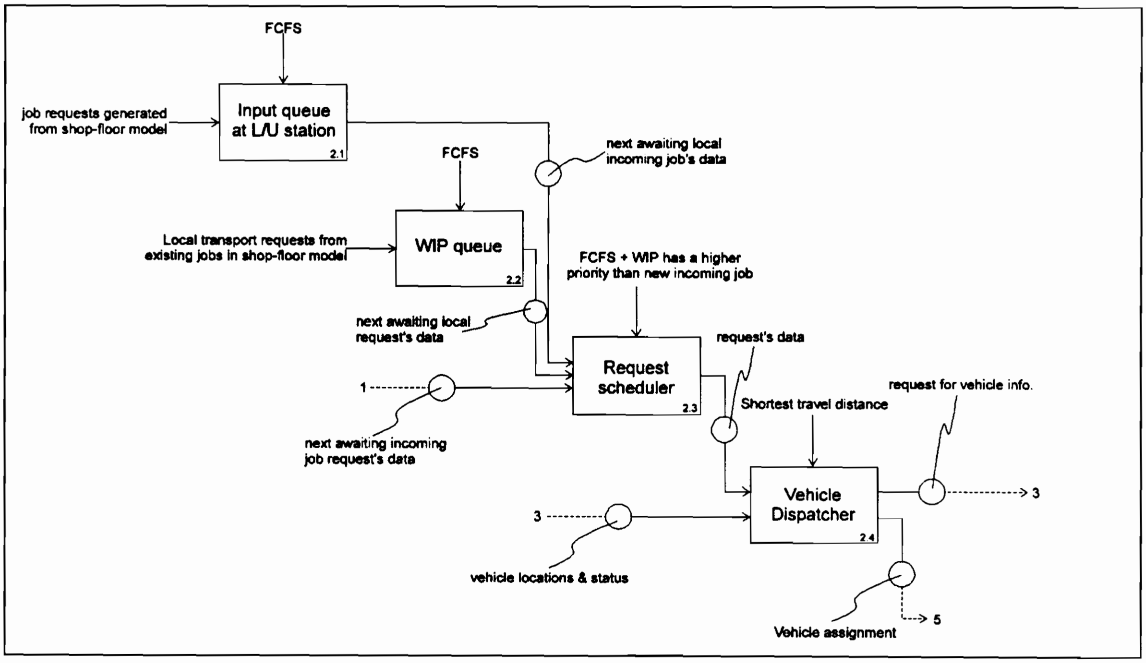


Figure 11. Information flow diagram 2 of the centralized AGVS model.

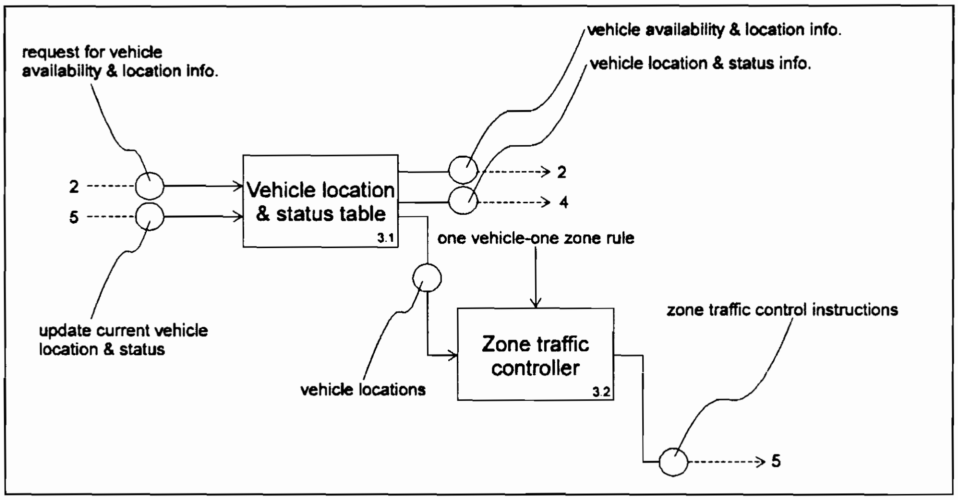


Figure 12. Information flow diagram 3 of the centralized AGVS model.

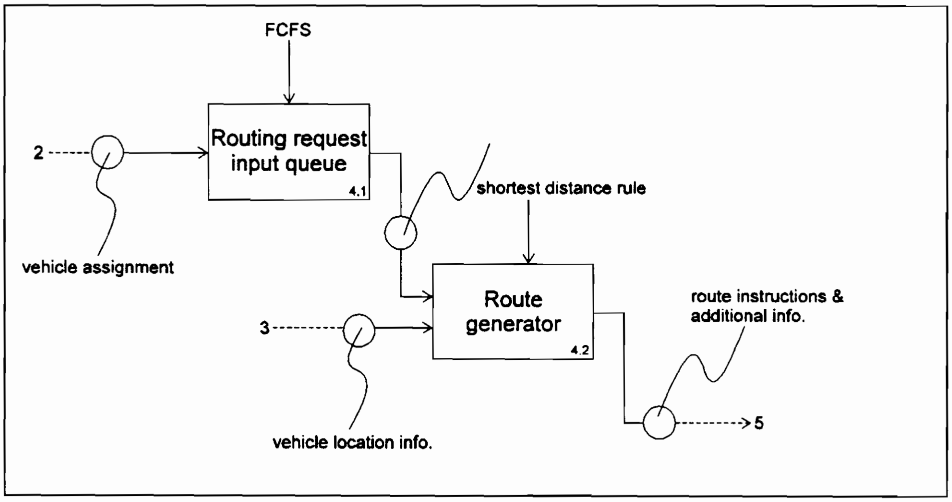


Figure 13. Information flow diagram 4 of the centralized AGVS model.

Another function for the traffic control component in the central controller is to monitor the traffic conditions in the shop floor model. The traffic management system uses a centralized zone traffic control technique to ensure a collision free traffic flow of vehicles on the shop floor.

At the central controller level, the traffic management system allows only one vehicle in a given zone at a time. If a vehicle is about to enter an occupied zone, the central controller sends a signal to the vehicle and instructs it to stop. When the zone is clear, the central controller will send a message to the vehicle to proceed.

3.6 Model 2 -- Hierarchical AGV Control System

Model 2 represents a common three level hierarchical control AGVS. The top level consists of a single central control unit; however, different from model 1, this central control unit is only responsible for vehicle dispatching, and system interface. Job requests generated by the shop floor controller enter into the input queue of the central control unit for dispatching. The dispatching module resides in the central control unit and draws the first job at the input queue using first-come-first-serve strategy. It assigns the next available vehicle to the request based on the shortest travel distance dispatching rule. The vehicle assignment is then passed on to the second level of control to determine the vehicle routing information.

The second level is the floor control unit. It is responsible for traffic management and vehicle routing. Each of these functions performs separate duties and does not share any information at a peer-to-peer level. Both functions report directly to the central control unit to ensure the immediate supervisor has complete control over its subordinates. The traffic management module performs two main functions at this level. First, it acts as a channel to receive information from the vehicle control level, and process and pass the information upward to the central control unit. The second function of the traffic management module is to maintain collision-free traffic flow on the shop floor. Another important function performed at this level is the routing control. The vehicle routing module receives the vehicle schedule from the central control unit and automatically generates the shortest path for the assigned vehicle to reach its destination. It then passes the routing instructions to the assigned vehicle.

The lowest level, or the vehicle control level, receives routing instructions from the vehicle routing module and executes the instructions to deliver the jobs to the right place at the right time. Vehicles at this level maintain continuous communication with the floor control units. They provide vehicle locations and status information for the levels above to make scheduling, routing and traffic control decisions. Message passing is allowed only between subsequent levels. No peer-to-peer communication is allowed. Figure 14 shows a representation of the proposed hierarchical AGV control system, and Figure 15 shows the information flow of the hierarchical model.

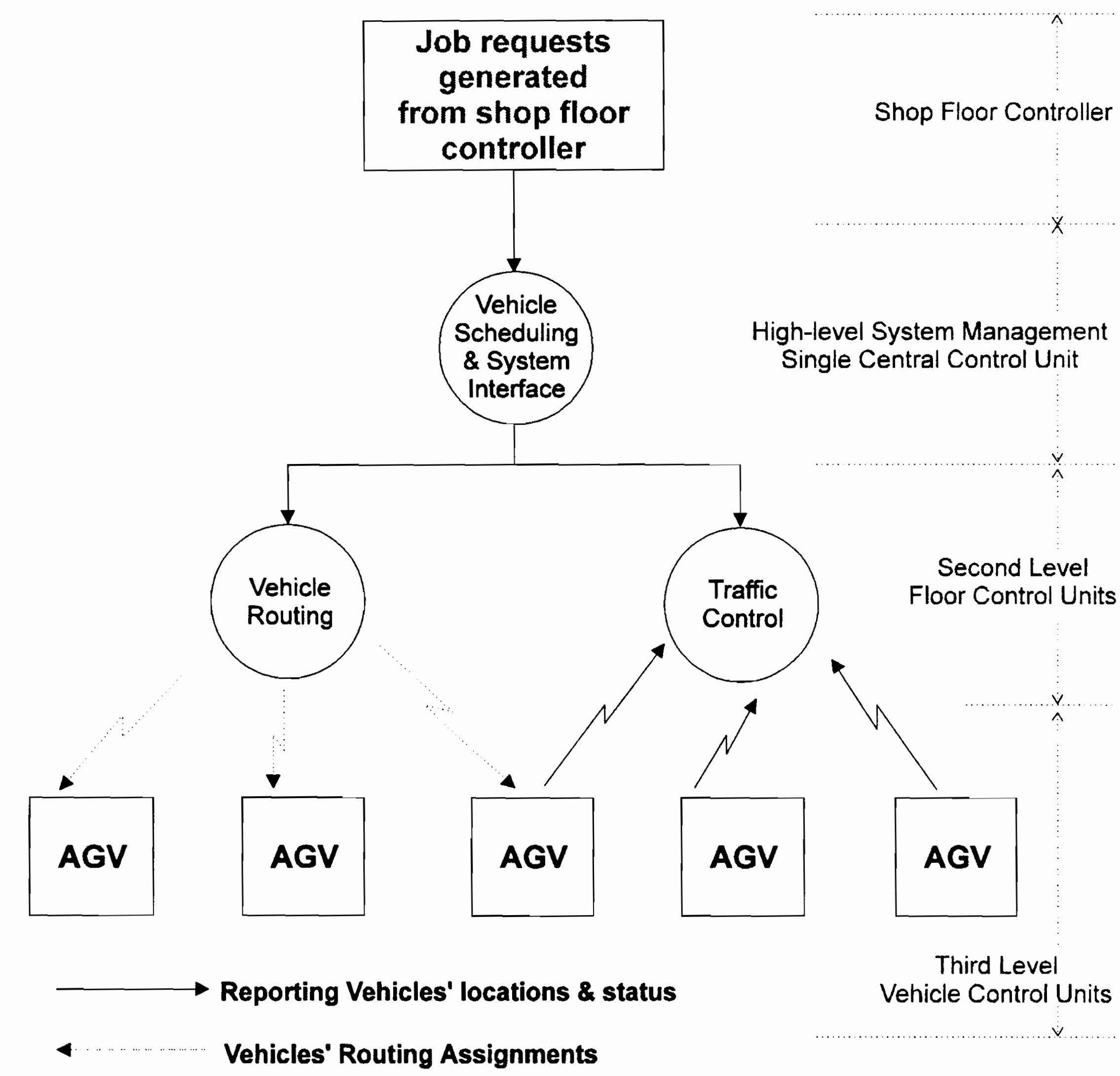


Figure 14. Model 2 -- Hierarchical AGV Control System.

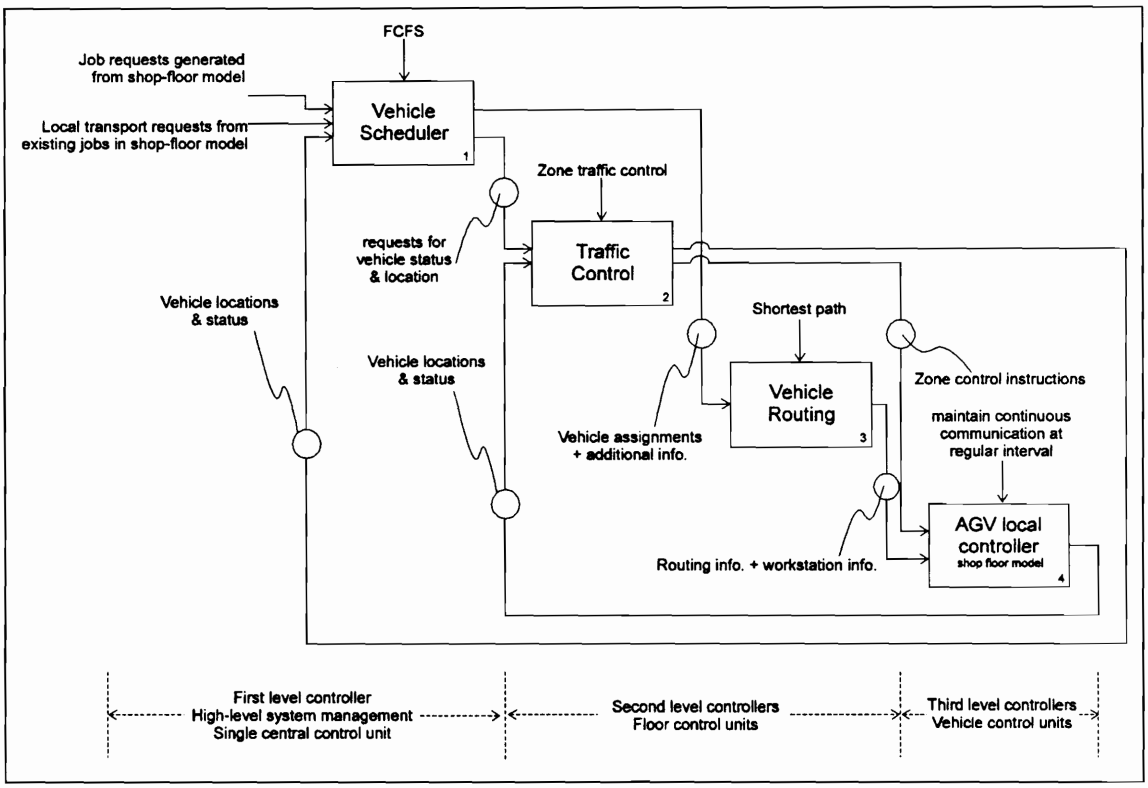


Figure 15. Information flow diagram of the hierarchical AGVS model.

3.7 Model 3 -- Heterarchical AGV Control System

This model eliminates any high level supervisory control in the system. Each AGV is modeled as an individual entity. Each has its own scheduling, routing and traffic management modules. They communicate through the bulletin board entities or directly to other vehicles. Entities included in the model are the job request bulletin, vehicle routing bulletin, traffic flow bulletin and traffic management unit.

The vehicle scheduling and routing functions employ the contract net approach. When a job request enters into the system, it enters into an input queue at the job request bulletin. The job request bulletin draws the request from the queue on a first-come-first-serve basis. It then announces the request to the vehicles. The schedule modules residing in the vehicles bid on the request by returning their locations and available times. The bulletin then assigns the request to the earliest (time) and nearest (distance) available vehicle. After the request is assigned to the appropriate vehicle, the routing module in the vehicle automatically generates the shortest path to the assigned work station. Not knowing the traffic conditions on the shop floor, the routing module sends and registers the selected path at the routing bulletin. If a conflict occurs, the routing module simply compromises with the conflicting vehicle by stopping to avoid collision. All vehicles in the system maintain continuous communication with the traffic flow bulletin. They constantly report their locations and status to the bulletin. The traffic control unit examines the vehicle routes via the traffic flow bulletin at close interval. If a vehicle is found to enter an occupied zone, the traffic control unit will issue a message to stop the vehicle. When the zone is free, the traffic control unit will issue another message and allow the vehicle to proceed. Figure 16 shows a representation of the proposed heterarchical (distributed) AGV control system, and Figure 17-18 show the information flow diagrams of the heterarchical AGVS model.

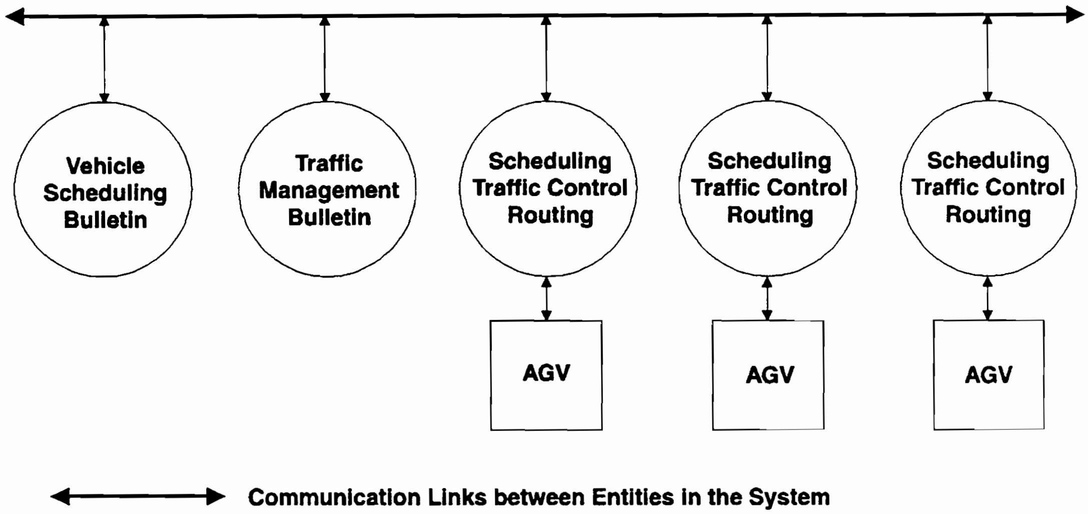


Figure 16. Model 3 -- Heterarchical (Distributed) AGV Control System.

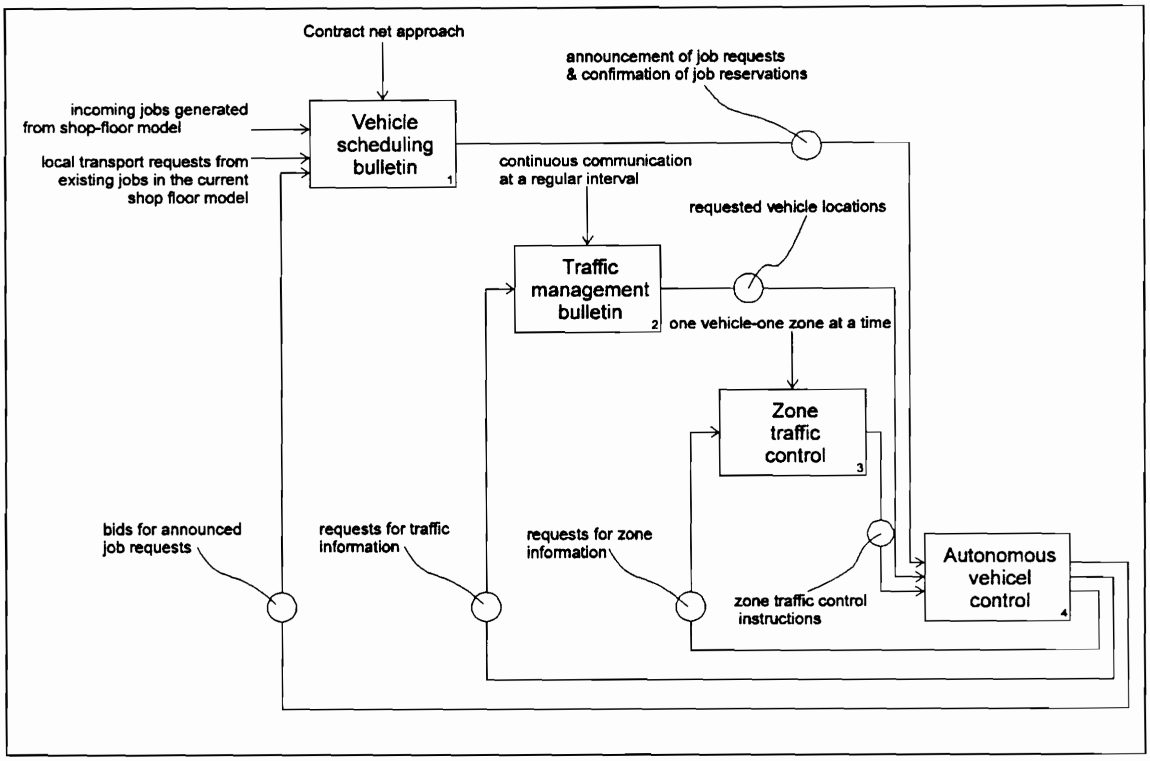


Figure 17. Information flow diagram 1 of the heterarchical AGVS model

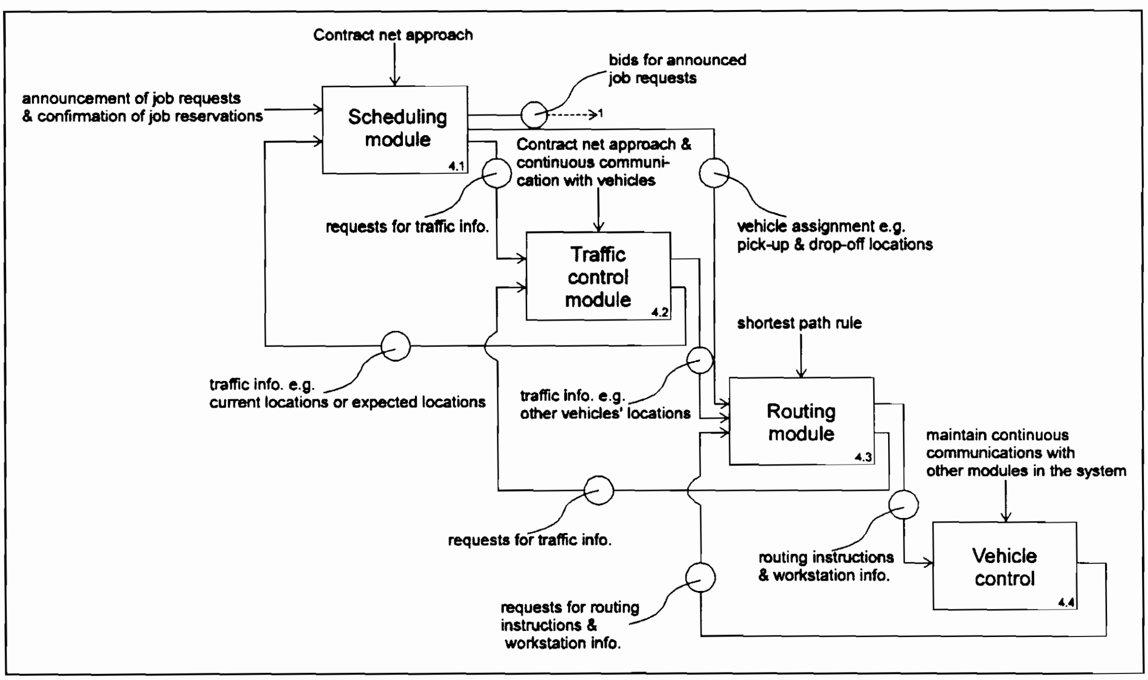


Figure 18. Information flow diagram 2 of the heterarchical AGVS model.

3.8 Performance Measures

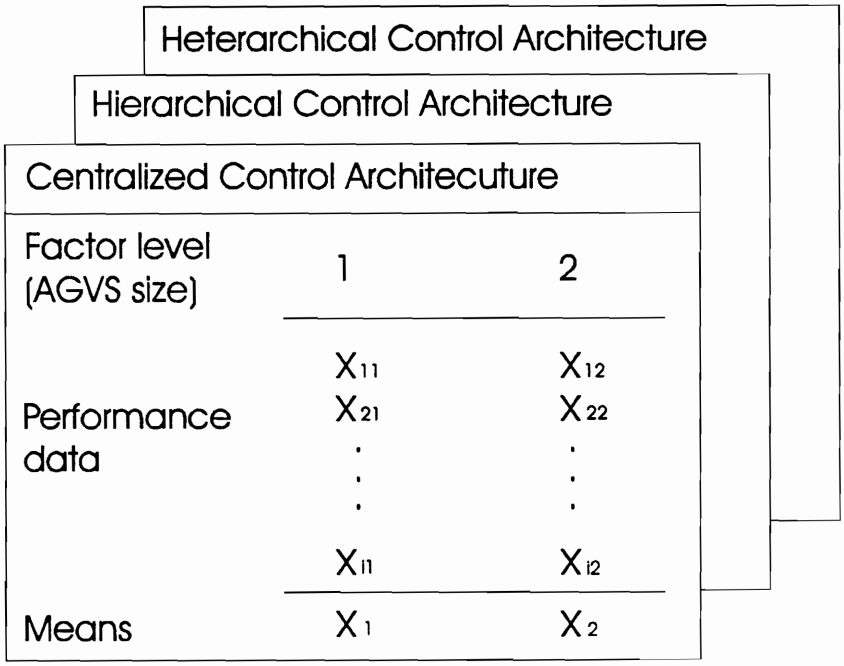
The performance measures used in the simulation study examine how well AGV control structures respond and service machines in a facility. Five performance measures are used. The first two measures, *AGV idle time* and *AGV empty-travel time*, address vehicle performance. The last four measures, *machine wait time*, *AGV wait time, job flow time*, and *throughput*, address the relative performance of the overall system.

- AGV idle time
  - time spent waiting at the input and output buffers, and time spent waiting at the docking station.
- AGV empty-travel time
  - time spent traveling to pick up station, and docking station while AGV is empty.
- Machine wait time
  - time spent by a job in the input queue of a work center awaiting processing. It is one of the two components of waiting time.
- AGV wait time
  - the other component of waiting time, refers to the time spent by a job in the output queue of a work center waiting an AGV to transport it to its destination.
- Job flow time
  - starting from the time the job arrives at the input queue of the load/unload station until the entire job is completed and returned to the load/unload station.
- Throughput
  - the number of jobs processed through the system.

3.9 Design of Experiment

The objective of this experiment is to analyze the interactions between the control architectures and the AGVS performance. A single factor experiment is designed for each control architecture with the system size as the varying factor; in this case, the number of stations and number of vehicles in the AGVS.

There are two levels of factors in this experiment: (1) AGVS with four stations, (2) AGVS with twelve stations. The number of vehicles in the system is adjusted accordingly. Each control system model was executed in a small system configuration and in a large system configuration. Figure 19 shows the design of experiments for this simulation study. In the small system configuration, there are four stations and three vehicles. In the large system configuration, there are twelve stations and nine vehicles. Stations 1, 3, 5, 7, and 9 are identical type A workstations, while stations 2, 4, 6, 8, and 10 are identical type B workstations. These two scenarios reflect the effectiveness of each control architecture as the number of components in the system increases.



Factor Level 1 -- Small Configuration

- Four stations:
  - Station 1 -- Docking station
  - Station 2 -- Load/Unload station
  - Station 3 -- Work Station 1
  - Station 4 -- Work Station 2
- Three vehicles

Factor Level 2 -- Large Configuration

- Twelve stations:
  - Station 1 -- Docking station
  - Station 2 -- Load/Unload station
  - Station 3 -- Work Station 1
  - Station 4 -- Work Station 2

    ⋮ ⋮

  - Station 12 -- Work Station 10

  * Stations 1, 3, 5, 7, 9 are stations of the same type.

  * Stations 2, 4, 6, 8, 10 are stations of the same type.
- Nine vehicles

Figure 19. Design of Experiment for this Simulation Study.

3.10 Experimental Conditions

Classical statistical analysis has assumed that the data involved are independent. However, simulation output data are frequently correlated. If the effect of correlation is ignored, then the results can be dangerously misleading. Procedures used in calculating the auto-correlation of the simulation output data are included in Appendix A on page 84.

This simulation experiment uses the sequential procedures listed below to obtain uncorrelated batch means. By eliminating the first batch in the simulation run, the initial transient phase effect is reduced.

The sequential procedures used to obtain batch means are:

1. Fix the number of batches;
2. Select a batch size;
3. Run the simulation to generate the sample data (sample size = batch size x number of batches);
4. Find the batch means.
5. Increase the batch size until the estimated value of auto-correlation coefficient reaches 0.1 or below.

3.11 Statistical Analysis

This study employs 90 percent confidence interval procedures to compare the models with the same configuration. Based on the results from the confidence interval, one can conclude whether one model is significantly different and superior to the other model. The procedures to compute the confidence interval are included in Appendix B on page 85.

3.12 Summary

The purpose of this simulation study is to analyze and characterize the performance of different types of control architecture implemented in the AGVS. Three AGV control system models have been developed. Each model represents the structure and functions of its corresponding control architecture. Simulation of each model is divided into two parts: (1) AGV controller, and (2) shop floor controller. Both controllers were modeled in C language. The AGV controller is comprised of three basic components: (i) vehicle scheduling, (ii) vehicle routing, and (iii) traffic management. Each of these three components is modeled according to the nature and characteristics of the corresponding control architecture. The shop floor controller uses two flow path layouts. The two layouts are different in system size and number of work stations. The purpose of applying these two layouts is to examine the effect of a system's size on the performance of the control architecture. Performance measures chosen for this study are intended to reflect the responsiveness of the system and the overall system performance under the impact of different control structures.

CHAPTER IV
RESULTS

4.1 Introduction

This simulation studies the AGVS control architectures in two scenarios: (1) small system, and (2) large system. The small system has four work stations and three vehicles. The large system has twelve work stations and nine vehicles. The objective of this simulation is to determine if the system's size has an effect on the performance of each control architecture. The data from the simulation runs is displayed in a graphical form, and briefly summarized. This is followed by an analysis of the data, which includes explanations, and implications of the results.

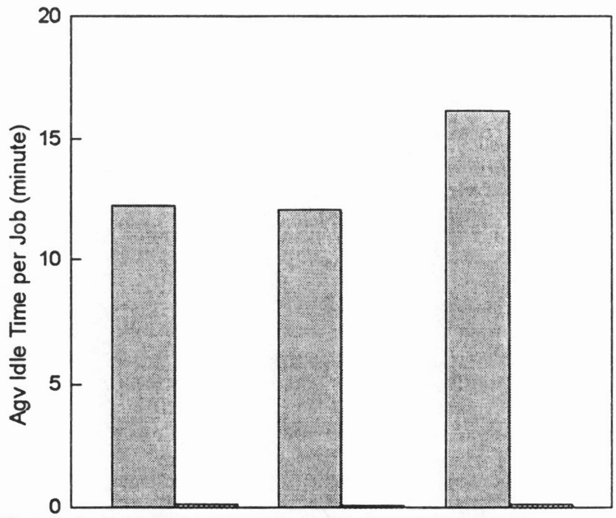
4.2 Small Systems

The small system has relatively fewer work stations and vehicles than the large system. Jobs enter into the system at a rate of 15 jobs per minute. A single run for each control system model resulted in a total of three runs. The auto-correlation among the batch means are maintained at approximately 0.1 and below. The performance of the system is summarized below in terms of the previously described measures. Figures 20 to 31 show the results of the simulation study in the small systems. Model 1 is the centralized control model; model 2 is the hierarchical control model; model 3 is the heterarchical control model. Table 4 on page 61 shows a summary of the results drawn from the difference of means between models at a 90 percent confidence interval.

4.2.1 Results

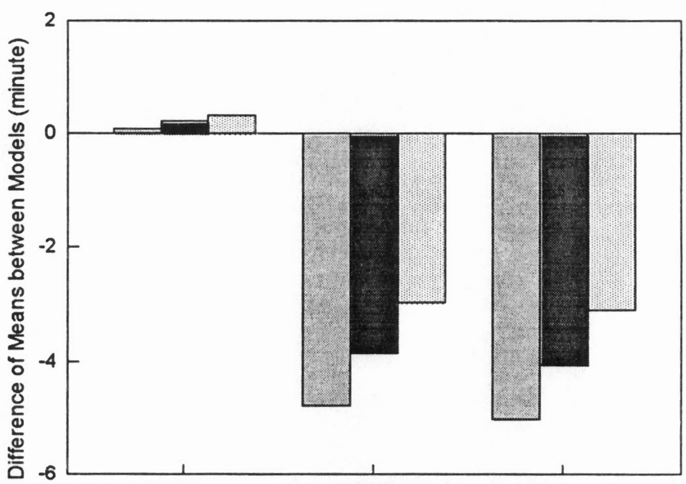
AGV Idle Time: The heterarchical control model (model 3) has a relatively higher mean AGV idle time than the centralized model (model 1), and the hierarchical model (model 2). Figure 20 shows the mean AGV idle time for the three models of the small system. Figure 21 shows the difference of means between models at a 90 percent confidence interval. Results from the confidence interval in Figure 21 show that AGV idle times of the three models are significantly different from one another. It also appears that the hierarchical model (model 2) is the superior control model in the AGV utilization, because it leads to a lower average AGV idle time (between 0.0842 to 0.3222 lower than model 1, and between 3.1086 to 5.0311 lower than model 3). Furthermore, the centralized model (model 1) is better than the heterarchical model (model 3) in terms of AGV utilization. Nonetheless, the heterarchical model (model 3) 's high AGV idle time could be an advantage for the system. The heterarchical system may be capable of performing at a higher system capacity than the centralized and hierarchical systems given the same configuration.

AGV Empty Travel Time: The mean AGV empty travel time for the heterarchical model (model 3) is approximately 40 percent lower than the means for the centralized model (model 1) and the hierarchical model (model 2).



X-Axis	Model 1	Model 2	Model 3
Mean	12.2668	12.0636	16.1335
Variance	0.1236	0.0484	0.1168

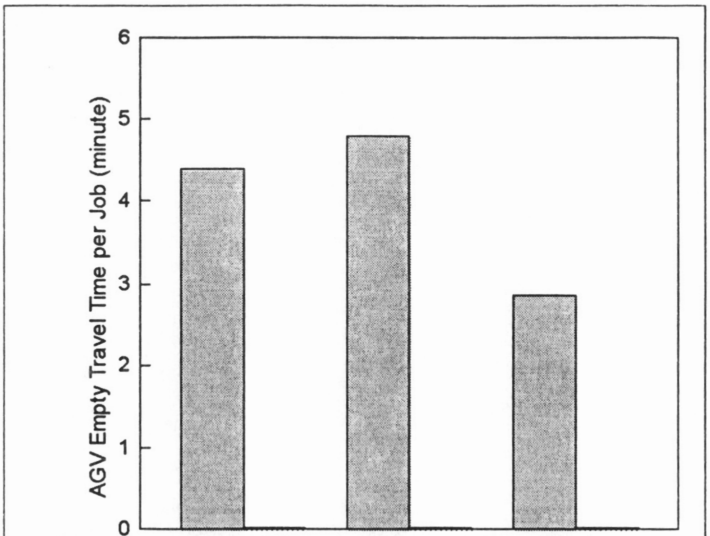
Figure 20. Mean AGV Idle Time for the Three Models in the Small System, with Batch Size=5000 and 50 Batches.



Diff.of Means	mean 1 - mean 2	mean 1 - mean 3	mean 2 - mean 3
L bound	0.0842	-4.7824	-5.0311
Mean	0.2032	-3.8667	-4.0699
U bound	0.3222	-2.9510	-3.1086

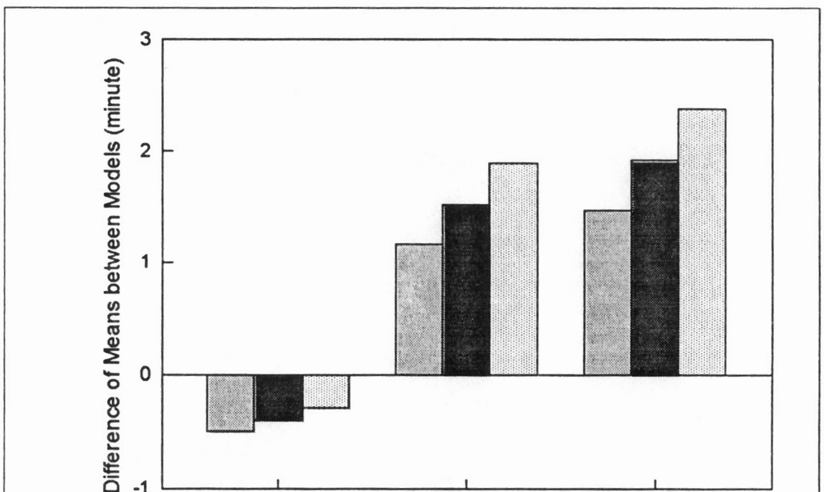
Figure 21. 90 Percent Confidence Interval for the Difference between Mean AGV Idle Times of the Three Models in the Small System.

Note: Model 1 -- Centralized Control Architecture; Model 2 -- Hierarchical Control Architecture; Model 3 -- Heterarchical Control Architecture.



X-Axis	Model 1	Model 2	Mode 3
Mean	4.3991	4.7924	2.8727
Variance	0.0291	0.0137	0.0188

Figure 22. Mean AGV Empty Travel Time for the Three Models in the Small System, with Batch Size=5000 and 50 Batches.



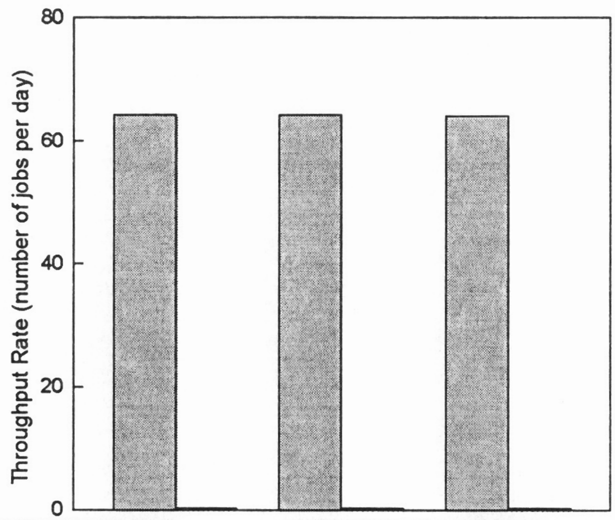
Diff.of Means	mean1 - mean2	mean1 - mean3	mean2 - mean3
L bound	-0.4958	1.1637	1.4661
Mean	-0.3933	1.5264	1.9197
U bound	-0.2909	1.8890	2.3734

Figure 23. 90 Percent Confidence Interval for the Difference between Mean AGV Empty Travel Times of the Three Models in the Small System.

Note: Model 1 -- Centralized Control Architecture; Model 2 -- Hierarchical Control Architecture; Model 3 -- Heterarchical Control Architecture.

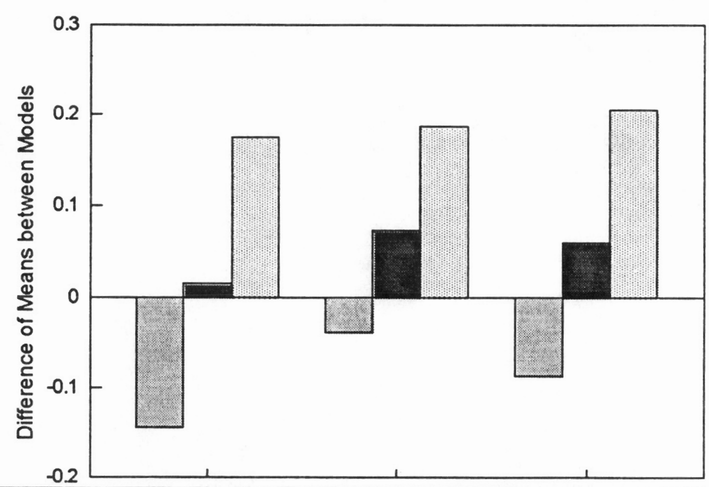
As with the AGV idle time, the AGV empty travel times for all three models are significantly different and the heterarchical model (model 3) has the superior performance from the results of the 90 percent confidence interval. Model 3 is between 1.1637 to 1.8890 minutes lower than model 1, and it is also between 1.4661 to 1.9197 minutes lower than model 2. All three models use the same job incoming rate, vehicle speed, and shop layout. Each model should yield a relatively similar travel distance. The only explanation for the significantly lower AGV empty travel time for the heterarchical model (model 3) is the efficient communication and processing properties found in its structure. The centralized and hierarchical structures predefine and limit the channels of information flow in the system. Therefore, when demand for decision processing increases, the information channels become the bottleneck of the control system. This usually results in longer processing queues and longer delays. In the heterarchical structure, each decision components, such as vehicles, dispatching entities or traffic control entities, are decentralized into several different processing units. Each processing unit has its own queue which greatly reduces the queue length and delays.

Throughput: The mean throughput rates for all three models are nearly identical. Figure 24 shows the mean throughput rate of the three models. Results from the 90 percent confidence interval in Figure 25 are inconclusive. Usually in a system free of capacity constraints, throughput is expected to be dependent only on the job arrival rate. Since this simulation uses an identical arrival rate for all three models, the throughput is expected to be similar.



X-Axis	Model 1	Model 2	Model 3
Mean	64.1606	64.1459	64.0871
Variance	0.2165	0.1673	0.1483

Figure 24. Mean Throughput Rate for the Three Models in the Small System, with Batch Size=300 and 50 Batches.



Diff.of Means	mean1 - mean2	mean1 - mean3	mean2 - mean3
L bound	-0.1444	-0.0389	-0.0867
Mean	0.0147	0.0735	0.0587
U bound	0.1739	0.1858	0.2042

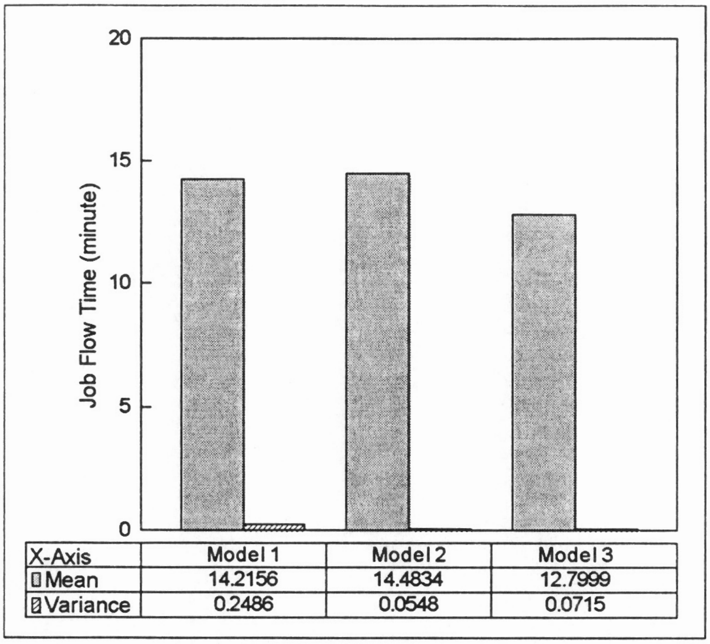
Figure 25. 90 Percent Confidence Interval for the Difference between Mean Throughput Rates of the Three Models in the Small System.

Note: Model 1 -- Centralized Control Architecture; Model 2 -- Hierarchical Control Architecture; Model 3 -- Heterarchical Control Architecture.

Job Flow Time: Among the three models, the heterarchical model (model 3) has the lowest job flow time, followed by the centralized control model (model 1), and by the hierarchical control model (model 2). The same evidence is shown in the difference of means in Figure 27. Model 3 appears to be significantly better than model 1 and model 2. It is between 1.0568 to 1.7746 lower than model 1, and between 1.2792 to 2.0878 lower than model 2. Results from Figure 27 also show that model 1 is significantly different from model 2 (between 0.1159 to 0.4197 less than model 2). One of the major variable components of the job flow time is the wait time. There are two subcomponents of the wait time which are analyzed below.

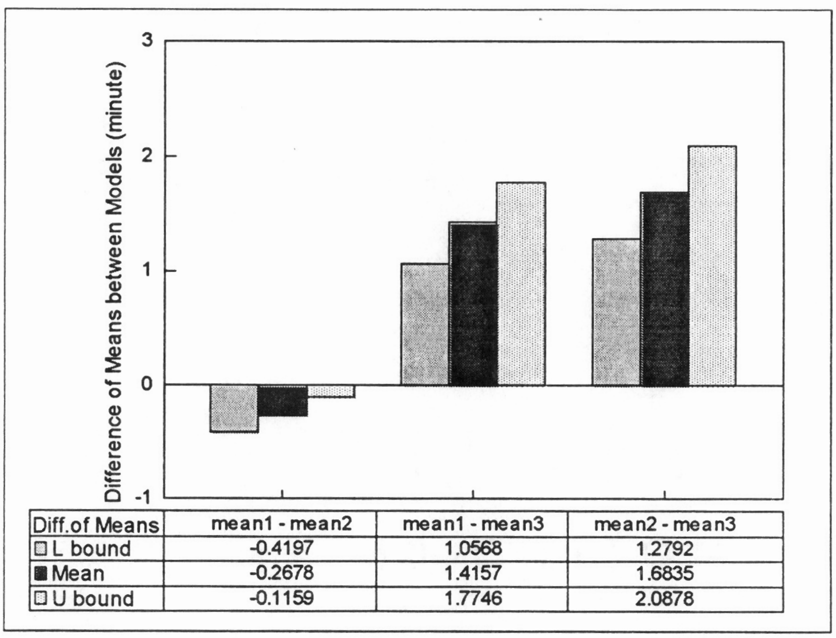
Machine Wait Time: As seen in Figure 29, the mean machine wait times between models 1 and 2 and models 2 and 3 are statistically significantly different; however, the values are so small (see Figure 28) that they are practically meaningless. A moderate job arrival rate is the major contribution to the practically insignificant machine wait time.

AGV Wait Time: The mean AGV wait times for the centralized model (model 1) and the hierarchical model (model 2) are almost identical, while the mean AGV wait time for model 3 is slightly lower. When using the 90 percent confidence interval to compare the difference of means for model 1 and model 2 (Figure 31), no explicit conclusion could be drawn. The lower bound of their difference lies on the negative side while the upper bound lies on the positive side. Therefore, one cannot draw the conclusion that model 1 is better than model 2 or vice versa. Among the three models, the heterarchical model (model 3) yields superior performance since it produces a relatively lower mean AGV wait time than the others. Model 3 is between 0.1282 to 0.3182 lower than model 1, and it is also between 0.1663 to 0.2892 lower than model 2.



X-Axis	Model 1	Model 2	Model 3
Mean	14.2156	14.4834	12.7999
Variance	0.2486	0.0548	0.0715

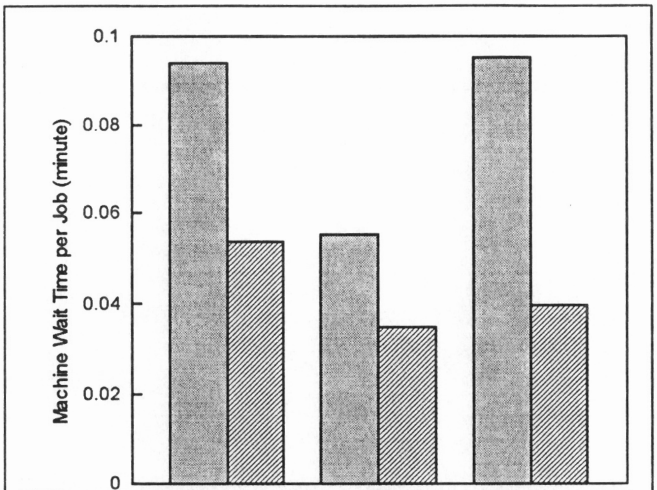
Figure 26. Mean Job Flow Time for the Three Models in the Small System, with Batch Size=5000 and 50 Batches.



Diff.of Means	mean1 - mean2	mean1 - mean3	mean2 - mean3
L bound	-0.4197	1.0568	1.2792
Mean	-0.2678	1.4157	1.6835
U bound	-0.1159	1.7746	2.0878

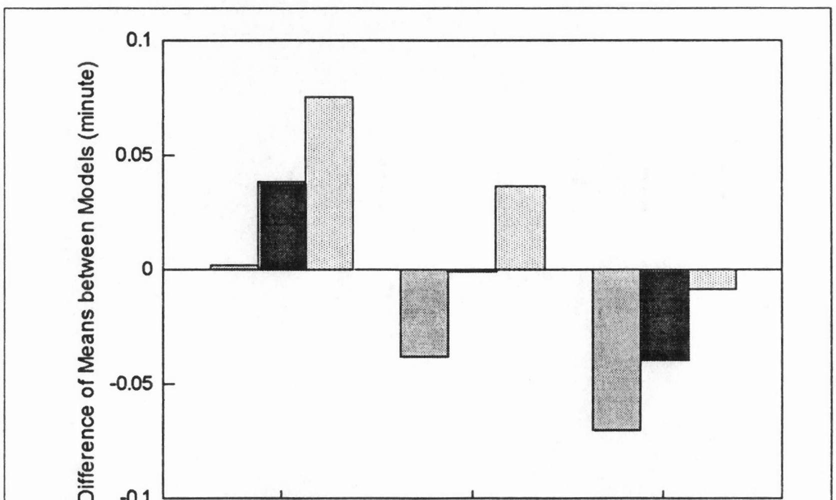
Figure 27. 90 Percent Confidence Interval for the Difference between Mean Job Flow Times of the Three Models in the Small System.

Note: Model 1 -- Centralized Control Architecture; Model 2 -- Hierarchical Control Architecture; Model 3 -- Heterarchical Control Architecture.



X-Axis	Model 1	Model 2	Model 3
Mean	0.0937	0.0554	0.0949
Variance	0.0538	0.0348	0.0395

Figure 28. Mean Machine Wait Time for the Three Models in the Small System, with Batch Size=5000 and 200 Batches.



Diff.of Means	mean1 - mean2	mean1 - mean3	mean2 - mean3
L bound	0.0017	-0.0386	-0.0703
Mean	0.0383	-0.0012	-0.0395
U bound	0.0750	0.0362	-0.0088

Figure 29. 90 Percent Confidence Interval for the Difference between Mean Machine Wait Times of the Three Models in the Small System.

Note: Model 1 -- Centralized Control Architecture; Model 2 -- Hierarchical Control Architecture; Model 3 -- Heterarchical Control Architecture.

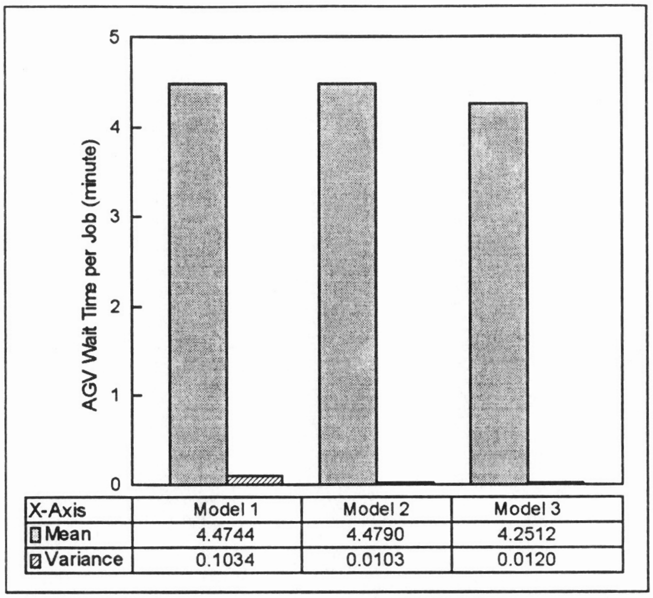


Figure 30. Mean AGV Wait Time for the Three Models in the Small System, with Batch Size=5000 and 50 Batches.

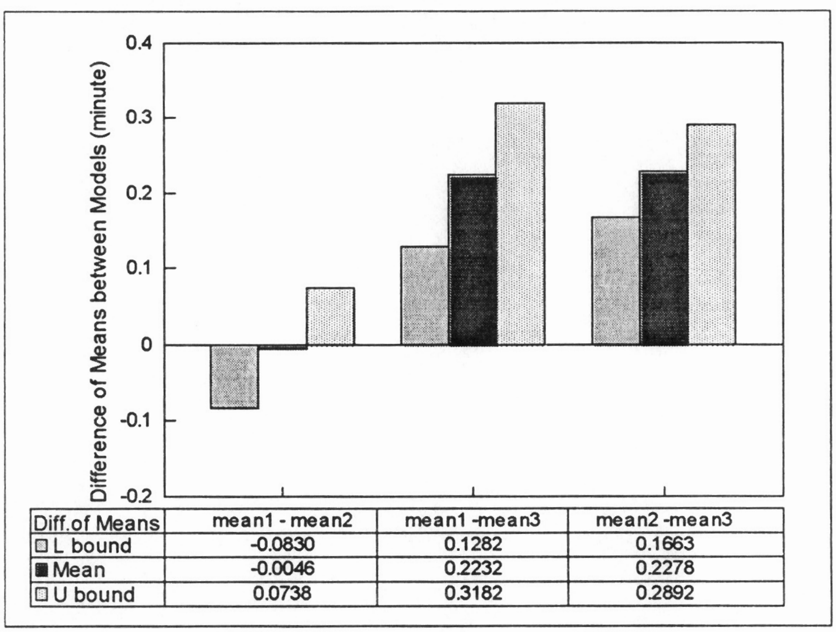


Figure 31. 90 Percent Confidence Interval for the Difference between Mean AGV Wait Times of the Three Models in the Small System.

Note: Model 1 -- Centralized Control Architecture; Model 2 -- Hierarchical Control Architecture; Model 3 -- Heterarchical Control Architecture.

4.2.2 Analysis

Among all three models tested in the small system, no one model appears to be far better than the others. All three models yield an almost identical throughput rate. The heterarchical control model (model 3) turns out to have a significantly lower job flow time than the other two models. The major variable components in the job flow time are AGV wait time, machine wait time, and the vehicle traveling time. The mean AGV wait time, and mean machine wait time for the three models are considerably alike. Thus, it appears that the vehicle traveling time in the heterarchical system is much lower than the vehicle traveling time in the centralized and hierarchical systems. This phenomenon can also be observed in the significantly lower empty travel time found in model 3.

Since all three models are studied under the same guide path layout and the system always chooses the shortest distance to travel, the actual traveling distance should remain constant. However, when the vehicles travel from one zone to another, they communicate to the controller for approval to enter into the next zone. When the controller receives the vehicle message, it processes and updates the information and sends out a signal to the vehicle. This communication handshake is greatly facilitated in the heterarchical system. Its autonomous structure decentralizes the different AGVS functional entities into individual controller units. For instance, the traffic control bulletin is specifically for traffic updates, and the dispatching bulletin is specifically for vehicle dispatching. Each functional unit has its information processing queue, and vehicles can communicate directly to each unit via the local area network. Whereas in the centralized and hierarchical models, there is a predefined hierarchy of communication channels or sometimes a single channel to process the information in the AGVS. When demand for decision processing increases, the information channels become the bottlenecks of the control system. This usually results in a longer processing queue and longer delays. Therefore, the autonomous nature of the heterarchical system can greatly reduce the processing and communication delays found in the centralized or hierarchical systems. Table 4 shows the general results drawn from the 90 percent confidence interval in this section.

Table 4. General Results drawn from the 90 percent Confidence Interval Performed on the Three Models in the Small System.

	Statistical Significant Difference?		
Models	1 & 2	1 & 3	2 & 3
AGV Idle Time	Yes	Yes	Yes
AGV Empty Travel Time	Yes	Yes	Yes
Throughput	*Inconclusive	*Inconclusive	*Inconclusive
Job Flow Time	Yes	Yes	Yes
Machine Wait Time	Yes	*Inconclusive	Yes
AGV Wait Time	*Inconclusive	Yes	Yes

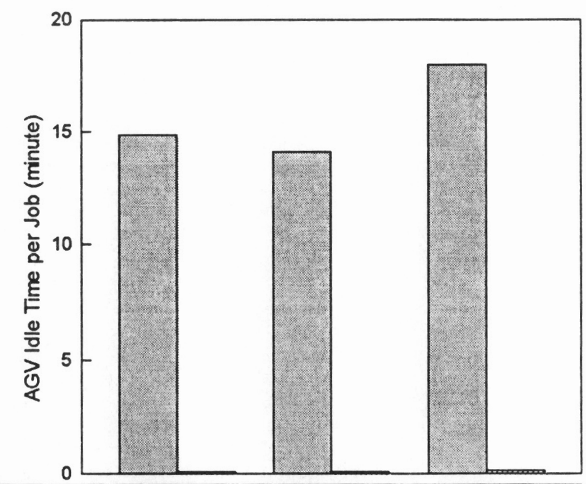
4.3 Large Systems

In the large system, jobs enter at a rate of 7 jobs per minute. A single run for each control system model resulted in a total of three runs. The auto-correlation among the batch means are maintained at approximately 0.1 and below. The performance of the system is summarized below in terms of the previously described measures. Figures 32 to 42 show the results of the large system in a graphical form. Model 1 is the centralized control model; model 2 is the hierarchical control model; model 3 is the heterarchical control model.

4.3.1 Results

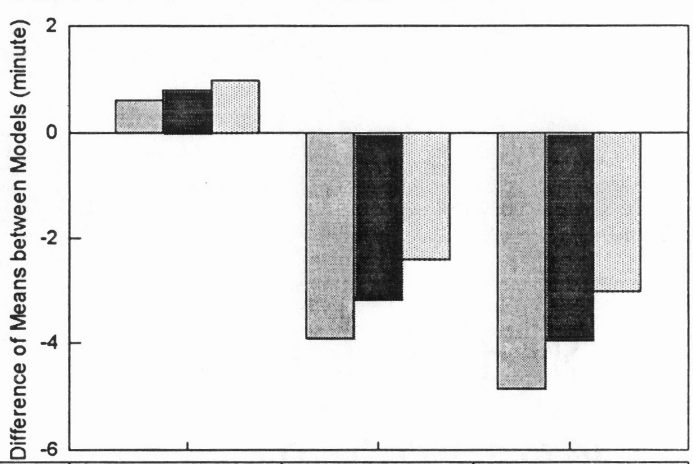
AGV Idle Time: Similar to the results found in the small system, the heterarchical model (model 3) has a significantly higher mean AGV idle time, followed by the centralized model (model 1) and the hierarchical model (model 2). At a 90 percent confidence interval in Figure 33, all three models are significantly different. Performance of model 2 is slightly ahead of model 1 since model 2 has a lower AGV idle time. Lower AGV idle time usually implies a higher AGV utilization.

AGV Empty Travel Time: As shown in Figure 34, the mean AGV empty travel times for the centralized model (model 1) and the hierarchical model (model 2) are relatively close. At a 90 percent confidence interval in Figure 35, model 1 is significantly different from model 2 by a small margin (between 0.0103 to 0.1809).



X-Axis	Model 1	Model 2	Model 3
Mean	14.8851	14.1046	18.0278
Variance	0.0797	0.0295	0.1359

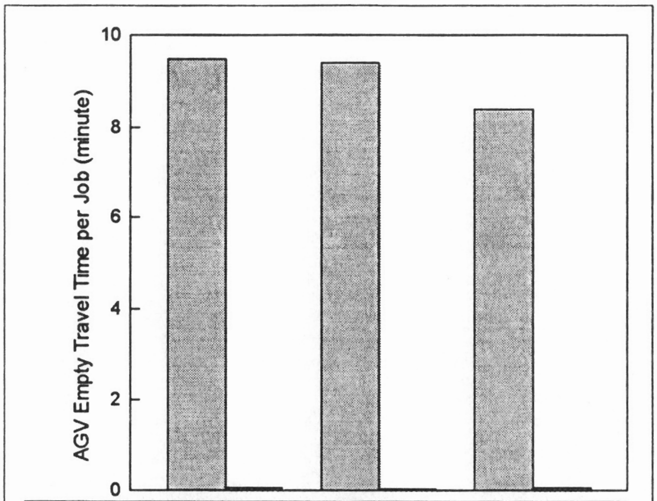
Figure 32 Mean AGV Idle Time for the Three Models in the Large System, with Batch Size=12000 and 50 Batches.



Diff.of Means	mean1 - mean2	mean1 - mean3	mean2 - mean3
L bound	0.5840	-3.8897	-4.8496
Mean	0.7805	-3.1427	-3.9232
U bound	0.9771	-2.3957	-2.9969

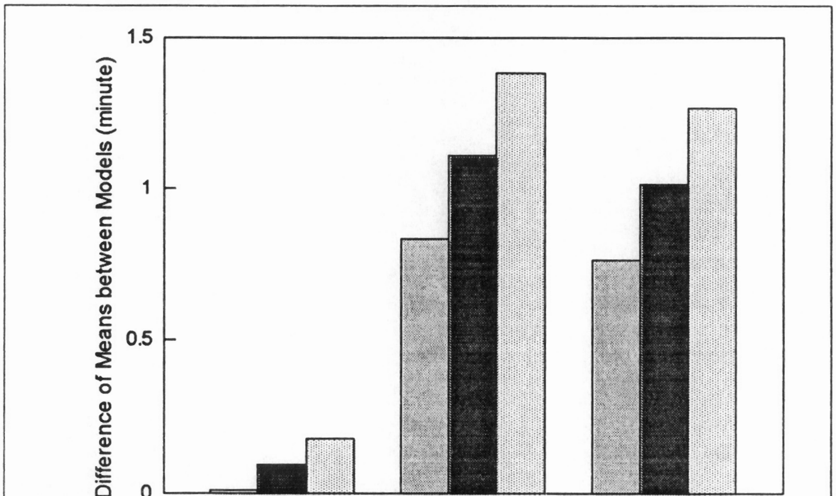
Figure 33. 90 Percent Confidence Interval for the Difference between Mean AGV Idle Times of the Three Models in the Large System.

Note: Model 1 -- Centralized Control Architecture; Model 2 -- Hierarchical Control Architecture; Model 3 -- Heterarchical Control Architecture.



X-Axis	Model 1	Model 2	Mode 3
Mean	9.4743	9.3787	8.3643
Variance	0.0742	0.0390	0.0543

Figure 34 Mean AGV Empty Travel Time for the Three Models in the Large System, with Batch Size=6000 and 50 Batches.



Diff.of Means	mean1 - mean2	mean1 - mean3	mean2 - mean3
L bound	0.0103	0.8367	0.7619
Mean	0.0956	1.1099	1.0143
U bound	0.1809	1.3832	1.2668

Figure 35. 90 Percent Confidence Interval for the Difference between Mean AGV Empty Travel Times of the Three Models in the Large System.

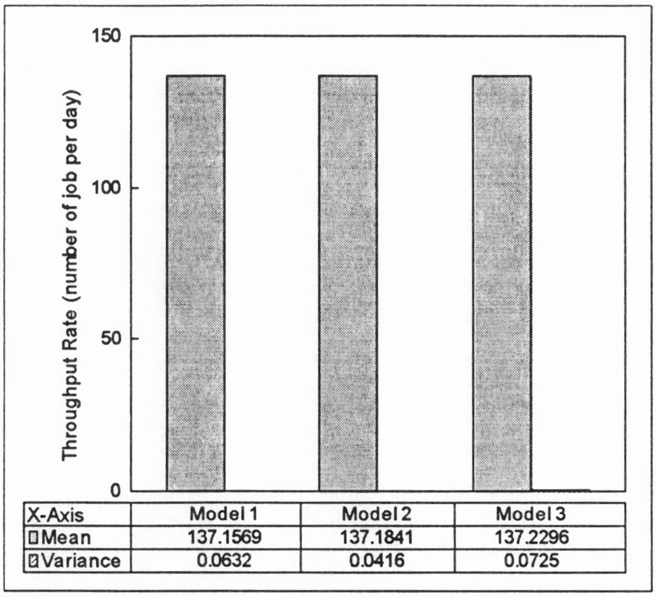
Note: Model 1 -- Centralized Control Architecture; Model 2 -- Hierarchical Control Architecture; Model 3 -- Heterarchical Control Architecture.

However, the heterarchical model (model 3) is significantly different and yields superior performance. Model 3 produces a relatively lower mean AGV empty travel time. It is between 0.8367 to 1.3832 minutes lower than model 1, and it is also between 0.7619 to 1.0143 minutes lower than model 2. As mentioned in section 4.2.2, the autonomous structure of the heterarchical control system reduces the processing and communication delays found in the AGV control system.

Throughput: As with the throughput result from the small system, the mean throughput rates for all three models in the big system are nearly identical. Results from the difference of means at a 90 percent confidence interval are inconclusive.

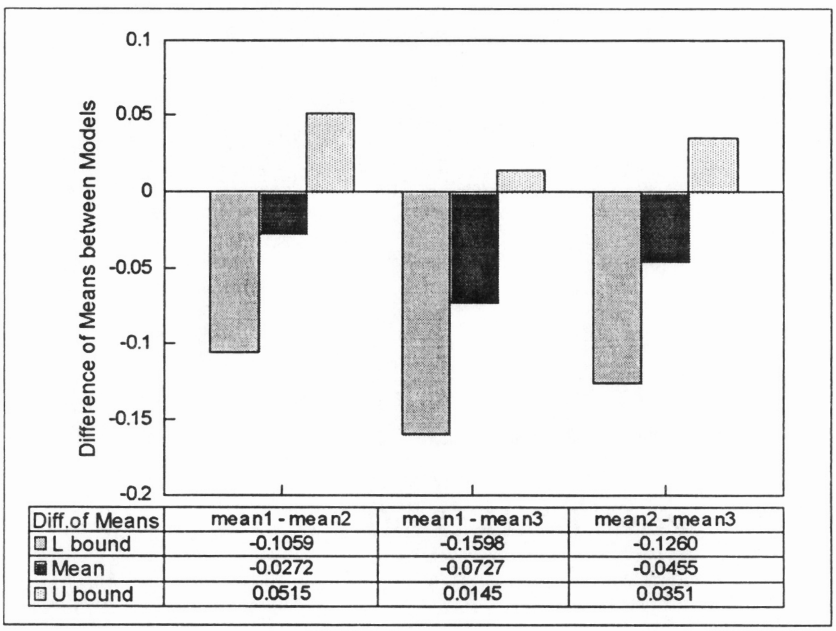
Job Flow Time: As with the AGV idle time and the empty travel time, mean job flow times for the centralized model (model 1) and the hierarchical model (model 2) are considerably similar. Consequently, at a 90 percent confidence interval in Figure 39, model 1 and model 2 are significantly different with a relatively small margin (between 0.1811 to 0.4622). As expected from observing the mean values in Figure 38, model 3 has a very significant difference from model 1 and model 2. Model 3 is between an interval of 2.1638 and 4.4986 lower than model 1, and it is also between 1.9456 to 4.0735 lower than model 2. Thus, in terms of job flow time, the heterarchical model (model 3) is superior to the centralized and hierarchical models.

Machine Wait Time: The mean machine wait time for the centralized model (model 1) is relatively high, followed by the heterarchical model (model 3), then by the hierarchical model (model 2).



X-Axis	Model 1	Model 2	Model 3
Mean	137.1569	137.1841	137.2296
Variance	0.0632	0.0416	0.0725

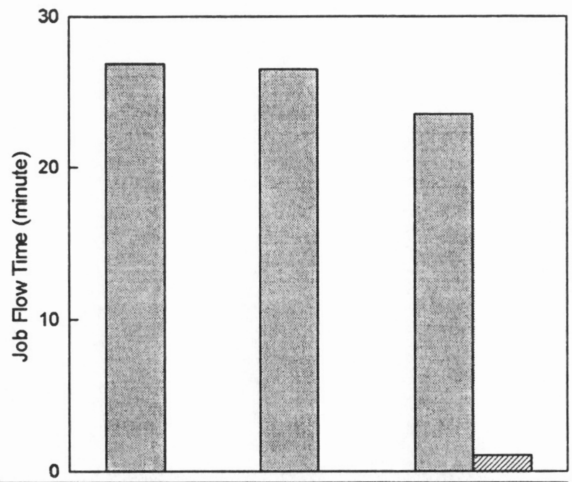
Figure 36. Mean Throughput for the Three Models in the Large System, with Batch Size=150 and 50 Batches.



Diff.of Means	mean1 - mean2	mean1 - mean3	mean2 - mean3
L bound	-0.1059	-0.1598	-0.1260
Mean	-0.0272	-0.0727	-0.0455
U bound	0.0515	0.0145	0.0351

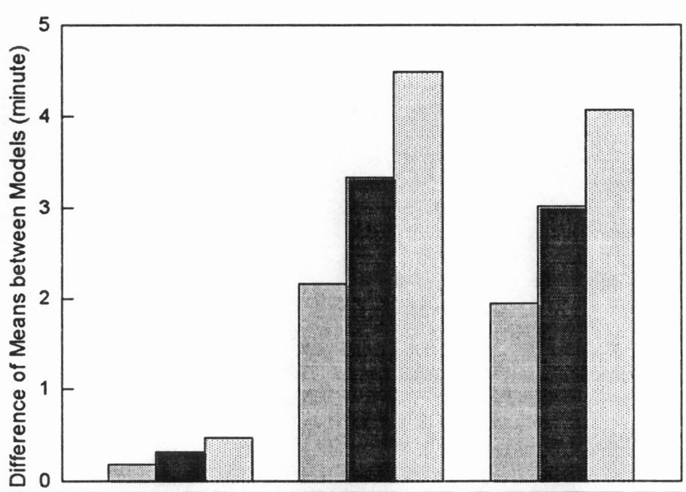
Figure 37. 90 Percent Confidence Interval for the Difference between Mean Throughput Rates of the Three Models in the Large System.

Note: Model 1 -- Centralized Control Architecture; Model 2 -- Hierarchical Control Architecture; Model 3 -- Heterarchical Control Architecture



X-Axis	Model 1	Model 2	Model 3
Mean	26.8879	26.5663	23.5567
Variance	0.0539	0.0152	1.0204

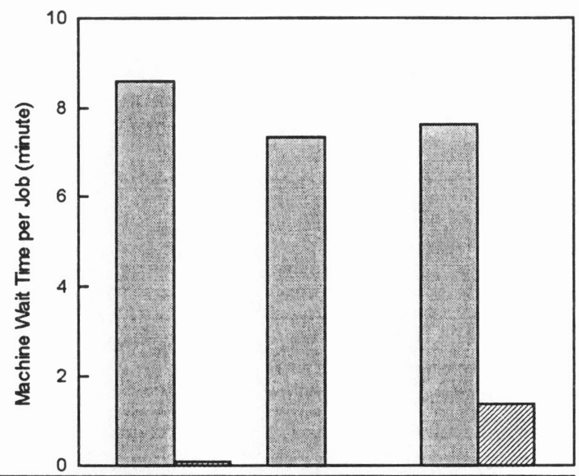
Figure 38. Mean Job Flow Time for the Three Models in the Large System, with Batch Size = 35000 and 27 Batches.



Diff.of Means	mean1 - mean2	mean1 - mean3	mean2 - mean3
L bound	0.1811	2.1638	1.9456
Mean	0.3216	3.3312	3.0096
U bound	0.4622	4.4986	4.0735

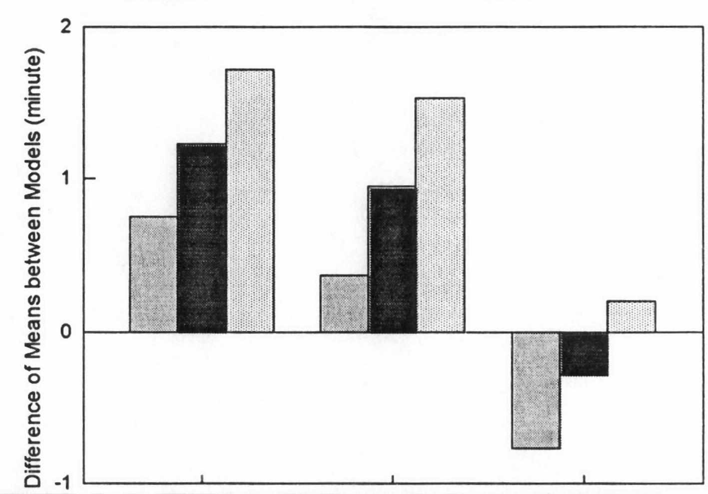
Figure 39. 90 Percent Confidence Interval for the Difference between Mean Job Flow Times of the Three Models in the Large System.

Note: Model 1 -- Centralized Control Architecture; Model 2 -- Hierarchical Control Architecture; Model 3 -- Heterarchical Control Architecture



X-Axis	Model 1	Model 2	Model 3
Mean	8.5761	7.3467	7.6310
Variance	0.0524	0.0096	1.3599

Figure 40. Mean Machine Wait Time for the Three Models in the Large System, with Batch Size=45000 and 21 Batches.



Diff.of Means	mean1 - mean2	mean1 - mean3	mean2 - mean3
L bound	0.7444	0.3677	-0.7639
Mean	1.2294	0.9451	-0.2843
U bound	1.7144	1.5225	0.1952

Figure 41. 90 Percent Confidence Interval for the Difference between Mean Machine Wait Times of the Three Models in the Large System.

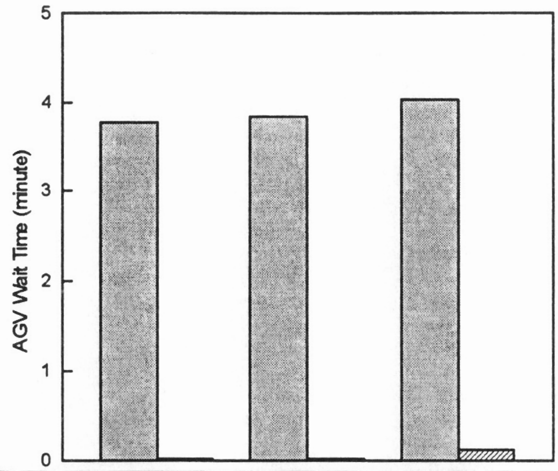
Note: Model 1 -- Centralized Control Architecture; Model 2 -- Hierarchical Control Architecture; Model 3 -- Heterarchical Control Architecture

Figure 41 shows that model 1 is significantly different from model 2 and model 3 at a 90 percent confidence interval. However, no conclusion can be drawn from the comparison between model 2 and model 3, because the range of their difference of means lies on zero. This inconclusive result is mostly caused by the large variance found in model 3.

AGV Wait Time: Results in Figure 42 show that the centralized model (model 1) and the hierarchical model (model 2) have a similar mean AGV wait time; whereas, the heterarchical model (model 3) has a moderately higher mean AGV wait time. Figure 43 shows that model 3 is significantly different from model 1 and model 2 at a 90 percent confidence interval. Model 1 and model 2 also show a significant difference. Thus, with the results from the difference of means at a 90 percent confidence interval, it appears that the centralized model (model 1) has superior performance with lower AGV wait time, trailed closely by the hierarchical model (model 2) closely behind (between 0.1164 to 0.0136), then by the heterarchical model (model 3).

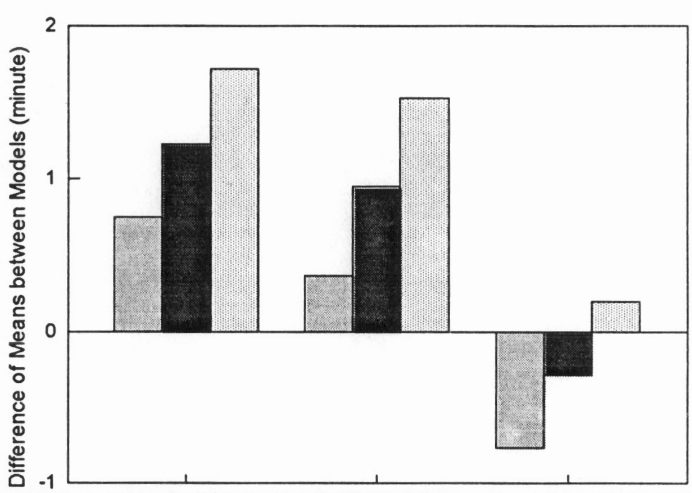
4.3.2 Analysis

Results from the large system test show similarity to those of the small system. As with the small system, the throughput rate in the large system remains almost identical. Thus, it shows that in a system free of capacity constraints, throughput is expected to be dependent only on the arrival rate of jobs. The heterarchical model continues to produce significantly higher AGV idle time, lower AGV empty travel time, and lower job flow time.



X-Axis	Model 1	Model 2	Model 3
Mean	3.7785	3.8436	4.0457
Variance	0.0178	0.0218	0.1174

Figure 42. Mean AGV Wait Time for the Three Models in the Large System, with Batch Size=6000 and 50 Batches.



Diff.of Means	mean1 - mean2	mean1 - mean3	mean2 - mean3
L bound	0.7444	0.3677	-0.7639
Mean	1.2294	0.9451	-0.2843
U bound	1.7144	1.5225	0.1952

Figure 43. 90 Percent Confidence Interval for the Difference between Mean AGV Wait Times of the Three Models in the Large System.

Note: Model 1 -- Centralized Control Architecture; Model 2 -- Hierarchical Control Architecture; Model 3 -- Heterarchical Control Architecture

Table 5. General Results drawn from the 90 Percent Confidence Interval Performed on the Three Models in the Large System.

	Statistical Significant Difference?		
Models	1 & 2	1 & 3	2 & 3
AGV Idle Time	Yes	Yes	Yes
AGV Empty Travel Time	Yes	Yes	Yes
Throughput	*Inconclusive	*Inconclusive	*Inconclusive
Job Flow Time	Yes	Yes	Yes
Machine Wait Time	Yes	Yes	*Inconclusive
AGV Wait Time	Yes	Yes	Yes

However, the performance of the AGV wait times have shifted slightly. As the system size increases, the centralized model yields a relatively superior performance in lowering the AGV wait time than the hierarchical and heterarchical models. Whereas the performance of the mean machine wait time remains very much alike with the small system. Table 5 shows the general results drawn from the 90 percent confidence interval in this section.

4.4 Conclusion of the Results

Comparisons between the small and large systems are done by observing the results from sections 4.2 and 4.3, and no further statistical analysis is intended. Among the two system layouts, the distances between stations vary, which contributes to the different empty travel times and job flow times in the results of the two systems listed in the previous sections. In addition, the incoming job arrival rate has been adjusted in each system to maintain a moderately busy shop.

Results from the previous sections show that no one model appears to be significantly better than the others. The throughput rates across all three models of the same system are almost identical. Thus, this simulation experiment concludes that the control architecture has no effect on the shop throughput under a moderate production capacity. However, as the system grows, the heterarchical model (model 3) continues to maintain a significantly higher AGV idle time, lower AGV empty travel time, and lower job flow time than the centralized model and the hierarchical model.

In the small system, the mean AGV wait time for the heterarchical model is the highest among all three models. With a larger system size and a higher job arrival rate, the heterarchical model exhibits a significantly lower AGV wait time, and it appears to become a superior choice to the centralized and hierarchical models. Furthermore, the performance of the centralized model and the hierarchical model in both systems remains competitive while the system grows and the job arrival rate is being adjusted.

All the comparisons performed in this chapter describe the statistical significant difference between models. In most cases, performance between the models are found statistically significantly different; however, sometimes the actual performance values are so small that they are practically insignificant. The most obvious example is the machine wait times for the small system. Statistical comparisons show that models 1 and 2 and models 2 and 3 are statistically significantly different (see Figure 29 on page 57). The mean machine wait times range between 0.0554 to 0.0949 (see Figure 28 on page 57). The values are so small that they become negligible, and their statistical significance becomes meaningless. The negligible machine wait times are the results of a moderate incoming job rate.

Chapter V

CONCLUSIONS AND FUTURE RESEARCH

5.1 Conclusions

This research discusses the purpose of the control architecture in an AGV control system. It identifies three basic types of control architecture. They are centralized, hierarchical, and heterarchical control architectures. When designing an AGVS, most designers do not consider control architecture as a design factor, and do not analyze its effect on the system's performance. In fact, control architecture is the backbone of the physical and the informational infrastructure of a system. It should be the single most important decision to be made in the early design stage to facilitate the development and future changes.

The major objective of this research is to analyze the effect of control architectures on the relative performance of the AGVS using simulation experiments. A single factor experiment is designed for each control architecture with the system size as the varying factor; in this case, the system size meant the number of stations and vehicles in the system. The simulation of each control architecture is divided into two parts: (1) AGV controller, and (2) shop floor controller. Both controllers are modeled using the C programming language. The AGV controller performs three main functions: (i) dispatching, (ii) routing, and (iii) traffic management. As mentioned earlier, the variable factor in the experiment is the system size. Thus, two different floor plans with different numbers of work stations are designed and used in the simulation experiment. This study focuses on understanding the effect of control architecture on the overall performance of a system. Therefore, measures such as throughput rate, and job flow time are included in the study. In addition, measures that analyze the vehicle performance, such as vehicle idle time, and vehicle empty travel time, are also used.

Results from the simulation experiment show that control architecture does not affect the overall shop performance significantly. Throughput rate across each model of the same system remains almost identical. In both the small and the large systems, the heterarchical model continues to maintain significantly higher AGV idle time, lower AGV empty time, and lower job flow time. However, when the system grows, the difference of performance between the centralized model and the hierarchical model become more competitive.

In addition, the values of mean machine wait time in the small system are much lower than the values obtained in the large system. This is because the incoming job rate for the large system is relatively higher than the rate in the small system. The different incoming job rates trigger different system utilization. It has been observed through the simulation runs that the large system occasionally becomes congested with jobs waiting to be processed at the stations. This leads to an increase in the machine wait time, and consequently, it also increases the job flow time in the large system. The increase of machine wait time increases the dependency of the simulation data. Therefore, a larger batch size is required to reduce the auto-correlation among the simulation data.

5.2 Future Research

A common observation with respect to this research is that for both system sizes, AGV control architectures did not significantly affect shop performance, with reference to the throughput, and wait time. On the other hand, control architecture appears to have a significant effect on the vehicle idle time, and travel time. Therefore, this research could extend its analysis to analyze the range of system capacity given with a specific configuration. Increased system capacity, such as vehicle utilization, machine utilization, or job arrival rate could have a direct impact on the system throughput. However, increased system utilization can introduce bottlenecks into the system, which increase the auto-correlation of the simulation data. To reduce the auto-correlation among the data requires a large batch size and a longer simulation run.

There has been some research reporting the advantages and disadvantages of different control architecture approach in terms of their complexity, flexibility, modifiability, and fault-tolerance *[Boyd91, Duffie87-91, Roger91]*. However, no research has been performed to link these intangible properties to the actual shop performance of a system. Future research should be directed to understand the relationships between the control approach and performance of the manufacturing systems. The definition of measures such as complexity and flexibility are also worth further investigation.

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APPENDIX A

AUTOCORRELATION

Autocorrelation is the correlation between samples of a single variable, x. This gives the internal correlation of a series of samples of the same variable x, displaced in time.

Equation for the autocorrelation coefficient is:

$$\rho(p) = E[(x_i - \mu)(x_{i+p} - \mu)]$$
$$= \frac{1}{n-p} \sum_{i=1}^{n-p} (x_i - \bar{x})(x_{i+p} - \bar{x}) \quad \text{for } 1 \le p \le n-1$$

APPENDIX B

Confidence Interval Procedure

For $i = 1, 2, ..., n$
let $X_{i1}, X_{i2}, ..., X_{in_i}$ be a sample of n_i observations from system i, and $n_1 = n_2$;
let $\mu_i = E(X_{ij})$ be the mean response of interest;

Construct confidence interval for $\zeta = \mu_1 - \mu_2$

pair X_{1j} with X_{2j} to define $Z_j = X_{1j} - X_{2j}$ for $j = 1, 2, ..., n$
in which, Z_j's are random variables and $E(Z_j) = \zeta$, the quantity for which we want to construct a confidence interval.

Thus,

$$\bar{Z}(n) = \frac{\sum_{j=1}^{n} Z_j}{n} \quad \text{and} \quad \hat{\sigma}^2[\bar{Z}(n)] = \frac{\sum_{j=1}^{n} [Z_j - \bar{Z}(n)]^2}{n(n-1)}$$

and form the (approximate) $100(1 - \alpha)$ percent confidence interval

$$\bar{Z}(n) \pm t_{n-1, 1-\frac{\alpha}{2}} \sqrt{\hat{\sigma}^2[\bar{Z}(n)]}$$

In case of this study, if $\alpha = 0.1$, we can be 90 percent confident that the mean values fall within the intervals $\bar{Z}(n) \pm t_{n-1, 1-\frac{\alpha}{2}} \sqrt{\hat{\sigma}^2[\bar{Z}(n)]}$.
Then, by comparing the confidence intervals for difference of means, one can interpret if one model is superior than the other.

VITA

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