Dynamic Scheduling of Flexible Manufacturing Systems: A Study of Machine and Material Handling Control Strategies

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ABSTRACT

Dynamic Scheduling of Flexible Manufacturing Systems: A Study of Machine and Material Handling Control Strategies

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In recent years there has been an increased interest in automated and Flexible Manufacturing Systems (FMS). These systems are comprised of a number of computer-controlled machines and material handling devices integrated together for the purpose of producing different parts with little or no setup. Scheduling and control of all manufacturing systems is an area that receives considerable attention because of the potential for significant improvement in shop performance and associated cost benefits that can be realized.

Planning and control of FMS differs considerably from the problems cited in traditional flow shop and job shop environments due to a different set of operating conditions such as the integrated material handling system and the limited buffer capacity. Furthermore, the operating environment of an FMS is dynamic, so static rules based on having all information in advance are not appropriate.

The focus of this research is to develop and test on-line scheduling rules for both machines and material handling sub-systems of an FMS. The scheduling rules use various priority attributes and relevant information concerning the availability status of resources in the decision making process. These rules are dynamic in nature because the priority of a job in the system can change continually. The scheduling rules are applied to control a hypothetical FMS consisting of multiple shared resources for different operating conditions. Simulation is used to model the system and consequently test the performance of different scheduling rules with respect to mean flowtime, consistency of output, and efficient operation of the material handling system.

Design of experiments is used to explore the relative effectiveness of scheduling rules on the system performance measures for a variety of experimental conditions. Analysis shows that there is a significant difference in the performance of scheduling rules. The performance of machine and material handling scheduling rules can be dependent, and the choice of rules depends on the operating environment. The results are summarized to make recommendations on rule selection for a given FMS operating condition against each of the important performance measures.

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To my late mother Dr. K. Porkodi.

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LIST OF SYMBOLS

I_f	Flow shop index
I_b	Bottleneck index
N	Number of job arrivals per hour
m	Total number of machines
n	Number of job-types
r_j	Proportion of job-type j
p_{ij}	Processing time of job-type j on machine i
x_i	Position in sequence of machine i
f_{ij}	Total flow from machine i to machine j
M_i	Utilization of machine i
M_{max}	Maximum utilization of m machines
M_{avg}	Average utilization of m machines
TP	Total throughput
FT	Average flowtime per job
Avg(WT)	Average waiting time per job
Var(WT)	Variance of average waiting time of job-types
WIP	Average work-in-process
AGV.UTZ	Average AGV utilization
EL	Empty to loaded travel ratio
TBA	Mean time between arrivals

AD	Arrival distribution
SHOP	Type of shop
BNK	Bottleneck machine
TD	Tool duplication
AS	AGV speed

LIST OF ACRONYMS

FMS	Flexible Manufacturing System
AGV	Automated Guided Vehicle
CNC	Computer Numerically Controlled
JIT	Just-In-Time
FIFO	First-In-First-Out
SPT	Shortest Processing Time
SIO	Shortest Imminent Operation
LQM	Longest Queue of Machines with tie-breaking
MRT	Maximum Request for Tools with tie-breaking
NS	Nearest Station
QSNS	Queue Size Nearest Station
NUJ	Nearest Unassigned Job
ANOVA	Analysis of Variance

Chapter 1

Introduction

1.1 Background

Flexible Manufacturing Systems (FMS) are automated systems where a number of different types of resources work together under computer control to transform a workpiece into a final product or a sub-assembly. This transformation process is a sequence of processing steps. At each processing step, a number of resources are simultaneously needed to complete the operation. An FMS processes a number of different parts simultaneously with little or no setup and it combines automation suitable for mass production with flexibility suitable for job shop production.

An FMS is highly capital-intensive and its users are concerned with achieving high system utilization. Because of cost, the majority of FMS are installed in large manufacturing corporations, namely automotive, aerospace, major defense industries, large, heavy equipment manufacturers, and machine tool builders. Vought Aerospace, Dallas, Texas for example uses FMS to produce component parts for aircraft fuselage. Another example of FMS installation is Cincinnati Milacron Plastics Machinery Division that manufactures parts for plastic processing machines.

The resources typically used in an FMS include Computer Numerically Controlled (CNC) machines, fixtures, tools, robots, and material handling equipment.

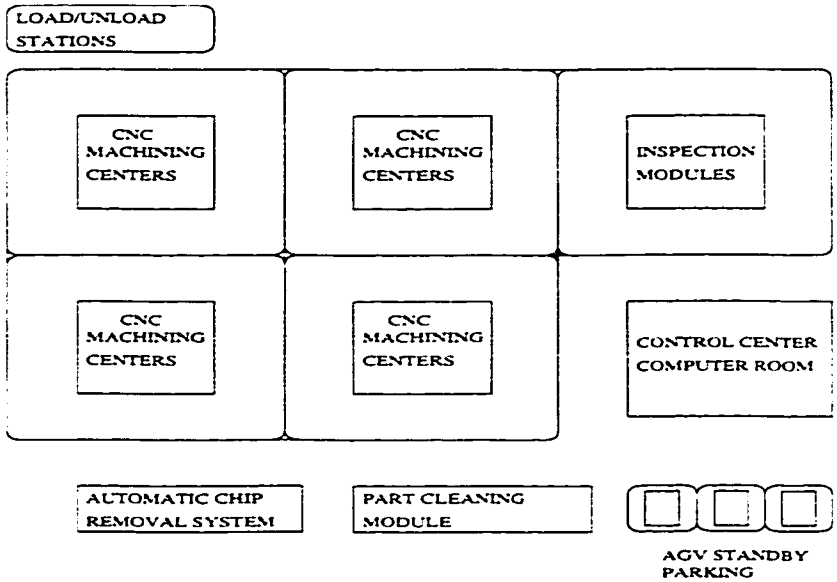


Figure 1.1: Layout for Vought Aerospace.

Figure 1.1 illustrates the layout for Vought Aerospace consisting of four CNC horizontal machining centers with automatic tool delivery and exchange system. Three Automated (wire) Guided Vehicles are employed for material handling purpose. Other equipments used are pallets, manual inspection station, part cleaning unit, and automatic chip removal and separation. The system processes 600 part types. Limited buffer space in an FMS also imposes a constraint similar to having a limited shared resource which is the number of buffer spaces. Occasionally, there may also be a human operator overseeing the overall operation of one or more cells. Machining operations require the availability of the machine as well as certain tools, and possibly a robot or worker to place the workpiece. A transportation task requires the availability of the material handling equipment as well as a buffer space at the destination station. The resources are usually expensive and therefore cannot be dedicated to a certain process, but are rather shared between the various processes in the FMS.

1.2 FMS-Related Problems

FMS problems can be grouped into two areas: design problems dealing with the optimal selection of the FMS components; and operational problems dealing with the optimal utilization of the FMS.

FMS design problems are related to the decisions that must be made before the installation of an FMS. These decisions include: the selection of parts to be made, the selection of appropriate machine tools, the selection of material handling equipment, the computer system configuration, the process design of each part, and the evaluation of different layouts. Of these design issues, the selection of parts to be made and its process design determine the level of flexibility and may undergo changes after installation.

FMS operational problems involve production planning and scheduling. Production planning in an FMS is more difficult than in assembly lines or job-shops because each machine is versatile and is capable of performing different operations, the system can process several different part types simultaneously, the system is characterized by limited local buffers, and each part may have more than one route in the system. The limited size of buffers in particular can cause system blocking, a state in which all operations come to stop because of conflicting resource requirements.

FMS operational control is usually coordinated by a central computer or control unit, as shown in Figure 1.1, that is equipped with comprehensive software modules for scheduling, tool allocation, traffic, production processing, and possibly system simulation. The control unit takes as input information on the state of all resources and continuously monitors the activities of the equipment and provides supervisory and engineering reports. Under computer control, parts are prioritized to use the resources.

The criteria used to evaluate different operational control strategies are based on performance related measures such as the production rate (i.e., number of parts processed per period), the mean flowtime of parts, work-in-process, average waiting time, variance of waiting times and resource utilization. Some of the measures of performance can be conflicting. For example, the scheduling strategy that reduces average work-in-process may not necessarily improve production rate.

1.3 Scope of the Research

The focus of this study is on the scheduling of jobs for an FMS. The performance and efficiency of an FMS is highly dependent on the efficient allocation of resources. Prior studies indicate that FMS performance is significantly affected by the choice of scheduling rules. Montazeri et al. (1990) evaluated scheduling rules for an FMS and the results indicated that the developed heuristics significantly reduced average waiting times and improved machine utilization. Sabuncuoglu et al. (1992) investigated the performance of several job shop rules in a hypothetical FMS. They found which scheduling rule significantly reduced the mean flowtime measure.

Static and deterministic off-line scheduling techniques, commonly used for production scheduling in traditional job shops, are not appropriate for FMS control. Instead, a more dynamic decision making process is generally used to react quickly to changes in the state of the system as different parts arrive for processing in the system at random points in time.

It is important that the scheduling rules co-ordinate the allocation of all types of resources (CNC machines, tools, material handling equipment, buffer spaces, etc.) depending on their current status of availability. The objective of this research is to develop and test dynamic scheduling rules for machine and material handling subsystems for different FMS operating conditions against multi-criteria performance measures.

A part undergoing an operation on a machine will have to request all the required machining resources before processing can take place. Machine scheduling rules prioritize jobs on a machine upon the completion of current machining operation. Priority rules are developed based on the current status of machining resources required for processing a job. A part that has completed its processing on the current machine will have to be physically transported to the next machine in sequence. This study utilizes Automated Guided Vehicles (AGV) to transport raw materials and work-in-process for the hypothetical FMS. However, the dispatching rules proposed in this study can also be applied to operate FMS which uses robots for material handling. AGVs are driverless, battery powered, and can be programmed from a system controller to travel along a predetermined path. The control system dispatches idle vehicles to perform material handling functions in the shop floor, carrying materials from one station to the other. Failure to design an efficient on-line AGV dispatching algorithm may lead to poor performance of the FMS. An AGV dispatching rule assigns an idle AGV to move a part from one location to another location in the FMS. If there is no part waiting for pick-up, the AGV remains idle and awaits for a travel request to emerge. Possible interaction between the machine scheduling and AGV dispatching rules are also studied.

The FMS scheduling literature includes research studies ranging from analytical techniques (Sawik 1995, Sabuncuoglu and Suleyman 1998) to simulation (Mahadevan and Narendran 1990, Lee 1996) and artificial intelligence/expert systems (Seifert et al. 1998). While research through each technique is necessary for better understanding and solving the problems associated with FMS, this study focuses on simulation-based experimental studies of the FMS scheduling problem. Discrete-event simulation models are developed to implement the scheduling rules in an example FMS with an uni-directional AGV track layout. An example FMS problem is specially designed to study the effectiveness of machine-scheduling in combination with AGV dispatching rules under varying conditions. The simulation models were developed in SIMSCRIPT II.5 language.

This research investigates the relative effectiveness of machine and AGV scheduling rules against the performance criteria based on the mean flowtime, consistency of output, and efficient operation of AGVs. The operation of AGVs is judged based on empty-to-loaded travel time ratio and average AGV utilization. The FMS scheduling rules are tested under a variety of experimental conditions. A factorial experiment is conducted to investigate the importance of several system operating parameters related to the performance of the FMS scheduling rules. Statistical analysis was carried out using the STATISTICA software package.

1.4 Organization of the Thesis

The remainder of this thesis is organized as follows:

Chapter 2 "Literature Review" provides a detailed literature survey of FMS scheduling.

Chapter 3 "Scheduling Rules" explains the machine scheduling and AGV dispatching rules that are developed in this research.

Chapter 4 "System Description and Simulation" discusses the hypothetical FMS with the AGV track layout and system parameters. Also, the simulation technique to test the rules and performance measures is described.

Chapter 5 "Experimental Design and Analysis" discusses the design of the simulation experiments to evaluate the performance of the rules. Experimental analysis of the output are also presented.

Chapter 6 "Conclusion" lists some recommendations.

In addition there are three appendices containing detailed results.

Chapter 2

Literature Review

This chapter reviews the work done by some researchers in evaluating scheduling rules against different performance measures in different environments. The literature on design and operational control of FMS are both extensive, but this chapter discusses only the scheduling aspect.

2.1 Classification of Scheduling Problems

A typical job in an FMS needs a primary resource and possibly a number of additional secondary resources. For instance, if the job is a machining operation, the primary resource is the machine, and the secondary resources may be tools, fixture, pallet, human operator or a robot. If the job is a transport operation, the primary resource is the material handling equipment, and the secondary resource may be the buffer space at the destination machine, and a robot or human for loading the part.

One of the most important aspects of operational control in an FMS is the allocation of limited resources to waiting jobs. Decisions made in this regard can be classified into:

- AGV dispatching - Assigns an idle vehicle to move a part from one location to another in the manufacturing system. Decisions such as which AGV a job requiring service should select among a set of vehicles available, and which job a released AGV should consider for pick-up assignment from one of the work-stations are made.

- Scheduling and dispatching of jobs in FMS - Allocation of primary resources for which multiple jobs are waiting with its required additional resources available.
- Tool sharing strategies in FMS - Allocation of secondary resources to satisfy the needs of component parts and products.

The following sections summarize some of the previous papers relevant to each of the categories.

2.2 AGV Dispatching

The structure of industrial production has drastically changed due to automation and the material handling system is one of the main areas that has looked to automation to improve system performance. An AGV system is a computer-controlled factory-wide transporter. The flexibility of an AGV system makes the task of controlling the AGVs challenging. The issues of controlling AGVs may include dispatching, routeing and scheduling. Dispatching involves a decision rule or methodology for selecting a vehicle or station for pick-up or delivery assignments. The routeing problem is concerned with finding a route that will allow a vehicle to reach a destination in the shortest possible time without interruption. Scheduling encompasses the dispatching and routeing issues with the introduction of time.

The following review addresses the operational control of AGV-based material handling systems. According to Klein and Kim (1996), AGV dispatching rules can be classified into single-attribute dispatching and multi-attribute dispatching based on the number of attributes included in the decision making process. Possible attributes include information with respect to the AGV track layout, location of

AGVs, AGV status, and queue size of pick-up and destination workstations. In the literature, different AGV dispatching rules are developed and tested under different manufacturing environments such as FMS and job-shop involving uni-directional and bi-directional layouts.

2.2.1 Single-Attribute Dispatching

Single-attribute dispatching models are based on just one dispatching criteria in the decision making process.

Mahadevan and Narendran (1990) studied the design and operation of AGV based material handling systems for an FMS. They addressed the key issues such as the traffic flow pattern along the AGV tracks, decisions regarding provision of control zones, number and capacity of buffer for the vehicles, the number of vehicles required, and vehicle dispatching rules. The vehicle dispatching rules tested in the study are all based on single attribute. The discussion on vehicle dispatching rules is made following the design issues that are addressed in the paper.

According to the authors, if a single AGV operates in a closed loop, the traffic control problem is simple, and the need for control zones and buffers does not arise. However, when more vehicles circulate in the system, decisions regarding control zones, buffers, traffic flow pattern along the AGV tracks, and vehicle dispatching have to be made. For resolving traffic problems, the use of control zones and buffers would help. A control zone will allow only one vehicle to use a track at a time. In addition, buffers may be provided for the vehicles waiting to use the control zones. Another strategy suggested by the authors to overcome collisions is to design a single vehicle loop configuration which divides the entire network of AGV tracks into few small closed loops, each of which allows only one vehicle to circulate. This design removes the problems of vehicle collision and interference and simplifies traffic management. Buffers have to be suitably placed in order to facilitate inter-loop transfer of jobs. As mentioned by the authors, the drawback of this arrangement would be its inability to tackle vehicle breakdowns which will paralyze the loops. Additional problems such as creation of bottleneck loops, requirements of additional space, guide path and storage points may also arise. To overcome these problems, the authors suggested an alternate strategy wherein the vehicles are restricted to travel along selected AGV tracks only. This scheduling strategy retains the advantages of the small closed-loop configuration and also adapts to vehicle breakdowns.

Next, they developed a formula to estimate the minimum number of vehicle required. This estimate is for an FMS processing jobs in more than one sequence which allows alternate routeing of the jobs due to machine failure or work-load balance considerations.

A simulation model for a system producing five job types with six machines, a load/unload station and a central buffer for work-in-process was constructed using GPSS/PC and some of their suggested strategies were tested. They estimated the number of AGVs required to be three for a set of processing times at the machines and two for the same system with larger values of processing times.

They studied the same model with 3 AGVs based on three vehicle dispatching rules, namely, the least utilized vehicle rule, the farthest idle vehicle rule, and the sequential dispatch rule. All the three dispatching rules use the following single attributes: the least utilized vehicle rule considers the amount of time an AGV is held busy, the farthest idle vehicle rule uses the distance between idle vehicle and the job, and the sequential dispatch rule is based on the arrival time of jobs. Besides dispatching rules, the performance based on the single vehicle loop configuration was also studied. The performance measures used were the mean flow-time of the jobs, the utilization of the AGVs and the average number of jobs waiting for an AGV.

In the study, the single vehicle loop configuration and the sequential dispatch rule is found to fare better than the other rules in the system considered for the study. This is because, the system under consideration has small number of machines and few inter-loop transfers.

More recently, Seifert, Kay and Wilson (1998) introduced a dynamic vehicle routeing strategy based on hierarchical simulation. When routeing is dynamic, different paths can be taken by an AGV at different times when moving between two given nodes. Taking into consideration the current status of the system, the vehicle router selects a path for the AGV at the time that the vehicle is dispatched (Hodgson et al. 1987) and if there is a communications link between the router and the vehicle, then the router modifies the vehicle's path during travel.They observed that the shortest travel-distance route may not be the shortest travel-time route. Along any given route, the actual travel speed of a vehicle depends on the amount of congestion encountered. This can affect the overall performance of the AGV system. The research uses single-attribute, namely the travel-time for AGV routeing decision.

In their proposed hierarchical simulation, whenever there is an AGV routeing decision in the main simulation, subordinate simulations are performed to evaluate a limited set of alternative routes in succession until the current routeing decision is finalized and the main simulation resumed. Also, they used the global vision as information support to avoid obstacles in the way of an AGV. Global-vision-system refers to the use of cameras (or other types of sensors) placed at fixed locations in a work space to extend the local sensing available on board each vehicle in a free-ranging AGV system (Kay 1992, Kay and Luo 1993). Information from the cameras is used to:

1. Monitor the workspace to detect and track potential obstacles in the immediate vicinity of each AGV and over its intended path.
2. Track each AGV along its intended path to bound errors in the vehicle's dead-reckoning sensors.
3. Monitor the load aboard each AGV to detect positioning errors

4. Provide video images of the entire work space so that a human operator can monitor the status of operations throughout the facility.

The authors have used item (1) in their study to evaluate the use of a computer simulation model as a short-term decision tool for AGV routeing that accounts for the current system status and determines the current optimal path with the minimum travel time to reach a certain destination. A case study of a prototype AGV system consisting of ten P and D stations, seven intersection region nodes, varied number of AGVs and pedestrians and operating under the control of a global vision system is used to test the static and dynamic vehicle routeing strategies.

To evaluate the performance of the AGV system, they formulated a specific performance measure referred to as the 'relative delay' of an AGV, which is the difference between the AGV's actual travel time to its current destination, and the corresponding theoretical minimum travel time of the AGV as determined by its maximum speed and the shortest-travel-distance path between the AGV's current origin and destination nodes.

The results of the case study indicated the superiority of dynamic approach in comparison to the deterministic shortest travel-distance path. However, as indicated in the paper, these results cannot be generalized without much more extensive experimentation. Moreover, to enjoy the full benefits one can gain from the dynamic vehicle routeing approach, the authors suggest to account for the capabilities of this approach during the design phase of the AGV system by including more flexibility in AGV system design. Specifically, the AGV system design should provide a sufficient number of alternative paths that can be chosen so that critical bottlenecks can be bypassed dynamically, allow for dynamic selection of P and D stations corresponding to the same work-center, and allow for varying degrees of sensing capabilities to provide information concerning the congestion status of the system, ranging from purely local, vehicle-based sensing to full global vision capabilities.

2.2.2 Multi-Attribute Dispatching

Multi-attribute dispatching models consider several dispatching criteria concurrently in the decision making process.

Lee (1996) evaluated three composite rules which combine the primary dispatching rules with tie-breaking rules in a job-shop environment. He considered an assembly system with AGV-based material handling system. Multiple vehicles were used on an uni-directional track layout. The system consisted of four major assembly lines and each has a pair of drop-off station and pick-up station for material handling purpose. The possible routes of AGVs among the workcenters and the warehouse can be thought as directed links of a network.

Four types of assembly jobs arrive at incoming dock. As incoming jobs are generated, four AGVs are available to carry loads of materials from the warehouse to the drop-off stations of the assembly lines. The materials are then assembled into finished products which can be picked up from the pick-up station at the end of the assembly line. Since multiple vehicles are allowed in the system, collisions are avoided by the zone control capability that allows only one AGV to access the junction or a section of the track at a time.

Four vehicle-initiated dispatching rules namely Stay in Same Station (SS), Nearest Station and Stay in Same Station (NS-SS), Nearest Station and High activity area (NS-HA) and High queue and Nearest Station (HQ-NS) were evaluated in this study. SS was used as a benchmark for comparison purpose. Of the rules tested, SS and NS-SS are single-attribute dispatching rules, and NS-HA and HQ-NS are multi-attribute dispatching rules.

Discrete-event simulation models were developed in SIMAN language to implement the composite dispatching rules. A dispatching rule is used when an AGV completes a drop-off task and looks for the next task. When an AGV approaches a junction, a FCFS control scheme is used to avoid possible collisions.

He used the design of simulation experiments to evaluate the performance of the scheduling rules. He identified mean time between arrivals, arrival distribution and ratio of AGV travel time to the assembly time as the three factors which might affect the performance of the rules. The factors were tested at 2 by 2 by 3 levels resulting a 2 x 2 x 3 factorial design with 12 experiments. With 4 rules and 3 replications, the total number of simulation experiments performed was equal to 144. The performance measures collected from the simulation were throughput, average flow-time per job and average inventory level in the system. An analysis of variance (ANOVA) procedure was then performed to identify the factors and the factor interactions that may affect the performance measures.

The results reveal that the NS-SS and HQ-NS performed equally well in throughput and WIP, while NS-SS outperformed HQ-NS on flow time. The performance difference between the SS rule and the composite rules was significantly affected by the job inter-arrival time (TBA), the ratio of AGV travel time to assembly time (RT), and the interaction between the two factors (TBA*RT).

The above study has not showed importance over the performance of machine scheduling rules in relation to the AGV dispatching rules. Further tie-breaking is required when considering a layout wherein two or more stations are equi-distant to eachother.

Klein and Kim (1996) proposed a multi-attribute decision models (MADM) which consider several dispatching criteria concurrently in the decision making process. They presented four such rules namely simple additive weighing method (SAWM), Yager's multi-attribute decision making method (YAGER), modified additive weighing method (MAWM) and max-max method (MMM). There is no clear mention of the list of attributes used in the priority calculation of MADM.

SAWM is the widely used method of MADM. Suppose the decision maker assigns a set of importance weights to the attributes, $W\{w_1, w_2, \ldots, w_n\}$. Then the most preferred alternative, A^* is selected such that

$$A^* = \left\{ A_i \middle| \max_i \frac{\sum_{j=1}^{n} w_j x_{ij}}{\sum_{j=1}^{n} w_j} \right\}$$

where x_{ij} is the outcome of the ith alternative about the jth attribute with a numerical comparable scale. x_{ij} can be the values that represent the number of loads in output buffers, the waiting time of a part, or a travel distance of a vehicle.

Yager (1977,1978,1981) developed a fuzzy MADM model which employs a fuzzy numeric rating approach. Consider the objectives, $G_1, G_2, \ldots, G_n$, each associated with a fuzzy subset over the set of alternatives $A_1, A_2, \ldots, A_m$. Let $R_{i1}, R_{i2}, \ldots, R_{im}$ be fuzzy numerical ratings of each alternative assessed by objective i. Each objective may be represented as

$$G_i = \sum_{i=j}^{m} \frac{R_{ij}}{A_j}, i = 1, \ldots, n.$$

The decision D is denoted as

$$D = \min \{G_1, G_2, \ldots, G_n\}.$$

In order to normalize attribute values MAWM uses membership functions of the fuzzy sets which represent the objectives. By this, the MAWM is able to take an expert's opinion or previous experience of operating a shop into account when converting an attribute value to a new value that will represent the situation of each department more adequately.

MMM determines the value of an alternative by selecting the maximum value of the objectives rather than adding up all the values of objectives. In other words, the most urgent or desirable situation of an objective is used to represent the situation of the alternative. The most preferred alternative, A^*, is selected such that

$$A^* = \{A_i \mid \max_i \max_j (w_j x_{ij})\}$$

where x_{ij} is the outcome of the ith alternative about the jth attribute (or objective) which is obtained from a membership function of the attribute.

A simulation model was developed to test the dispatching rules for an AGV system. The four MADM methods along with three other single attribute dispatching rules namely, shortest travel time/distance rule, maximum queue size rule and longest waiting time rule were tried for a three-department and thirteen-department layout configurations. The results of the simulations under different rules were analyzed and compared according to the performance measures collected such as the job completion time, total travel time of empty vehicles, maximum and average queue length and waiting time. Analysis showed the multi-attribute dispatching rules outperformed the single-attribute ones and MAWM appeared to be the most robust rule overall. Thus the superiority of the multi-attribute dispatching rules for AGVs is observed in this paper.

Akturk and Yilmaz (1996) proposed a micro-opportunistic approach to solve the AGV scheduling problem. Automated Manufacturing Research Facility (AMRF) is a well-known factory reference model at the National Institute of Standards and Technology in the USA. There are five levels in the AMRF hierarchy, which are factory, shop, cell, workstation and equipment. The paper presents a new approach to incorporate AGV into the overall decision-making hierarchy. To achieve this, they proposed a hybrid approach in which the control mechanism for the AGV module is designed using a heterarchical structure, so it can interface both shop and cell levels directly.

In the shop level's scheduling problem, the beginning and ending times of jobs in cells are determined with approximate transportation time requirements, which will be passed to the proposed AGV module. Furthermore, the cell level is responsible for scheduling the jobs to workstations. With some approximate time requirements for material movement, each cell prepares an initial schedule. Similar to those of the shop level, a release time and due-date for each move is determined. The AGV module receives move orders between and within cells in the form of time windows in which the corresponding move request has to be completed. This forms a special case of multi-attribute dispatching since the move requests are known in advance and an off-line schedule is determined satisfying certain constraints (attributes) of the problem formulation. Therefore, the proposed method is an off-line scheduling algorithm for the AGV dispatching problem.

The objective of the AGV module's scheduling problem is to minimize the amount of deviation from the given time windows. They considered N move requests with given time windows and pick-up drop-off points and M identical vehicles in a planning horizon. The AGV track layout is assumed to be uni-directional. The loads are unit loads, and one vehicle is sufficient for a load request. For the traffic management problem, the control at intersection points of the uni-directional guide path is used to avoid collisions. The above problem is modeled as a mixed integer program (MIP), where the objective is to minimize the total deviation from the time windows.

The developed algorithm was tried on a 20-job problem with the required parameters such as release time, due-date, and transportation time of jobs with the pick-up and drop-off points. The system is served by two vehicles operating on an uni-directional layout. The final schedule obtained is feasible, i.e. the total deviation is equal to zero, and also free of collisions.

The experimental factors that might affect the performance of the proposed algorithm were the number of jobs to be scheduled, layout, tightness factor and number of vehicles. Each factor has three levels in the design resulting in 3^n full-factorial design, which corresponds to eighty-one treatment combinations. The number of replications of each combination is taken as five, that gives 405 different runs. Finally, an ANOVA model is performed to observe the effects of factors on the performance measure. All factors were found to be significant on the performance of the proposed method. For combination of factors, only the layout-time window tightness interaction is found to be significant.

2.3 Scheduling and Dispatching of Jobs in FMS

Scheduling of machines and vehicles in an FMS environment are considered under this category. Job dispatching rules can further be classified based on the information required to prioritize the jobs waiting for the resources to process its request. The priority calculations may require information purely related to the job or the resource or both. Job information may include its arrival time to the shop, processing time on each machine and the number of operations required to complete processing. Resource information may include the queue size of jobs in the input and output buffers. Also, some research studies use the same information to schedule both machines and vehicles.

Montazeri and Van Wassenhove (1990) used modular FMS simulator to analyze scheduling rules. The modular FMS simulator is a general-purpose, user-oriented, discrete-event simulator designed to help the user in design, operation, and scheduling of manufacturing systems. It provides the user with a wide range of priority rules to choose from and enables the user to define his/her own rules if required. The software configuration of the simulator includes three subsystems: an input part to allow user to input various kinds of data in an interactive mode; a process part which forms the main body of the simulator consists of four major sections namely event section, control section, decision-rule section, and a simulation section; and an output part primarily designed to generate statistical reports.

The authors tested fourteen different scheduling rules for a hypothetical system with the modular FMS simulator. The hypothetical FMS consists of three machine families, three load/unload stations, five machines, three carriers, and 11 work-in-process buffer positions. All machines in the families have their own dedicated shuttle and a worker is assigned to each station to load parts on the pallets and unload parts from the pallets. The scheduling rules tested were:

- SIO - Shortest Imminent Operation time

- SPT - Shortest Processing Time
- SRPT - Shortest Remaining Processing Time
- SMT - Shortest SIO.TP multiplication value
- SDT - Shortest SIO/TP ratio
- LIO - Longest Imminent Operation time
- LPT - Longest Processing Time
- LRPT - Longest Remaining Processing Time
- LMT - Largest LIO.TP multiplication value
- LDT - Largest LIO/TP ratio
- MRO - Largest number of remaining operations
- FRO - Fewest number of remaining operations
- FIFO - First In First Out
- FASFO - First At Shop First Out

Based on the classification, all the above tested rules use information related to job alone.

At each decision point in the system, the authors assign the same priority rule in every run. The performance measures for evaluating scheduling rules were average waiting time per part, average machine utilization, average buffer utilization, average shuttle/carrier utilization, and makespan. Results indicated that no single scheduling rule performed well with respect to all measures. SPT based rules minimized average waiting times and LPT based rules maximized machine utilization. SPT rule performed well with respect to average buffer and shuttle utilization, and both LDT and SPT performed well with respect to average carrier utilization. SDT had the lowest makespan.

This paper clearly showed that dispatching rules may have an important impact on system performance. Since in the above study, a part type visits just one machine, the results cannot be carelessly generalized to other systems involving jobs that go through a sequence of machines.

Sabuncuoglu and Hommertzheim (1992) attempted to investigate the performances of machine and AGV scheduling rules against the mean flow-time criterion. Since only the machines and materials handling aspects of a FMS are under study, they classified scheduling rules into: (1) Machine scheduling rules and (2) AGV scheduling rules. The following rules under each category were tested:

1. Machine scheduling rules:
   - Shortest processing time (SPT)
   - Smallest value of operation time multiplied by total operation time (SPT.TOT)
   - Smallest value of operation time divided by total operation time (SPT/TOT)
   - Largest value of operation time multiplied by total operation time (LPT.TOT)
   - Largest value of operation time divided by total operation time (LPT/TOT)
   - Least work remaining (LWKR)
   - Most work remaining (MWKR)
   - Fewest number of operations remaining (FOPNR)
   - Most number of operations remaining (MOPNR)
   - First come first served (FCFS)
   - First arrived first served (FAFS)
   - RANDOM (job priority is random)

Based on the classification, all the above tested rules use information related to job alone.

2. AGV scheduling rules:

   - First come first served (FCFS)
   - Largest output queue size (LOQS)
   - Shortest travelling distance (STD)
   - Largest queue size (LQS), including incoming and outgoing parts
   - Most work remaining (MWKR)
   - Fewest number of operations remaining (FOPNR)

   FCFS, STD, MWKR, and FOPNR rules use job information. LOQS and LQS rules use resource information.

The above rules were tested on a hypothetical FMS consisting of eight workstations. Six of these workstations are typical machining centers which perform a wide variety of operations, such as turning, milling and drilling. The two remaining stations are used for washing and inspection. Each workcenter has a limited input/output buffer queue in which parts can wait before and after an operation. In addition, there is an input/outout carousel where parts are mounted/demounted to fixtures and palletized for transfer. The arriving parts are held in the carousel and allowed into the system on FCFS basis as long as both an AGV and one queue space at the destination workcenter are available. There are also two central buffer areas at which parts are temporarily stored to prevent system locking or when the destination station queue is full for a part travelling to this station. Materials and parts are transferred by AGVs. The path (material flow) is assumed to be unidirectional. The job inter-arrival time is exponentially distributed. Each job is processed by a series of workcenters. The number of operations (number of machines to visit) was determined by a discrete uniform distribution between one and six. Only two AGVs were employed in the study.

An FMS simulation model was constructed to study the scheduling rules. The scheduling rules were tested under a variety of experimental conditions such as by varying machine and AGV load levels, queue capacities and AGV speeds. Mean flow-time is the average of the flow-times of all jobs measured during a simulation run. They analyzed the performance of scheduling rules with respect to elements of mean flow-time as it is a very critical indicator of the lead-time and it also provides important information that can be used for setting the due-dates or due-date allowances (Sabuncuoglu and Hommertzheim 1990). Analysis showed that SPT and SPT.TOT appeared to be the best rules with any combination of AGV rules. In most of the cases, SPT performed better than SPT.TOT. Among the AGV rules that they tested, STD and LQS were the best AGV rules with any machine scheduling rule combination. However, LQS always dominated the STD rule when the queue capacities were decreased. They found that with the increase in machine and AGV loads (or utilizations), the mean flow-time also increases.

As no single dispatching rule can dominate all other rules in all situations, importance have to be given to other measures of performance also. None of the rules tested in the above two research studies have used information related to both job and resource. Also, resource information of the downstream machine is not used.

2.4 Tool Sharing Strategies in FMS

Allocation of required tools to meet the processing needs of component parts and products is an important element of FMS production planning. The following research studies describe heuristics that can be used to allocate tools to an FMS.

Kashyap and Khator (1995) analyzed tool sharing in an FMS using simulation. They studied the impact of tool request selection and tool dispatching rules in a tool sharing environment. Request selection rules are invoked when more than one request for a tool are pending. Tool selection rules, on the other hand, come into play when there are more than one copy of tools in the system. The authors used a "look ahead" policy to determine the status and condition of a tool required for the next operation when the current operation is in progress. A control rule is then used for selecting a tool request. A tool selection rule is then applied when a tool is available at more than one machine.

Request selection rules that were studied are first come first served (FCFS), least number of operations remaining (LOR) and shortest processing time (SPT). Tool selection rules that were studied are shortest distance traveled by tool transporter (SDT) and high value of tool life (HVTL). The above rules are tested on a four machine FMS system. AGVs are used for the transportation of workpiece and tools. Performance measures collected were makespan and tool transporter utilization. Design of experiments technique was used to analyze simulation outputs. The experimental factors considered were tool duplication (single copy, two copies, and three copies), request selection (FCFS, LOR, SPT), product mix (four job-types equal mix, randomly generated job-types) and tool selection (SDT, HVTL).

Results from ANOVA indicated that tool duplication and product mix significantly affects the performance of the system for both makespan and tool transporter utilization. Request selection rules do not significantly affect the utilization of the tool transporter and makespan. However, both measures are significantly affected by request selection rules when there is only one copy of tools. Tool selection rules significantly affect the tool transporter utilization, while it has no significant effect on makespan.

Amoako-Gyampah and Meredith (1996) evaluated three heuristic procedures: tool and part batching, tool sharing and flexible tooling to allocate the required tools in order to meet the cutting needs of component parts and products in an FMS. The main purpose behind this research was to compare tool allocation procedures that are aimed at reducing the frequency of tool changes with those aimed at better utilization of tool magazine capacity.

Tool and part batching approach partitions part types for a specified planning period into separate batches to be machined individually. Assuming there is enough machine capacity to process all parts during a planning period, the need to divide the parts into batches arises mainly because of limited tool magazine capacity at the machines. In this approach, the authors assign parts to batches based on first selecting part types that require the largest number of tool slots which would mean fewer tool changes may be required. Main drawbacks of this approach, as pointed out by the authors are excessive tool inventory and greater tool handling time as it ignores tool sharing among part types.

Tool sharing approach recognizes tool commonality among part types. Failure to recognize this may lead to unnecessary tool duplication and underutilization of tool magazine capacity. By this way, more orders can be selected into a batch.

Flexible tooling approach aims at minimizing the bottleneck effects of the tool magazine capacity at each machine. This approach is implemented by the authors as follows: when part types are selected for production, their required tools are allocated to the machines, and the tool slot consumption at each machine is updated just as in the tool-part batching procedure. Following the completion of the part types requiring those tools, any tools not fully consumed are removed from the tool magazine while another part is being machined. This frees up space on the tool magazine to permit the selection of another part type to be processed and the allocation of the needed tools to the machine. The tools that are removed can be migrated to other machines or to the central toolcrib. The authors suggest that this approach has the potential of reducing cutting tool inventory and leads to higher utilization of the tool magazine capacity.

The authors tested the above heuristics for an FMS processing 10 and 25 part types. The FMS consists of five identical machines capable of processing any part types if allocated with the needed tools. The tool magazine at each machine has a tool slot capacity of 30. AGVs are used to move parts to and from the machines. In addition to the AGVs, there is one robot that loads and unloads parts from the machines. The robot also changes and shuttles the cutting tools.

The performance of heuristics were tested against mean tardiness, percentage of orders tardy and mean flow time of orders processed on the FMS. Results indicated that for both low and high part type mix, the flexible tooling approach outperforms the tool batching and tool sharing approaches on all performance measures.

Merchawi et al. (1996) developed dynamic dispatching rules in FMS where multiple shared resources are needed to complete one task. The study includes modeling of five expensive tool types that are shared among four machines for processing four part types.

They tested three resource allocation rules, namely Strict Wait for Resources (SWFR), Strict Available Resources First (SARF), and Available Resources Preferred (ARP). SWFR prioritizes jobs based on arrival time, i.e., on a First In First Out basis. SARF prioritizes jobs based on the smallest value of difference between number of required resources and number of available required resources. ARP prioritizes jobs based on the smallest value of the following calculation,

$$\text{Priority} = w1 \times \frac{\text{Current time- Arrival time}}{\text{Average flowtime}} +$$

$$w2 \times \frac{\text{Number of Required Resources - Number of Available Resources}}{\text{Number of Required Resources}}$$

The variables $w1$ and $w2$ are the weights to be assigned based on whether waiting time or resource availability is more important. The authors assign a larger weight to resource requirement over the waiting time, i.e., $w1 = 0.3$ and $w2 = 0.7$.

The authors used simulation to test the performance of the rules. The dispatching rules are applied to control the example FMS and their relative performance was studied. Results indicated that ARP rule performed well with respect to mean flowtime followed by SARF. ANOVA analysis between the different dispatching rules at various values of the inter-arrival time showed that the difference in performance of the dispatching rules is significant at a confidence factor of 93% at lower values of inter-arrival time.

2.5 Contributions of this Research

Note that the above review is by no means an exhaustive one. It is however fairly representative with respect to priority rules, performance measures and environments used in previous research.

Though the literature in AGV dispatching rules, job dispatching rules and tool management rules is very rich and extensive, very little research has been attempted to derive rules to govern the allocation of the mixture of resources in a shared multiple resource environment. In this study, the simultaneous scheduling of both machines and material handling system is considered, and composite scheduling rules which can flexibly cope with the change of system configuration are developed for FMS. These rules are dynamic since they incorporate the status of the system as it evolves over time. One of the machine-scheduling rules uses the information of downstream machine to schedule jobs in the current machine. Vehicle-initiated rules are developed for AGV dispatching in the study.

In the published research, there is not much importance given to the allocation of additional resources required for operating a job on each machine. These additional resources may include pallets, fixtures, cutting tools, or even a human operator. Throughout this study these additional resources are referred to as "tools." A part undergoing an operation on a machine will have to request the required tools before processing can take place. The requested tools are released after completion of that operation. The proposed machine-scheduling rules are then applied to allocate the released tools to waiting jobs. In practice, some types of additional resources, such as pallets and fixtures, are released after all operations on the job are completed. Though this study does not explicitly model such additional resources, it is expected that they would show similar effect as the job request for the other types of resources that are needed only for a particular process. In fact every resource in our study has a separate queue and the jobs in queue will have to be prioritized upon their availability.

Most of the scheduling rules proposed in previous research do not provide information to break the tie when two or more jobs receive the same prioroty. For instance, First-Come-First-Serve (FCFS) is a common rule for a resource to select a job. Considering a busy manufacturing environment, jobs may arrive at various workcenters at the same time. This situation calls for a tie-breaking rule to further prioritize the jobs. In general, the tie-breaking rule could be another simple scheduling rule. But whether a tie-breaking rule can significantly affect the FMS performance has not been fully explored in the published research. This research provides practical yet simple composite rules which combine the primary scheduling rules with tie-breaking rules.

The simulation experiments are carried out in more realistic situations than in the published research. That is, this study includes limited buffer capacity, limited number of AGVs, and simultaneously considers multi-criteria performance measures which are either not included at all or only partially included in the previous research studies. Also, the FMS scheduling rules are tested under a variety of experimental conditions including varying the nature of shop. Factors such as type of shop being flow shop or job shop, and machine load level were found to influence decision making in static environments, but were not addressed for FMS dynamic scheduling. So, these factors are considered in the study to see if they influence rule selection. The rules are studied for both flow shop and job shop types wherein for each shop type the machine load-level is balanced in one case and in the other a bottleneck machine is introduced. Also, a new approach is developed here to determine the nature of shop (i.e., flow shop or job shop) and presence of a bottleneck machine.

In this research, a comprehensive study of different rules in different environments is conducted and compared with respect to different performance measures such as flowtime, consistency of output, and efficient operation of AGVs.

Chapter 3

Scheduling Rules

This chapter describes the details of the FMS scheduling rules that are developed to improve system performance. Machine scheduling rules and AGV dispatching rules are dealt in separate sections.

3.1 Concepts Used in FMS Scheduling

The solution procedure of the FMS scheduling problem can be classified based on the type of scheme used to generate schedules. Sabuncuoglu and Hommertzheim (1992) have identified two types of scheduling schemes: off-line and on-line. Off-line scheduling refers to scheduling all operations of available jobs for the entire scheduling period, whereas on-line scheduling attempts to schedule operations one at a time when they are needed.

Off-line scheduling methods are better suited for static environment where the job arrivals and processing times are deterministic. The on-line scheduling approach is used for a stochastic system which involves variations in job arrival time and processing times. Dynamic scheduling is a short-term decision-making process which generates and updates the schedule based on the current status of the system and the overall system requirements and the scheduling decision is made when the state of the system changes, such as job completion, arrival of parts, etc.

According to the above classification, the scheduling procedure proposed in this research can be considered as an on-line approach that employs dynamic scheduling concepts.

Since scheduling of machines and AGVs are under study, scheduling rules can be classified into machine scheduling rules and AGV dispatching rules. These rules prioritize jobs for resources (i.e., machines or AGVs) upon their availability. And by their nature, these rules are very suitable for on-line scheduling implementations. Machine-scheduling rules do not consider the availability of AGVs when the priorities of jobs are set for any workstation. Similarly, AGV scheduling rules do not directly take into account availability of machines for jobs to be served. Therefore, in implementation, these rules form a dispatching mechanism consisting of two independent sets of rules, one for each type of resource (i.e., machining and AGV subsystems).

In a multiple shared-resource environment, an operation can only be started if all the required resources for that task are available. Therefore, the scheduling rules must be developed so that the time spent waiting for any resource is minimal. For instance, a transportation task requires the availability of an AGV as well as a buffer space at the destination machine. If an AGV was dispatched to this job, but no buffer space was available, the dispatched AGV ends up waiting when it could have been used for another transportation task. AGV dispatching rules that do not take into account the need for other resources would be inefficient. The same scenario applies to machining tasks that require a machine, a certain tool, and possibly a robot to be available. FMS scheduling rules should take into account the availability and the current status of all required resources.

Composite scheduling rules are developed in this research to prioritize jobs on resources. These rules incorporate tie-breaking concepts which is essential when two or more jobs receive the same priority.

3.2 Machine Scheduling Rules

Machine scheduling rules prioritize jobs on a machine upon the completion of current machining service. The allocation of additional resources required for operating a job on each machine is considered in this research. These additional resources are referred to as 'tools' and may include expensive cutting tools, robots or even a human operator that are needed only for the operation on that machine. A part undergoing an operation on a machine will have to request for the required tools before processing can take place and are released after processing is completed on that machine.

The request for resources, namely the machine and tools, can be sequential or simultaneous:

Sequential Request This mode allows a job to grab the required machine first and then seek to grab the tools as required. If any of those tools is not available, the machine cannot process any other job waiting at the input.

Simultaneous request This mode allows the job to place a simultaneous request for all the required resources namely, the machine and tools as required. If the request is not satisfied then the job joins a waiting queue and another lower priority job could use that machine in the meantime.

Consider a situation where jobs are awaiting service in front of a machine. Under sequential request mode, the high priority job will seize the machine even if the required tools are not available. Therefore, the machine would be left idle when it could have actually been used by some other low priority job for which tools are either not required at all or are available for use. Unnecessary blocking of the machine would cause the input queue size to increase. Since an FMS is characterized by limited buffer capacity, a blocking situation may also arise. To overcome this problem, simultaneous request mode is recommended which will assign the job to a machine for which all the required resources are available. Also, preliminary testing of the request modes showed that sequential request did not perform well as it caused a lot of blocking situations and so it was dropped.

All machine scheduling rules developed here use simultaneous mode of request for resources. Based on the classification for machine scheduling rules made in Chapter 2, the rules developed use information related to both job and resource. The following machine scheduling rules are tested:

3.2.1 Shortest Imminent Operation (SIO)

This rule works in the following manner: When a job arrives processing at a station, it starts immediately if all the required resources are available. Otherwise, the job joins a waiting queue that is common to the whole system. Then whenever any resource becomes available, the waiting queue is scanned and, among the jobs that have all their resources available, the one with shortest processing time at the current station is selected for processing. Ties are broken by First-In-First-Out (FIFO) to the waiting queue.

In single machine static scheduling problems, shortest processing time dispatching is known to minimize average flowtime and average lateness measures. SIO is a variation of this rule for the dynamic environment. In the published research of Montazeri et al. (1990) and Sabuncuoglu et al. (1992), machine scheduling rules for an FMS environment were evaluated and SIO rule showed better performance with respect to mean flowtime measure over the other rules that were tested. Therefore, SIO is used as a benchmark for comparison of the machine scheduling rules that are developed in this research.

The SIO rule uses only job information for performing priority calculation. Specifically, the processing time for each job at the current machine is required for implementing the rule.

3.2.2 Longest Queue of Machines with tie-breaking (LQM)

This rule allows the job to place a request for all the required resources. If the request is not satisfied, the job waits at the input buffer. Whenever a resource is relinquished after completing an operation, this rule permits the available tools to be used by the machine that has the highest number of jobs on the input side. Ties are broken by least number of jobs at the input of next destination machine of the job. Further ties are broken by SIO, then FIFO to the waiting queue.

This rule prevents machines from becoming the bottleneck resources since the jobs waiting at the machine with the longest queue size are given the highest priority to use the available tools for processing the jobs. Intuitively, this rule should work well in terms of preventing system blocking and in terms of reducing long waiting times for jobs in front of a single machine.

Compared to SIO, LQM rule uses additional information such as the queue size of primary resource, namely current and succeeding machines for implementation.

3.2.3 Maximum Request for Tools with tie-breaking (MRT)

MRT rule operates in the following manner: When a job arrives for processing at a station, it starts immediately if all the required resources are available. Otherwise, the job waits at the input buffer. Then whenever a resource becomes available, this rule checks the queue size of each tool. The tool with maximum pending requests is found and the corresponding jobs waiting for this tool in the queue are sorted based on the high queue size of the other tools required for the current operation. If there is still a tie, then the high queue size of current machine is used. Further ties are broken by SIO, then FIFO to the waiting queue.

This rule prevents tools from becoming the bottleneck resources since the tool with the highest queue size is always considered and jobs waiting for those tools are given the highest priority. Intuitively, this rule should have a similar effect to

LQM when the utilization of additional resources in the system is higher than that of primary resources.

Unlike SIO and LQM, MRT rule uses information related to additional resources to prioritize the jobs. Information such as queue size of tools, queue size of the current machine, and processing time of job at the current machine are used for implementing the rule.

3.3 AGV Dispatching Rules

An AGV dispatching rule prioritizes jobs on an idle AGV to move a part from one location to another location in the manufacturing system. If there is no request, the AGV remains idle and awaits for a transportation task to emerge. At each station, a job seizes the input buffer of the next station before it is physically transported to the next station. The proposed rules use important attributes in addition to the distance between the pick-up station of a job and free AGV locations for priority calculation. The following AGV dispatching rules are tested:

3.3.1 Nearest Station (NS)

A job in need for AGV first looks for an idle vehicle. If there are more than one idle vehicle, then the nearest AGV is selected. On the otherhand, if all AGVs are busy, then the job joins a queue for AGV. When an AGV gets relinquished later on in the system, the waiting queue is scanned and, the job which is at the pick-up workstation nearest to the relinquished AGV is selected. If there are no load requests, then the relinquished AGV stays in the same station.

This rule is used here as a benchmark for comparison purposes. Lee (1996) evaluated AGV dispatching rules for a job shop environment and showed that vehicle-initiated rules perform better than the workcenter-initiated rules. Of the vehicle-initiated rules that were tested, the NS rule showed superior performance.

The distance between the location of idle AGV and the pick-up station of jobs is the only attribute used in NS rule.

3.3.2 Queue Size and Nearest Station (QSNS)

A job in need for AGV looks for an idle vehicle. If there are more than one idle vehicle, then the nearest AGV is requested. On the otherhand, if all AGVs are busy, then the job joins a queue for AGV. Whenever an AGV gets relinquished in the system, it checks for the output queue size of all the stations. If there is a workstation with output buffer that is nearly full (output buffer capacity less one), then the AGV moves to this station for pick-up. Ties broken by nearest station to the relinquished AGV. Otherwise, it moves to the nearest station with travel request. Ties broken by high number of jobs in the output buffer. If there are no travel requests, then the relinquished AGV stays in the same station.

In summary, this rule can be written as:

- *When a job finishes processing and there is space at destination:*
  - If there is only one idle vehicle, select that vehicle.
  - If two or more idle vehicles are available, select the nearest vehicle.
  - If all AGVs busy, join a single waiting line and, wait until a vehicle is available.
- *When an AGV finishes delivery:*
  - If waiting line is not empty:
    * If there is one station with output buffer nearly full, select that station. Jobs in waiting line at that station are prioritized FIFO.
    * If two or more stations have output buffers nearly full, select the nearest station. Jobs in waiting line at that station are prioritized FIFO.

    * If no station is nearly full, the AGV selects the nearest station with travel request. Ties are broken by the highest number of jobs in the output buffer, then by FIFO to waiting line.

  - If waiting line empty, the AGV stays at the place where it became idle and waits for a pick-up request.

This rule is a modification of HQ-NS rule that was developed by Lee (1996). As explained in Chapter 2, HQ-NS is a vehicle-initiated rule that operates in the following manner: The AGV goes to the pick-up station of the assembly line with the highest number of in-process jobs. If there are two or more stations having the highest number of jobs, the AGV goes to the nearest station. If there is no load assignment on the list, it waits for the next assignment to emerge.

The HQ-NS rule is modified here to suit the FMS environment which is characterized by limited local buffers. Consider a situation where jobs may happen to be waiting for pick-up at the current drop-off station of the AGV for which the empty travel time is practically zero. Under HQ-NS rule, the idle AGV moves to the pick-up station which has relatively more number of jobs than the current drop-off station. If this station happens to be farther away from the current drop-off station, the empty travel time would be high enough that the station where it had left will start to have equal number of jobs waiting for pick-up. Therefore, to improve the efficiency of AGV operation, the QSNS rule is developed. An idle AGV serves a job waiting at the station nearest to it unless the output buffer of some other station is nearly full.

The QSNS rule uses attributes such as the distance between the location of idle AGV and the pick-up station of jobs, and the output queue size of each station.

3.3.3 Nearest Unassigned Job (NUJ)

A job in need for AGV first looks for an idle vehicle. If there are more than one idle vehicle, then the nearest AGV is selected. On the otherhand, if all AGVs are busy, then the job joins a queue for AGV. When an AGV gets relinquished later on in the system, it checks if there are jobs waiting at the current drop-off station. If so, it serves this job. Ties are broken by high difference between number of jobs waiting and number of AGVs destined at the destination station. If there are no jobs waiting at the current drop-off station, then the free AGV checks the destination of all other vehicles and chooses the nearest pick-up station for which the number of AGVs dispatched is less than the number of jobs waiting at the output buffer. Ties are broken by high difference between number of jobs waiting and number of AGVs destined. If there are no load requests, then the relinquished AGV stays in the same station. This rule can be written as:

- *When a job finishes processing and there is space at destination:*
  - If there is only one idle vehicle, select that vehicle.
  - If two or more idle vehicles are available, select the nearest vehicle.
  - If all AGVs busy, join a single waiting line and, wait until a vehicle is available.
- *When an AGV finishes delivery:*
  - If waiting line is not empty:
    * If only one job in the waiting line is at the current drop-off station, select that job.
    * If two or more jobs in the waiting line are at the current drop-off station, select the job which has the highest difference between number of jobs waiting and number of AGVs destined at the destination station.

    * If no job wait at the current drop-off station, the AGV selects the nearest station for which the number of AGVs dispatched is less than the number of jobs waiting at the output buffer. Ties are broken by the highest difference between number of jobs waiting and number of AGVs destined, then by FIFO to waiting line.

  - If waiting line empty, the AGV stays at the place where it became idle and waits for a pick-up request.

This rule is developed to avoid unnecessary assignment of an idle AGV to a job waiting at its pick-up station for which there is an AGV already assigned for a drop-off task, thereby reducing the empty travel of AGVs.

The NUJ rule uses attributes such as the distance between the location of idle AGV and the pick-up station of jobs, the output queue size of each station, and number of AGVs dispatched to each station.

3.4 Machine-AGV Rule Combinations

The three machine scheduling rules are each combined with the three AGV dispatching rules to study the possible interactions. Each of the nine combinations are treated as separate rules and applied to control the hypothetical FMS described in the following chapter. The relative performance of the rules are then studied.

Chapter 4

System Description and Simulation

This chapter is devoted to the description of the hypothetical FMS used to study the performance of scheduling rules. The system along with various scheduling rules has to be simulated to collect the relevant performance measures. This chapter also explains how the system was modeled and how the simulation experiments were carried out.

4.1 Strategy

The objective is to apply the scheduling rules to control a hypothetical FMS under different experimental conditions. Experimental factors such as time between arrivals, arrival distribution, type of shop, bottleneck machine, duplicating tools and AGV speed are considered in the study. A new approach is developed to implement the type of shop and bottleneck machine factors by varying the proportion of job-types. This requires to develop a system for which the experimental factors can be varied independently of one another.

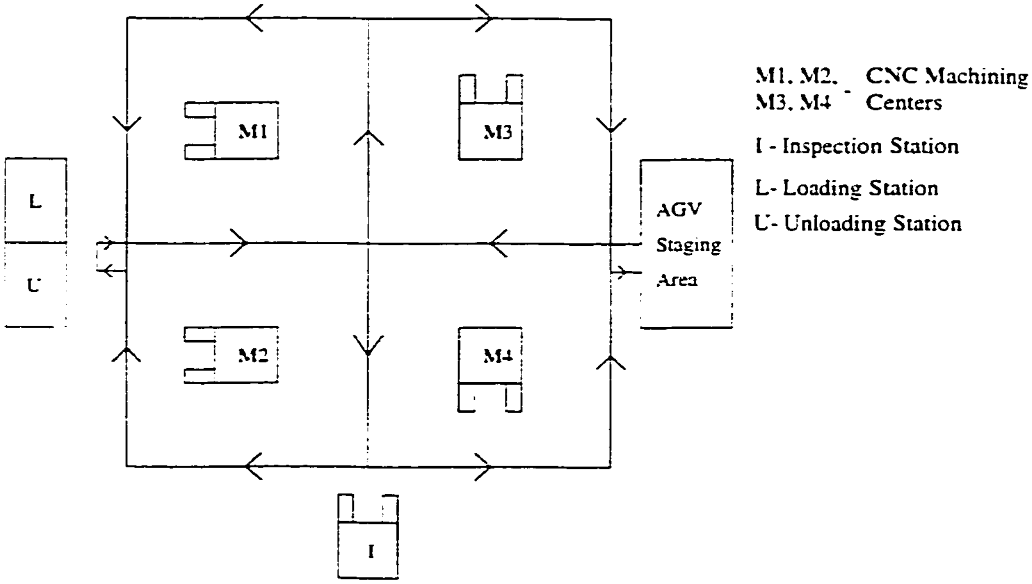


Figure 4.1: Layout of hypothetical FMS.

4.2 System Description

The hypothetical FMS under study shown in Figure 4.1 consists of four machines M1, M2, M3, M4 and an inspection station I. All jobs undergo inspection before leaving the system. Parts are transferred by three AGVs in the system. The number of AGVs needed in the system was determined based on a preliminary simulation study. Parts enter and leave the system through the loading/unloading station. Each machine has a set of input and output buffer space of a limited size with higher capacity on the input side (9) and a lower on the output side (4), which were also determined based on a preliminary study.

Four types of jobs are manufactured in this system and their processing sequence is given in Table 4.1. These routeings were selected in such a way that changing the proportion of job-types arriving in the system will result in varying the type of shop experimental factor. The job-types J3 and J4 involve opposite routes through machines M1 and M2, but job-types J1 and J2 do not. Therefore, by generating more number of job-types J1 and J2 than job-types J3 and J4, the shop is more of a flow shop type. On the other hand, if more number of job-types J3 and J4 are generated compared to J1 and J2, the shop is more of a job shop type.

All processing times are assumed log-normally distributed (Law and Kelton 1991) with mean as given in Table 4.1 and standard deviation equal to one. The processing times are selected so that proportions do not affect average utilization of any machine. Each job has three operations and each assigned operation is assigned to a different machine. At each of the machines, different types of tools are required by each of the jobs as shown in the table. Tools are distributed among the job-types in such a way that the variations in job-type proportions do not affect the average utilization of any tool.

Furthermore, the bottleneck machine factor can also be controlled by varying proportions of job-types, and this can be done independently of the type of shop variation. By keeping the total proportion of job-types J1 and J2 same, and varying their relative proportion will let the shop to be a flow shop type but the bottleneck machine factor can be varied. Similar concept is used for job-types J3 and J4 in the job shop case. This variation in proportion of job-types enables to vary the experimental factors independently. These are dealt in a detailed manner in the following chapter.

The mean inter-arrival time is treated as an experimental factor to study the FMS for different levels of system congestion.

4.3 AGV Layout

The distance between the two ends of each segment is 6.17 distance units in the layout. Also, the accompanying arrows show that the layout considered is uni-directional. The distance between any two locations of stations is shown in Table 4.2.

JOB-TYPE	OPERATION	MACHINE REQUIRED	TOOLS REQUIRED	PROCESSING TIME (min)
J1	1	M1	-	8
	2	M3	TA,TC	4
	3	M4	TB,TD	4
	4	INSPECTOR	-	4
J2	1	M2	-	8
	2	M3	TA,TB	4
	3	M4	TC,TD	4
	4	INSPECTOR	-	4
J3	1	M2	TB,TC	8
	2	M4	-	4
	3	M1	TA,TD	4
	4	INSPECTOR	-	4
J4	1	M3	-	8
	2	M1	TC,TD	4
	3	M2	TA,TB	4
	4	INSPECTOR	-	4

Table 4.1: Processing sequence of job-types with required resources.

	M1	M2	M3	M4	INSPECT	LOAD	UNLOAD
M1	-	24.69	18.52	18.52	15.43	6.79	5.56
M2	24.69	-	18.52	18.52	15.43	4.32	3.09
M3	30.86	30.86	-	24.69	21.60	35.19	33.95
M4	30.86	30.86	24.69	-	21.6	35.19	33.95
INSPECT	33.95	9.26	27.78	3.09	-	13.58	12.35
LOAD	22.84	22.84	16.67	16.67	13.58	-	3.70
UNLOAD	24.07	24.07	17.90	17.90	14.81	1.23	-

Table 4.2: Distance matrix of the hypothetical FMS.

AGV layout is designed such a way that the total loaded travel distance are the same for all job-types and, therefore changing proportion of job-types does not affect AGV load. The AGV load is varied by varying speed.

J1: LOAD $\rightarrow$ M1 $\rightarrow$ M3 $\rightarrow$ M4 $\rightarrow$ INSPECTOR $\rightarrow$ UNLOAD

$= 22.84 + 18.52 + 24.69 + 21.60 + 12.35 = 100$ distance units.

J2: LOAD $\rightarrow$ M2 $\rightarrow$ M3 $\rightarrow$ M4 $\rightarrow$ INSPECTOR $\rightarrow$ UNLOAD

$= 22.84 + 18.52 + 24.69 + 21.60 + 12.35 = 100$ distance units.

J3: LOAD $\rightarrow$ M2 $\rightarrow$ M4 $\rightarrow$ M1 $\rightarrow$ INSPECTOR $\rightarrow$ UNLOAD

$= 22.84 + 18.52 + 30.86 + 15.43 + 12.35 = 100$ distance units.

J4: LOAD $\rightarrow$ M3 $\rightarrow$ M1 $\rightarrow$ M2 $\rightarrow$ INSPECTOR $\rightarrow$ UNLOAD

$= 16.67 + 30.86 + 24.69 + 15.43 + 12.35 = 100$ distance units.

This way irrespective of the type of shop (flow shop, job shop) and machine load level (balanced, bottleneck machine) combination, the average loaded travel time would be the same.

4.4 Tool Utilization

Tools are distributed among job-types such that the utilization of tools are not affected by varying the proportion of job-types. This implies that the expected utilization of tools will remain the same irrespective of the nature of shop. Tool load is varied by varying the number of tool copies i.e., having a duplicate for each tool type.

4.5 Assumptions

The following assumptions are made in carrying out the simulation studies:

1. No job pre-emption is allowed. Thus, an operation once begun should be completed before starting the next operation.
2. Part routeing for each job as well as the resource requirements are predetermined and there are no alternatives.
3. Tool availability is immediate.
4. There are no major disturbances on the shop floor, e.g., no machine breakdowns or tool failures. Minor disturbances are assumed to be accounted for in the job machining times.

4.6 System Modeling and Simulation

Simulation is used to analyze the performance of the rules. One important advantage of a simulation experiment is that we can manipulate the different input parameters such as arrival distribution, mean inter-arrival time and so on to study their effects on the system and to evaluate performance of the scheduling rules.

In order to carry out the simulation experiment, it is necessary to model the system. The system described in Figure 4.1 along with the various scheduling rules is modeled using SIMSCRIPT II.5 language. The simulation modeling logic is shown in Figure 4.2.

For each queue in the system, namely queue for machine and queue for AGV, there is a corresponding routine which calculates the dynamic priorities of the

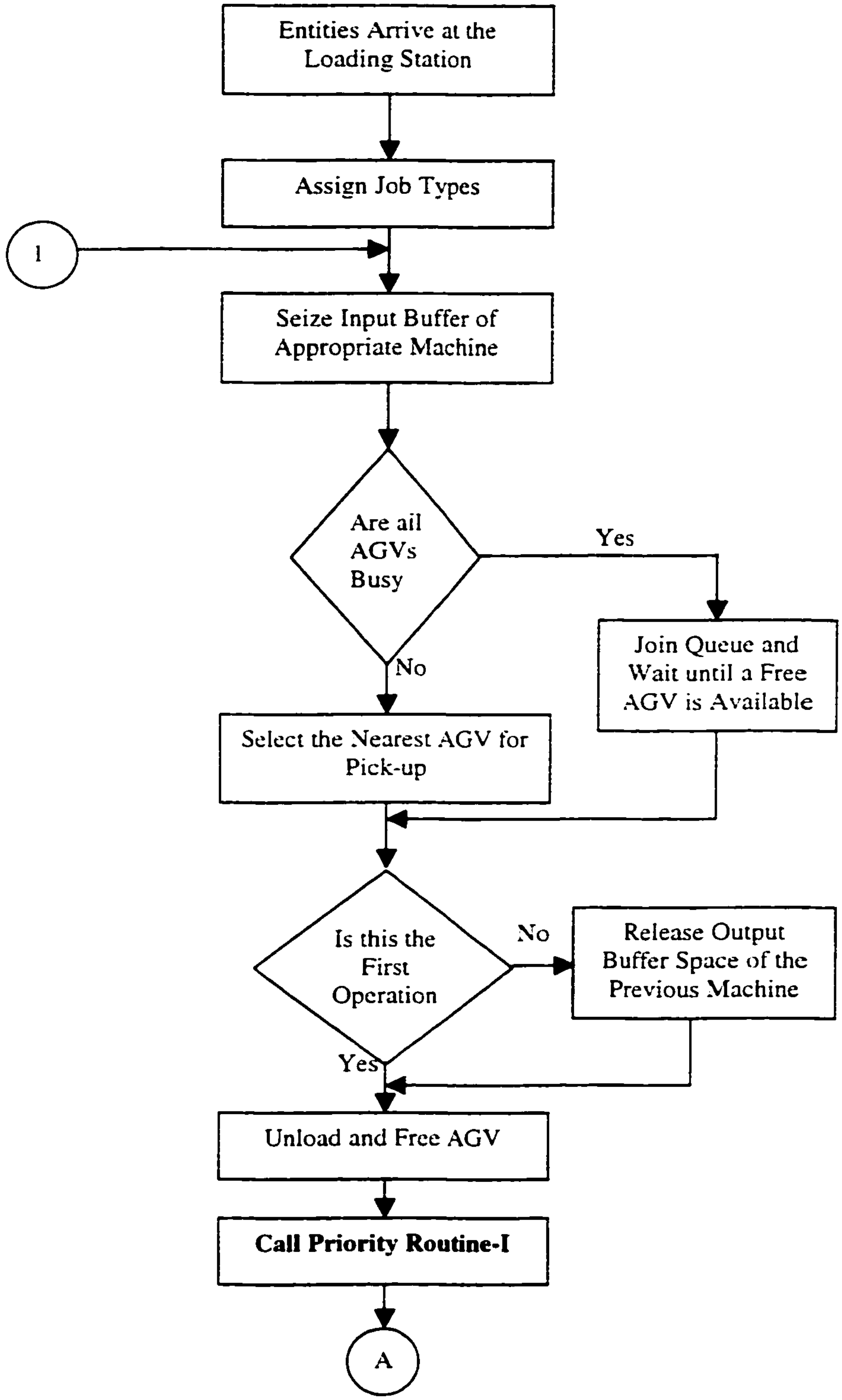


Figure 4.2: Flowchart of simulation program.

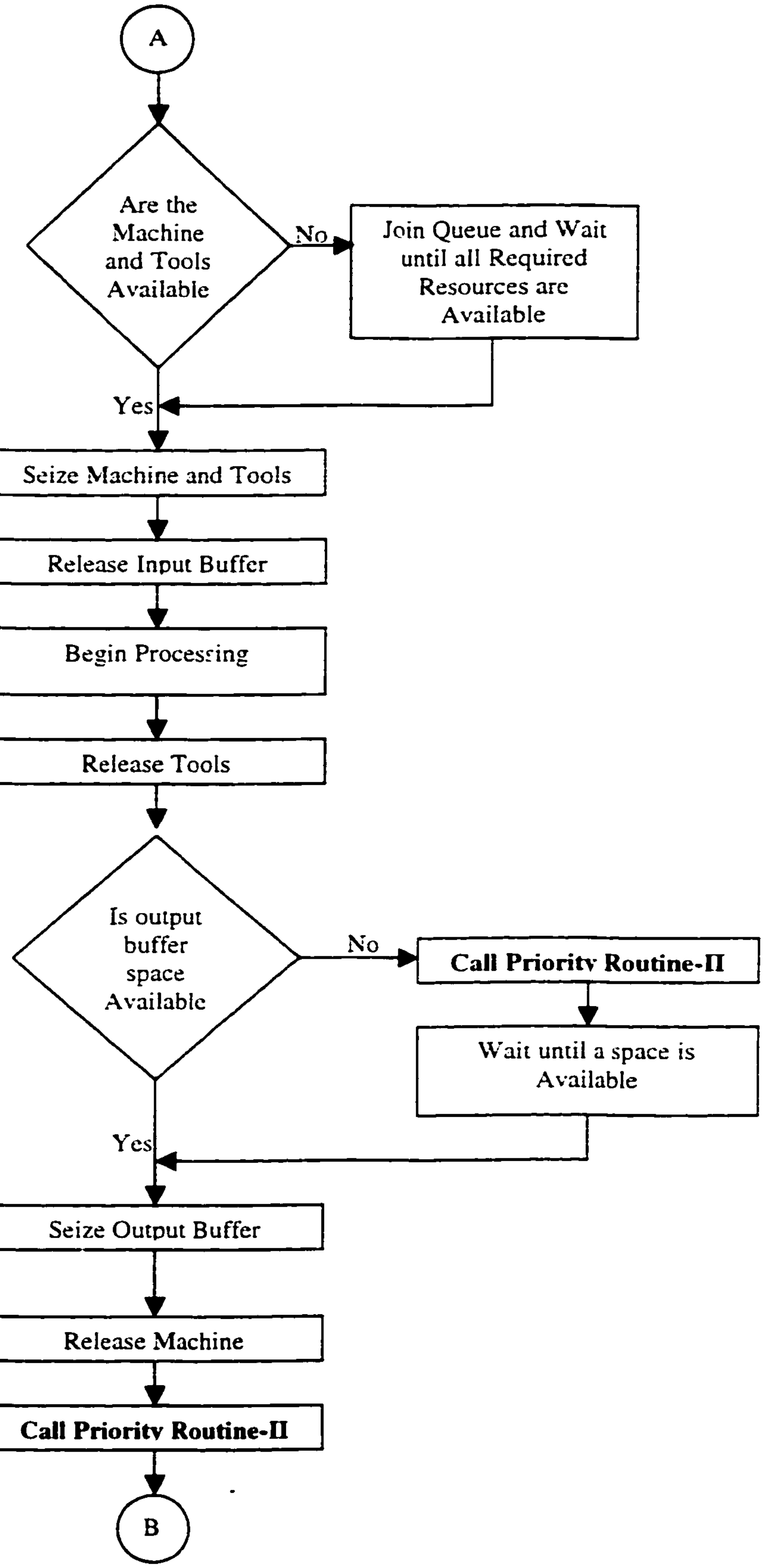


Figure 4.2: Flowchart of simulation program (continued).

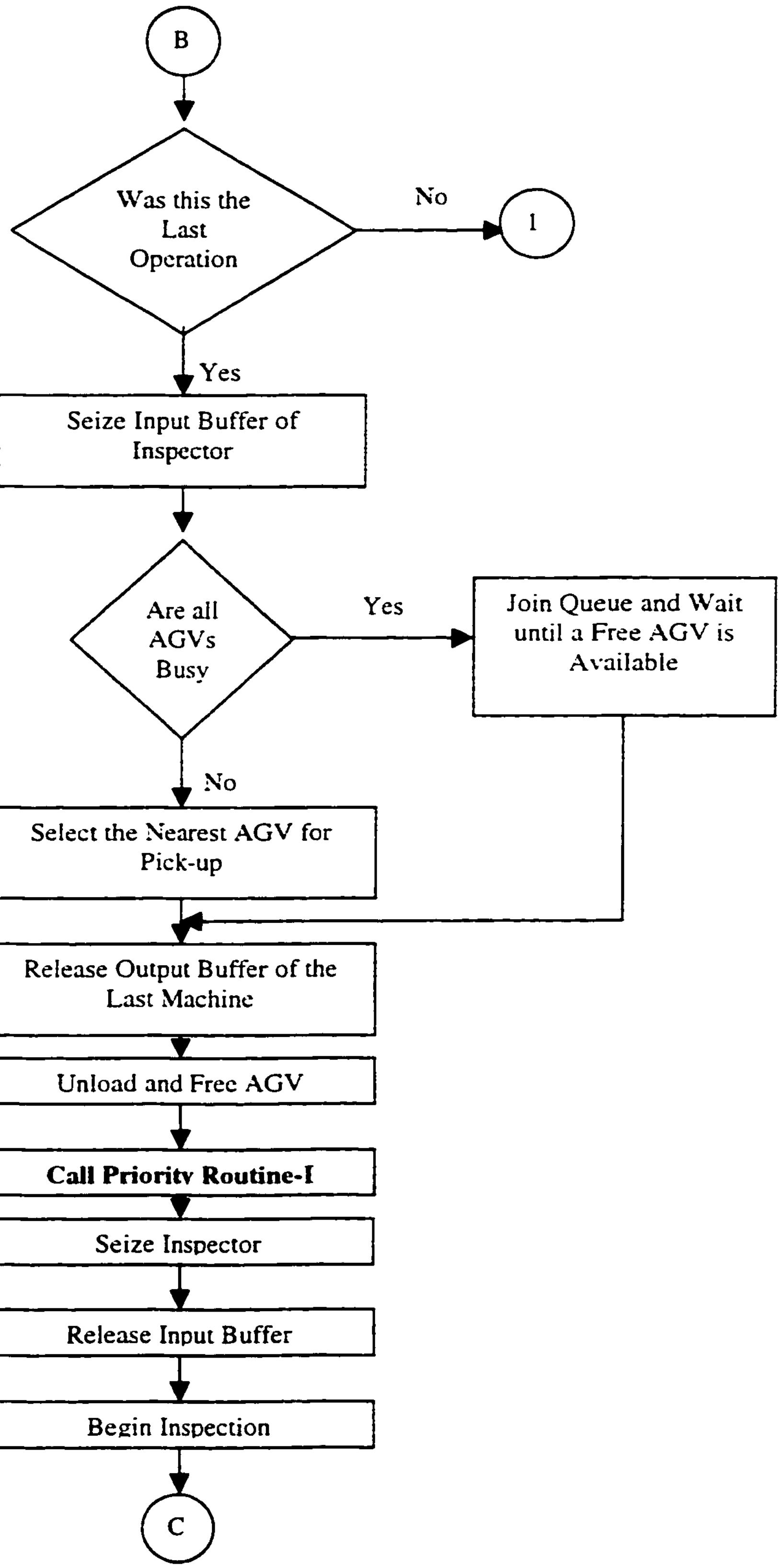


Figure 4.2: Flowchart of simulation program (continued).

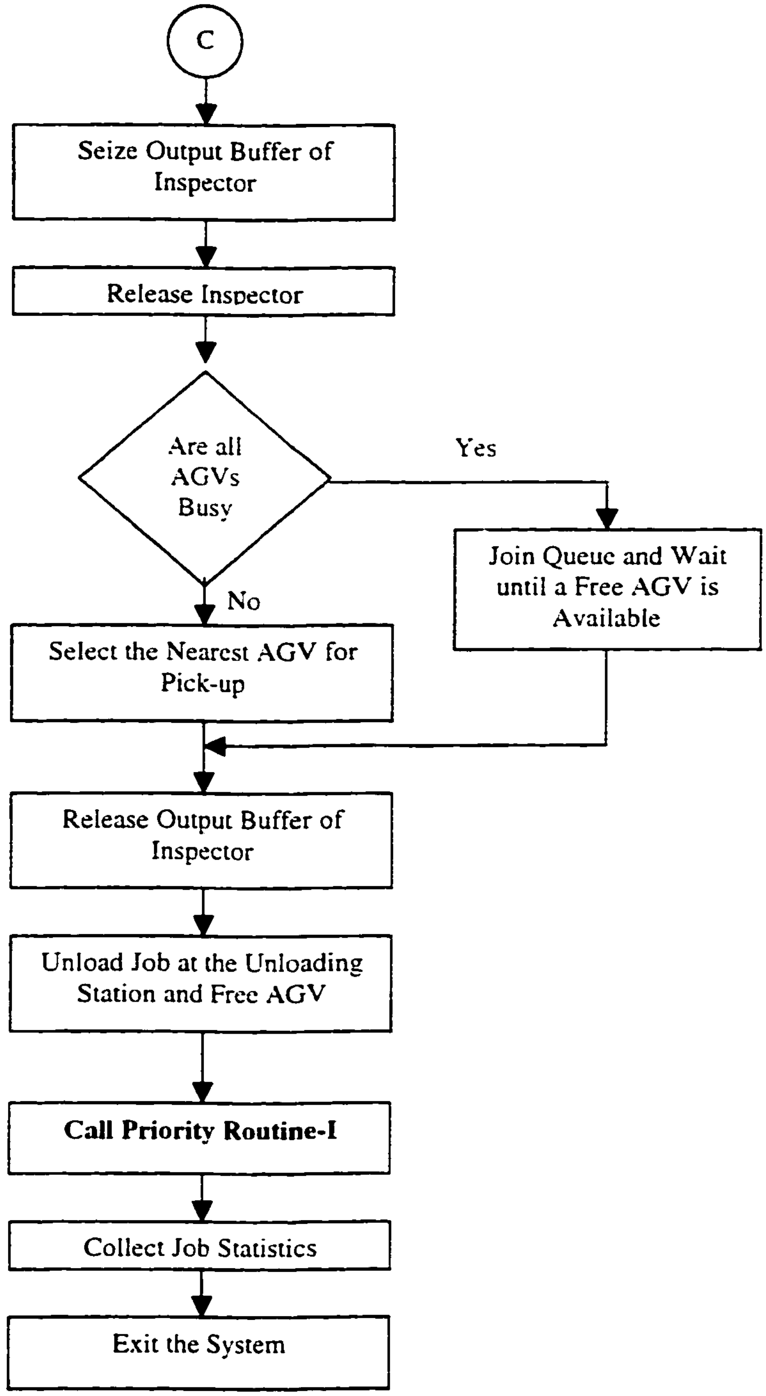


Figure 4.2: Flowchart of simulation program (continued).

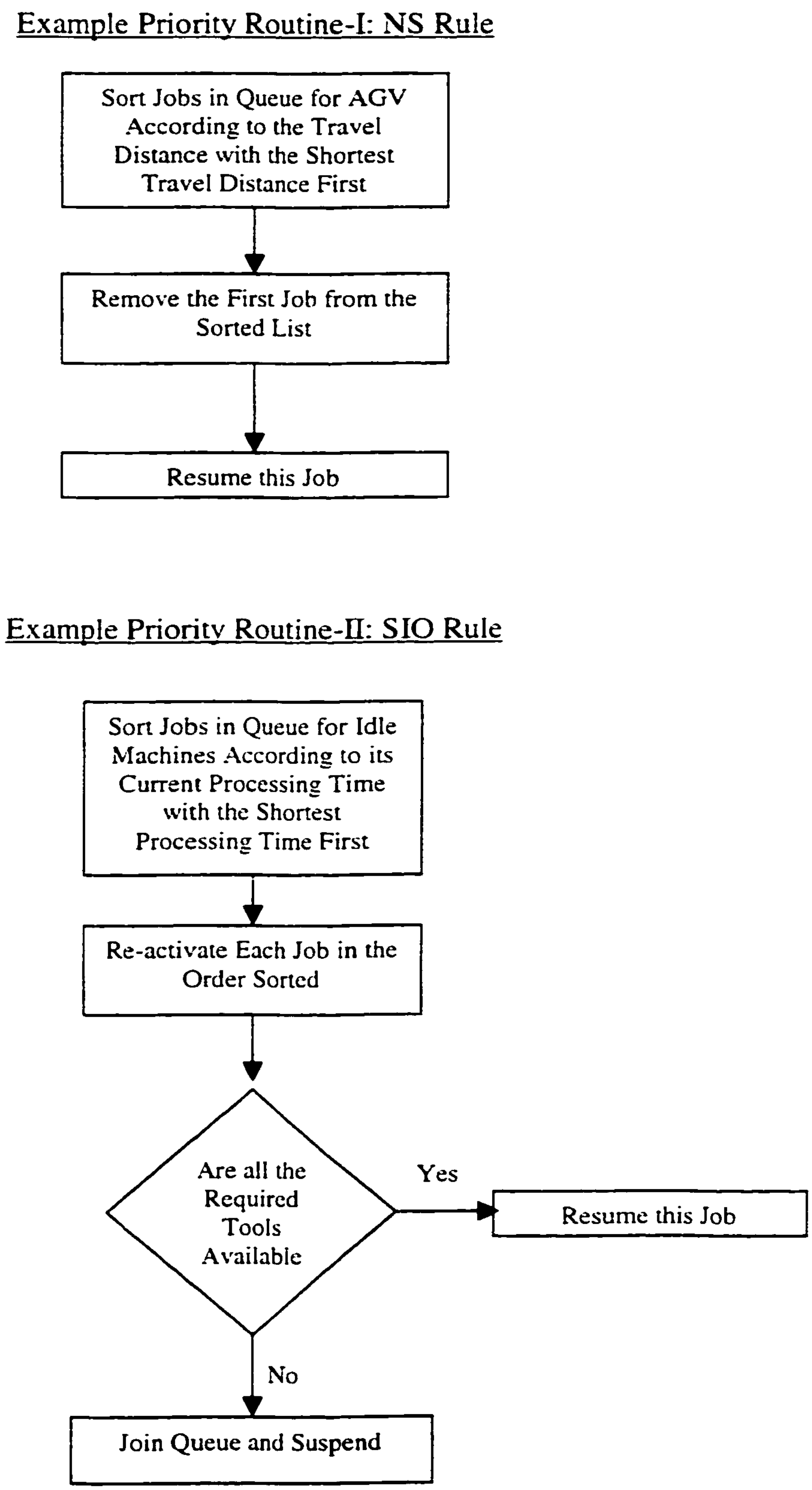


Figure 4.3: Priority routine for machine and AGV scheduling rules.

parts/jobs in the queue. Figure 4.3 explains the priority routines for SIO machine scheduling rule and NS AGV dispatching rule. The jobs in the queue are then automatically ordered according to the priority attribute. The priority calculation routines are called whenever a resource finishes a job and is ready to start a new job from its queue.

4.7 Experimental Conditions

The model is initially simulated for 200 hours and 10 replications in order to determine the warm-up period of the system using Welch's procedure. It is found that the system requires about 60 hours to reach steady state. For the purpose of analysis, the run length is fixed to be for 10 eight-hour shifts and the number of replications as 20. Initial testing showed that this is enough to get confidence in the results and draw statistically significant conclusions.

4.8 Variance Reduction Technique

Since the objective was to measure the relative performance of alternative rules, it was logical to compare them under identical conditions. The use of *common random numbers* variance reduction scheme ensured that each job arrived at the same time and was assigned identical set of processing and inspection times for all the rules analysed. According to Law and Kelton 1991, this method gives results with greater statistical precision, e.g., smaller confidence intervals. The basic idea is that we should compare the alternative configurations "under similar experimental conditions" so that we can be more confident that any observed differences in performance are due to differences in the system configurations rather than to fluctuations of the "experimental conditions."

4.9 System Blocking

FMS scheduling problem is associated with limited input and output queue capacities. Therefore, there is always a possibility that a particular machine can be blocked. Blocking occurs when a part cannot be taken to the destination station due to unavailable buffer space. These successive events can also cause deadlocks, i.e., the system is totally prevented from functioning and no part movement can be further achieved.

The study does not include preventing blocking situations. However, blocking occurs for some replications at exponentially distributed low inter-arrival time cases. The replication that had the blocking situation was ignored and simulation was resumed by manually setting the seeds for inter-arrival time, job-type generation, and processing times. This way the rules are tested under identical experimental conditions.

The number of blocking situations that occur for a fixed number of replications is noted and treated as a measure to evaluate the performance of different rules. A rule that minimizes the queueing time of jobs in front of the resources will tend to reduce the number of blocking situations.

4.10 Performance Measures

Performance measures relevant to make scheduling decisions in the areas of productivity, inventory-level, consistency of output, and efficient operation of AGVs are collected. Some of the performance measures are redundant, but are nevertheless included in the study for program verification. For each of the nine rule combinations the performance measures that are collected from the simulation are: total throughput (TP), average flowtime per job (FT), average waiting time per job (Avg(WT)), variance of waiting times (Var(WT)), average work-in-process (WIP), input queue (IP.Q), output queue (OP.Q), average empty to loaded travel ratio (EL), average AGV utilization (AGV.UTZ), and average queue for AGVs (AGV.Q). These measures are computed as follows:

Throughput, Flowtime and WIP: Throughput is measured as the total number of jobs completed in eighty hours. Flowtime is the average of the flowtimes of all jobs measured during a simulation run. WIP is the average number of jobs present in the system. In this research, flowtime is more relevant since it denotes maximum possible throughput. As measured, throughput cannot exceed total job arrivals which is finite.

Average waiting time per part: Waiting time is an important component of flowtime. Since in this study, the set-up time is included in the processing time, the only way to minimize the mean flowtime is to reduce the waiting times. Waiting time is the total time a job spends waiting in the input buffer and output buffer of each machine in its sequence. This can be expressed as follows:

$$\text{Total Waiting Time} = \text{Flowtime} - \text{Total Processing Time} -$$

$$\text{Total Transportation Time} - \text{Load/Unload Time}.$$

Average of total waiting time of all jobs completed during a simulation run is measured from the simulation.

Variance of Waiting times: Variance of waiting times is determined as the variance of the average waiting times across job-types. This measure of performance explains the consistency of output in a system. A scheduling rule that discriminates job-types will perform poorly in terms of this measure.

Input and Output queue: Input queue is the average number of jobs in the input buffer of all machines and output queue is the average number of jobs in the output buffer of all machines. It is expected that machine scheduling rules would affect the number of jobs waiting in the input buffer, and AGV dispatching rules would affect the number of jobs waiting in the output buffer. Therefore, IP.Q and OP.Q were collected.

EL ratio: EL ratio is the average total empty travel time to total loaded travel time of all the jobs completed in eighty hours. Loaded travel time is constant for a given AGV speed since the total loaded travel distance from loading to unloading (= 100 distance units) is the same for all job-types. The empty vehicle travel time of a load request depends on the location of the vehicles and the origin and destination of the load request. If a load request arrives at a station with at least one vehicle, then there will be no empty-vehicle travel time. However, if a load request arrives at a station with no vehicle, then the amount of empty travel time will depend on the location of the empty vehicles and the AGV dispatching rule utilized by the system. By minimizing the total travel time of empty vehicles, the transportation of parts will be accelerated and the efficiency of the whole manufacturing process will increase.

Average AGV.UTZ and AGV.Q: AGV.UTZ is the average utilization of all the three AGVs in the system. AGV.Q is measured as the average number of jobs waiting for AGV in the output buffer of all stations. AGV.Q is different from OP.Q as OP.Q counts all the jobs in the output buffer and AGV.Q counts those jobs for which an input buffer space is reserved at the destination station.

Chapter 5

Experimental Design and Analysis

Intuitively, the performance of dispatching rules depends on the environment in which they are used. This chapter presents the experimental factors selected for performance comparison and outlines the design of experiments approach used to perform the comparison. The main objective of experimental design is to evaluate the performance of scheduling rules under all possible combinations of the factors with respect to all performance criteria. This chapter also recommends decision makers to select appropriate rules based on their environment and the relative importance of different performance criteria.

5.1 Experimental Design

According to Ozdemirel et al. (1996), an experimental design approach is employed for three main reasons. First, experimental design provides a way of deciding which particular configurations to simulate before any runs are made, so that the desired information can be obtained with the minimum number of simulation runs. A carefully designed experiment is much more efficient than a trial and error sequence of runs that compares a number of alternative configurations unsystematically. Secondly, experimental design provides the analyst with a tool for determining which factors have the greatest effect on output performance measures (sensitivity analysis) or which combination of factor levels lead to the optimal performance. Finally, full or fractional factorial design experiments are the only statistical means of studying the interaction effects between two or more factors.

The experimental research design selected here is motivated by the need to determine how the performance of FMS scheduling rules are affected by the system parameters. This research design has two sets of experimental factors: controllable factors and uncontrollable factors. The controllable or managerial decision factors are duplicating tools and varying AGV speed. The uncontrollable or environmental factors are mean time between arrivals, arrival distribution, type of shop and bottleneck machine. Each of these experimental factors and their respective settings are tabulated and discussed below.

Experimental Factors	Levels	
Mean Time Between arrivals (TBA)	5 min.	6 min.
Arrival distribution (AD)	Exponential	Uniform
Type of shop (SHOP)	Flow shop	Job shop
Bottleneck Machine (BNK)	No	Yes
Tool Duplication (TD)	No	Yes
AGV Speed (AS)	15	20

Experimental factors such as mean time between arrivals, arrival distribution, tool duplication, and AGV speed are chosen for the study in order to be consistent with the previous FMS research. Type of shop and bottleneck machine factors were found to influence the performance of traditional job shops, but were not addressed for FMS dynamic scheduling. The shop is of a flow shop type when jobs tend to have similar routeings through the machines; and it is of a job shop type when the jobs tend to have different routeings. The scheduling of a job shop is usually more difficult than that of a flow shop. The type of shop factor is measured here in terms of flow shop index. Similarly, the bottleneck machine factor is measured in terms of the bottleneck index. Each of these factors is explained in detail as below.

Time Between Arrivals and Arrival Distribution

Lee (1996) used mean time between arrivals and arrival distribution to evaluate the AGV dispatching rules. On the average, a job may arrive to the shop at every 5 minutes or every 6 minutes. At inter-arrival time equal to five, the resource utilizations are high. There is not much difference between the low and high levels of this factor because of the reason that at very high TBA, say 7 or 8 minutes the resource utilization are low thereby lowering the waiting times. This situation may not be good enough to test the effectiveness of the different machine scheduling and AGV dispatching rules as any rule will perform well since there will be little waiting in system. Therefore, the high level of this factor is set to 6 minutes. As suggested by Lee (1996), inter-arrival time can be uniformly distributed with a possible 50% variation above and below the mean, or exponentially distributed.

Flow Shop Index

Pinedo and Singer (1998) used flow shop index and bottleneck index to evaluate their heuristic algorithm for a static job shop problem.

They define flow shop index $0 \leq I_f \leq 1$ as a measure of the occurence of similar job routes within a job shop instance. For each pair of machines i and k, they identify the set of jobs that are processed on machine i and then immediately routed to machine k for subsequent processing, and let n_{ik} denote the number of such jobs ($n_{ik} = 0$ if $i = k$). They define

$$I_f^{ik} = \frac{(n_{ik} - 1)^+}{n - 1}$$

and

$$I_f = \frac{1}{m-1}\sum_{i=1}^{n}\sum_{k=1}^{n} I_f^{ik}$$

In the extreme case of the flow shop $I_f = 1$. If the jobs have different machine routes, the values n_{ik} tend to be close to 1 so the corresponding I_f remain close to 0.

The drawback of flow shop index as measured above is that it only considers the immediate successors of operations, and so it can fail to capture the overall flow picture.

Flow shop index is modified in this study as a two-level categorical factor, namely type of shop. In this study, the type of shop factor is implemented by varying the proportion of job-types. Job-type arrivals are such that the type of shop is either flow shop or job shop. By increasing the proportion of job-types J1 and J2 than job-types J3 and J4, the shop becomes more of a flow shop type. On the other hand, by generating more number of job-types J3 and J4 than job-types J1 and J2, the shop becomes more of a job shop type. In the example FMS, if the ratio of total percentage of job-types J1 and J2 to job-types J3 and J4 is 70:30 then the shop is flow shop and if the ratio is 30:70 then the shop is job shop.

The number of jobs of a particular type that flow through different machines depend on the proportion of job-types. Therefore, for a given job-type distribution, it is possible to determine a sequence of machines through which back-tracking of jobs is minimal, or in other words the amount of forward flow of jobs is maximum. Such a sequence of machines is called "the dominant flow sequence." Therefore, the first step is to determine the dominant flow sequence of m machines by solving the following pure integer linear programming (ILP).

Let

f_{ij} = total flow from machine i to machine j.

M = a large number

The decision variables are

x_i = position in sequence of machine i, $i = 1, \ldots, m$.

$$y_{ij} = \begin{cases} 1 & \text{if } x_i < x_j \\ 0 & \text{otherwise} \end{cases}$$

$$\max \sum_{i=1}^{m} \sum_{j=1}^{m} f_{ij} y_{ij}$$

s.t.

$$y_{ij} + y_{ji} = 1, i < j \tag{5.1}$$

$$x_i < x_j + M(1 - y_{ij}), i \neq j \tag{5.2}$$

$$1 \leq x_i \leq m \quad \text{integer}$$
$$y_{ij} = \quad 0, 1$$

The objective is to maximize the forward flow. The first set of constraints (5.1) ensure the precedence relation between a pair of machines i.e., either i before j or j before i. The second set of constraints (5.2) ensure that the positions of a pair of machines, say x_i and x_j satisfy the required precedence relation of those machines, y_{ij}.

Example: For the job-type distribution 35:35:15:15, and time between arrivals = 5 minutes the flow matrix $f_{i,j}$ (ref Table 4.1) is as follows,

	M1	M2	M3	M4
M1	-	1.8	4.2	-
M2	-	-	4.2	1.8
M3	1.8	-	-	8.4
M4	1.8	-	-	-

The optimal solution of ILP gave the dominant flow sequence to be M1 → M2 → M3 → M4. The algorithm was tried for a more complex problem consisting of five machines and ten jobs and the optimal solution was determined in a reasonable computation time.

Next, the flow shop index is computed as follows:

Let

N = number of job arrivals per hour

T = total number of job-types

p = number of operations, and

n_{tj} denotes number of jobs of particular type t that are processed on machine i and then immediately routed to machine k for a particular pair of consecutive operations j. n_{tj} is positive, if the route $i \rightarrow k$ follows the dominant flow sequence. Otherwise, n_{tj} is negative. The flow shop index $0 \leq I_f \leq 1$ is defined as,

$$I_f = \frac{\sum_{t=1}^{T} \sum_{j=1}^{p-1} n_{tj}}{N(p-1)}$$

I_f is equal to 1 for a case where all the consecutive pairs of operations involve machines that obey the dominant flow sequence which implies a pure flow shop. On the other hand, if the machines in each pair of consecutive operations do not follow the dominant flow sequence then I_f is equal to 0 and the shop is a pure job shop type.

For the dominant flow sequence M1 $\rightarrow$ M2 $\rightarrow$ M3 $\rightarrow$ M4, consider the routeings of consecutive operations of two different jobs to be M2 $\rightarrow$ M3 and M2 $\rightarrow$ M4. The fact that both these routeings satisfy the dominant flow sequence is not captured in Pinedo and Singer (1999).

Example: For the same example, the process routeing for each job-type is as follows (ref Table 4.1),

J1: M1 $\rightarrow$ M3 $\rightarrow$ M4

J2: M2 $\rightarrow$ M3 $\rightarrow$ M4

J3: M2 $\rightarrow$ M4 $\rightarrow$ M1

J4: M3 $\rightarrow$ M1 $\rightarrow$ M2

Therefore,

$$I_f = \frac{(4.2 + 4.2 + 4.2 + 4.2 + 1.8 - 1.8 - 1.8 + 1.8)}{12(3-1)} = 0.70$$

Since I_f is 0.70, the type of shop is more of a flow shop type.

Bottleneck Index

Pinedo and Singer (1998) define bottleneck index $0 \leq I_b \leq 1$ as a measure that determines the extent to which the utilization of the machines is concentrated. They developed a formula to determine I_b for a job shop with $n \geq 2$ jobs. The formula is based on the assumption that each job visits each machine exactly once. Let m_{ik} denote the number of jobs of which the k-th operation must be processed on machine i. They define

$$I_b^{ik} = \frac{(m_{ik} - 1)^{+}}{n - 1}$$

and

$$I_b = \frac{1}{m} \sum_{k=1}^{m} \sum_{i=1}^{m} I_b^{ik}$$

If the utilization of machines is less evenly distributed over time, then I_b is closer to 1. On the other hand, if the machine utilization is spread out over the scheduling horizon, the values m_{ik} tend to be close to 1 so the corresponding I_b remains close to 0.

The drawback of bottleneck index as measured above is that it does not involve processing times and inter-arrival time of jobs which measure the load on the machines.

This is modified in the study as a two-level categorical factor, namely bottleneck machine. Similar to type of shop, bottleneck factor is implemented by varying the proportion of job-types. Machine load level is balanced in one level and in the other there exists a bottleneck machine. The bottleneck machine is introduced by unbalancing the relative proportion of job-types J1 and J2 in the flow shop case, and job-types J3 and J4 in the job shop case. Whether or not a bottleneck machine exist, the ratio of total percentage of job-types J1 and J2 to job-type J3 and J4 is the same for a particular type of shop. The bottleneck machine in unbalanced flow shop is machine M2 and in unbalanced job shop is machine M3. As explained before, tool utilization remain unchanged whether or not a bottleneck machine exists in the system. AGV layout is designed such that irrespective of the distribution of job-types chosen, the average loaded travel is the same. Therefore, the type of shop and bottleneck machine factors can be varied independently. The approach developed to determine the bottleneck index is explained below.

First, determine the utilization of each machine for a particular time between arrival of jobs as follows:

Let

M_i = utilization of machine i

N = number of arrivals per hour

n = number of job-types

r_j = proportion of job-type j

p_{ij} = processing time of job-type j on machine i in minutes

$$M_i = \frac{N \sum_{j=1}^{n} r_j p_{ij}}{60}$$

Example: From Table 4.1, the utilization of machines for time between arrivals = 5 minutes and job-type distribution 35:35:15:15 are as follows.

$$M_1 = \frac{12(0.35 \times 8 + 0.35 \times 0 + 0.15 \times 4 + 0.15 \times 4)}{60} = 0.80$$

$$M_2 = \frac{12(0.35 \times 0 + 0.35 \times 8 + 0.15 \times 4 + 0.15 \times 4)}{60} = 0.80$$

$$M_3 = \frac{12(0.35 \times 4 + 0.35 \times 4 + 0.15 \times 0 + 0.15 \times 8)}{60} = 0.80$$

Type of Shop	Bottleneck Machine	Job-type Distribution	Dominant Flow	I_f	I_b
Flow shop	No	35:35:15:15	M1 → M2 → M3 → M4	0.70	0
Flow shop	Yes	30:40:15:15	M1 → M2 → M3 → M4	0.70	0.40
Job shop	No	15:15:35:35	M2 → M3 → M4 → M1	0.50	0
Job shop	Yes	15:15:30:40	M2 → M3 → M4 → M1	0.45	0.40

Table 5.1: Flow shop and bottleneck indices.

$$M_4 = \frac{12(0.35 \times 4 + 0.35 \times 4 + 0.15 \times 8 + 0.15 \times 0)}{60} = 0.80$$

From above,

$$M_{max} = max\{M_1, M_2, M_3, M_4\} = 0.80$$

$$M_{avg} = \frac{\sum_{i=1}^{4} M_i}{4} = 0.80$$

Next step is to determine the bottleneck index $0 \leq I_b \leq 1$ which is defined as,

$$I_b = 1 - \frac{(1 - M_{max})}{(1 - M_{avg})}$$

Example: For the same example,

$$I_b = 1 - \frac{(1 - 0.80)}{(1 - 0.80)} = 0$$

Since $I_b = 0$, the shop is balanced. For the same case, if the maximum utilization, M_{max} is 100%, then I_b is equal to 1 and the shop is severely unbalanced.

The formula for I_b involves processing times of each job-type and the arrival frequency of jobs in its calculation, which were not considered by Pinedo and Singer (1999). Table 5.1 shows the dominant flow, I_f, and I_b for the different levels of type of shop and bottleneck machine factors.

Tool Duplication

Hutchison (1991) showed that duplicating tools improves the performance of an FMS. The low level of tool duplication factor is to have no duplicate tooling. At the high level, there is one duplicate of every tool type. Tools are distributed among job-types such that all tool types have equal load. This way, other factors such as type of shop and bottleneck machine can be varied independently. For no tool duplication level, the expected utilization of tools at the low level of time between arrivals is 80% and at the high level is 67%.

AGV Speed

Sabuncuoglu and Hommertzheim (1992) suggested that the AGV load levels are adjusted by changing the AGV speeds. AGV speed can be 15 distance units/min or 20 distance units/min in the simulation.

5.2 Experimental Analysis

With six factors set at two levels each, the number of treatment combinations is $2^6 = 64$. Three machine scheduling rules and three AGV dispatching rules were tested which gives $9 \times 64 = 576$ experiments. The number of replications for each experiment is set to 20. Schmeiser (1982) suggested that making twenty replications per treatment combination is an often-used rule of thumb in simulation experiments. Ozdemirel (1996) also suggest that more than twenty replications are usually useless, because this would result in an unnecessarily large error degree of freedom in factorial designs. Preliminary testing showed that making twenty replications of eighty hours each gave acceptable confidence-interval.

Experimental analysis is carried out in two parts. In the first part, the main and interaction effects of experimental factors such as the inter- arrival time, arrival distribution, type of shop, bottleneck machine, tool duplication and AGV speed on the performance measures are studied for a specific rule. In the second part of the analysis, the effect of machine scheduling and AGV dispatching rules on performance measures for each of the treatment combinations are discussed in detail and recommendations are made based on selection criteria.

5.2.1 Main and Interaction Effects of Experimental Factors

A 2^6 full-factorial analysis is performed to determine which of the factors and their interaction effects are significant. The level of significance used is 0.05. The p-values for this design are tabulated in Table 5.2. The results are shown for LQM-NS rule. The discussion will hold for the other rules since similar response is displayed.

Main Effects

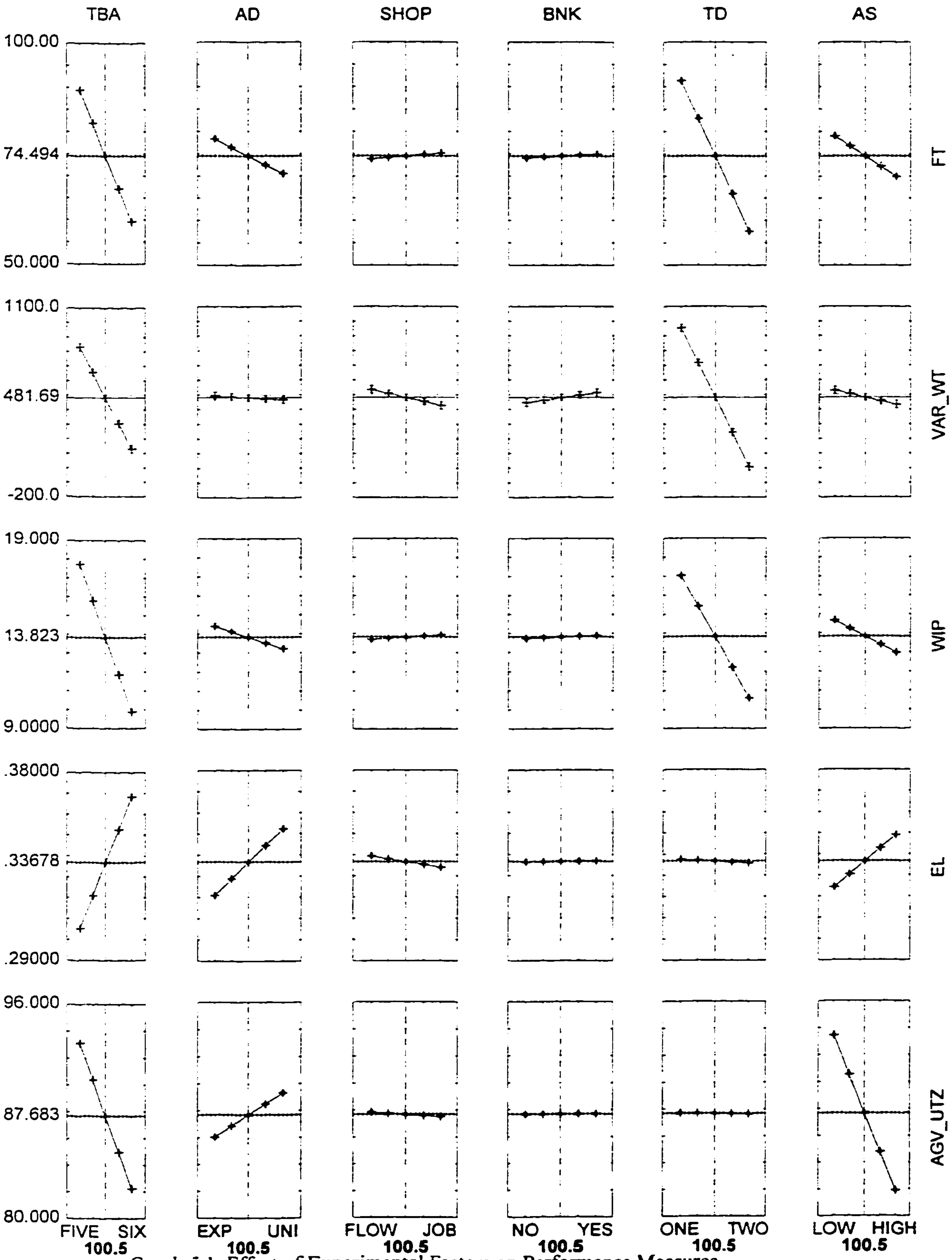
The type of shop and bottleneck machine factors affect the FMS performance. It can be seen that all the main effects are significant for flowtime and WIP measures while throughput is affected only by time between arrivals and arrival distribution. As shown in Graph 5.1, flowtime is high for job shop compared to flow shop. Unbalancing the load level on machines causes the flowtime, WIP and variance of waiting times to increase.

EL ratio is low for job shop compared to flow shop thereby causing AGV utilization to increase for the flow shop case. Since EL ratio is low for job shop case, it is evident that increase in flowtime is due to increased waiting of jobs in front of the machines. Increasing the arrival rate increases EL ratio because it is less likely that a part might find an AGV located at its pick-up point. It is also interesting to note that unbalancing the shop does not affect EL ratio and AGV utilization.

Factor	p-values					
	TP	FT	Var(WT)	WIP	EL	AGV.UTZ
(1) TBA	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*
(2) AD	0.0000*	0.0000*	0.1444	0.0000*	0.0000*	0.0000*
(3) SHOP	0.9433	0.0000*	0.0000*	0.0014*	0.0000*	0.0001*
(4) BNK	0.8185	0.0044*	0.0001*	0.0196*	0.4764	0.6796
(5) TD	0.4399	0.0000*	0.0000*	0.0000*	0.0059*	0.3465
(6) AS	0.9459	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*
1 by 2	0.0000*	0.0000*	0.0008*	0.0017*	0.0000*	0.3188
1 by 3	0.7885	0.3955	0.0000*	0.3528	0.2000	0.7572
1 by 4	0.9691	0.0083*	0.0003*	0.0278*	0.8124	0.9916
1 by 5	0.2220	0.0000*	0.0000*	0.0000*	0.0105*	0.6984
1 by 6	0.8564	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*
2 by 3	0.8539	0.2173	0.9879	0.2778	0.0038*	0.1110
2 by 4	0.9948	0.4766	0.5452	0.5894	0.4196	0.6189
2 by 5	0.4893	0.4815	0.3459	0.6023	0.0000*	0.0000*
2 by 6	0.9176	0.1828	0.4184	0.4123	0.0792	0.0020*
3 by 4	0.8920	0.0169*	0.1620	0.0428*	0.1067	0.4711
3 by 5	0.9794	0.0000*	0.0000*	0.0005*	0.4764	0.7283
3 by 6	0.9588	0.4086	0.6295	0.4933	0.0876	0.5051
4 by 5	0.9253	0.8720	0.0006*	0.9143	0.9621	0.9234
4 by 6	0.8286	0.4522	0.1469	0.5318	0.7041	0.9942
5 by 6	0.9356	0.0223*	0.0000*	0.0575	0.0000*	0.0005*

Table 5.2: ANOVA Results: Experimental factors affecting performance measures.

* Significant at 0.05 level.



Graph 5.1: Effect of Experimental Factors on Performance Measures.

Interaction Effects

It can be readily seen that not all two-way interactions are significant. In particular, the interaction of the type of shop (SHOP) and bottleneck machine (BNK) is significant for flowtime and WIP indicating that these measures show increase in values when the shop is unbalanced. The impact of duplicating the tool is significant with respect to the type of shop (SHOP), bottleneck machine (BNK) and AGV speed (AS) as far as variance of waiting times is concerned. This shows that irrespective of the nature of shop, variance of waiting times is reduced by duplicating the tool types. With respect to EL ratio and AGV utilization, the interaction effect of AGV speed (AS) with time between arrivals (TBA) and tool copy (TC) is significant showing that EL ratio increases with increase in AGV speed.

5.2.2 Effect of Dispatching Rules on Treatment Combinations

The machine scheduling rules and AGV dispatching rules are considered as factors and a 3^2 full-factorial analysis is performed on the sixty-four treatments separately.

Factors	Levels		
Machine-scheduling rule	SIO	LQM	MRT
AGV dispatching rule	NS	QSNS	NUJ

ANOVA results and recommendations for each of the sixty-four treatments are tabulated in appendices. Each treatment combination in Appendix A, B and C is expressed in terms of the levels set for each of the six factors. For example,

5/E/F/N/1/15 implies that the time between arrivals is (5) minutes, arrival distribution is (E)xponential, type of shop is (F)lowshop, (N)o bottleneck machine, no tool duplication (1), and AGV speed is (15) m/min.

6/U/J/Y/2/20 implies that the time between arrivals is (6) minutes, arrival distribution is (U)niform, type of shop is (J)obshop, bottleneck machine exists (Y), tool duplicate exists (2), and AGV speed is (20) m/min.

The results for the sixty-four treatments are summarized by categorizing them into eight categories. Categories are formed such that each of them differ in time between arrivals, arrival distribution and type of shop. This is because ANOVA results revealed that for the eight treatments within a category, the performance of rules were more or less identical. The eight categories are listed as follows,

1. TBA = 5, AD = Exponential, ST = Flow shop (5/E/F/x/x/x)
2. TBA = 5, AD = Exponential, ST = Job shop (5/E/J/x/x/x)
3. TBA = 5, AD = Uniform, ST = Flow shop (5/U/F/x/x/x)
4. TBA = 5, AD = Uniform, ST = Job shop (5/U/J/x/x/x)
5. TBA = 6, AD = Exponential, ST = Flow shop (6/E/F/x/x/x)
6. TBA = 6, AD = Exponential, ST = Job shop (6/E/J/x/x/x)
7. TBA = 6, AD = Uniform, ST = Flow shop (6/U/F/x/x/x)
8. TBA = 6, AD = Uniform, ST = Job shop (6/U/J/x/x/x)

Selection Criteria

It is important to make scheduling decisions in FMS. Scheduling decisions for an FMS is concerned with obtaining good performance measures such as the average flowtimes of all jobs, consistency of output of job-types, operation of material-handling transporters and so on. In this study, performance of scheduling rules are classified based on following criteria:

- Flowtime: The rules that perform well in terms of flowtime criteria will also show improvement in average waiting time, WIP and input queue measures.

- Variance of waiting times: Variance of waiting times is used to measure the consistency of output. If the variance of waiting times is small, then it means that the average waiting times of all job-types are more or less the same which is more appropriate for a JIT environment. A scheduling rule that discriminates among job-types and gives priority to certain job-types over others will tend to have larger variance of waiting times. As a result, the output of job-types per unit time will be affected.

- Efficient operation of AGVs: AGV related statistics such as the empty-to-loaded travel time ratio, output queue and average utilization of AGVs play an important role in the design and control of AGVs. These measures are expected to be affected more by the AGV dispatching rule than by the machine scheduling rule utilized in the system.

Based on these factors, machine scheduling and AGV dispatching rules are recommended for each category in Table 5.3 and for each treatment in Appendix-C. In addition, performance based on the frequency of blocking situations and overall performance of rules are studied.

Performance of rules based on flowtime

In terms of flowtime performance, NUJ AGV dispatching rule significantly performs well at the low level of inter-arrival time and AGV speed, and high level of tool duplication factor (i.e. 5/x/x/x/2/15) as seen in Appendix-C. About 10% improvement in flowtime measure can be seen when NUJ AGV dispatching rule is used. For those combinations MRT-NUJ and SIO-NUJ are recommended. For the other low inter-arrival time combinations SIO-NUJ rule is the best. For example, in 5/U/J/Y/1/20 treatment combination, there is about 7% improvement in flowtime

Category	Flowtime	Consistency of Output	Efficient Operation of AGVs
5/E/F/x/x/x	MRT-NUJ, SIO-NUJ	LQM-NUJ, LQM-QSNS	LQM-NUJ, MRT-NUJ
5/E/J/x/x/x	SIO-NUJ	MRT-NS, MRT-NUJ, MRT-QSNS	LQM-NUJ, MRT-NUJ
5/U/F/x/x/x	MRT-NUJ, SIO-NUJ	LQM-NUJ, LQM-QSNS	LQM-NUJ, MRT-NUJ
5/U/J/x/x/x	SIO-NUJ	MRT-NS, MRT-NUJ, MRT-QSNS	LQM-NUJ, MRT-NUJ
6/E/F/x/x/x	SIO-NUJ	LQM-NS, LQM-NUJ	LQM-NUJ, MRT-NUJ
6/E/J/x/x/x	SIO-NUJ	MRT-NS, MRT-NUJ	LQM-NUJ, MRT-NUJ
6/U/F/x/x/x	LQM-NUJ	LQM-NS, LQM-NUJ, MRT-NS, MRT-NUJ	LQM-NUJ, MRT-NUJ
6/U/J/x/x/x	LQM-NUJ, LQM-QSNS	LQM-NS, LQM-QSNS	LQM-NUJ

Table 5.3: Summary of best combination of M/C-AGV rules based on flowtime, consistency of output and efficient operation of AGVs.

when SIO-NUJ rule is used instead of LQM-NUJ. For all exponentially distributed high inter-arrival time combinations (6/E/F/x/x/x, 6/E/J/x/x/x) SIO-NUJ fares well while LQM-NUJ rule performs well for uniformly distributed high inter-arrival time combinations (6/U/F/x/x/x, 6/U/J/x/x/x).

Performance of rules based on consistency of output

Variance of waiting times is often affected by the machine scheduling rule factor. LQM and MRT rules perform well with respect to this measure. LQM rule is preferred for the flow shop combinations

(5/E/F/x/x/x, 5/U/F/x/x/x, 6/E/F/x/x/x, 6/U/F/x/x/x),

while MRT rule for the job shop combinations

(5/E/J/x/x/x, 5/U/J/x/x/x, 6/E/J/x/x/x).

Performance of rules based on efficient operation of AGVs

For all the treatment combinations, NUJ AGV dispatching rule performs well in output queue, EL ratio and AGV utilization. For the low-level of tool duplication case (e.g. 5/E/F/N/1/15) there is about 8% improvement in EL ratio and for the high level of tool duplication case (e.g. 5/E/F/N/2/15) there is about 13% improvement in EL ratio when NUJ AGV dispatching rule is used instead of NS and QSNS. It can be seen from Appendix-B that with no tool duplication, machine scheduling rule affects the operation of AGVs. LQM and MRT rules are preferred for those cases. For example, in 5/U/J/Y/1/20 treatment combination, about 6% improvement in EL ratio can be achieved when either LQM-NUJ or MRT-NUJ is used instead of SIO-NUJ. In general, LQM-NUJ and MRT-NUJ performed equally well in these measures.

Performance of rules based on average waiting time and variance of waiting times

In practice one may be interested in a dispatching rule which does reasonably well on both average waiting time and variance of waiting times. From the initial analysis discussed in section 1.3.1, it is seen that duplicate tools reduces average waiting time and variance of waiting times. Therefore, treatments which involve tool duplicates are eliminated and the mean values are shown in Table 5.4 for the machine scheduling rules combined with NUJ AGV dispatching rule as NUJ shows superior performance over NS and QSNS AGV dispatching rules. MRT-NUJ rule seems to be doing well for such an application. SIO rule performed poorly in variance of waiting times and LQM rule in average waiting time measure.

Performance of rules based on minimum blocking situations

MRT-NUJ also tries to minimize the blocking situations that arise for exponentially distributed low inter-arrival time treatments with no tool duplication. Graph 5.2

Rules	Average waiting time	Variance of waiting times
LQM-NUJ	82.30	1608.56
MRT-NUJ	81.22	2020.17
SIO-NUJ	79.86	2180.71

Table 5.4: Performance of rules based on average waiting time and waiting time variance.

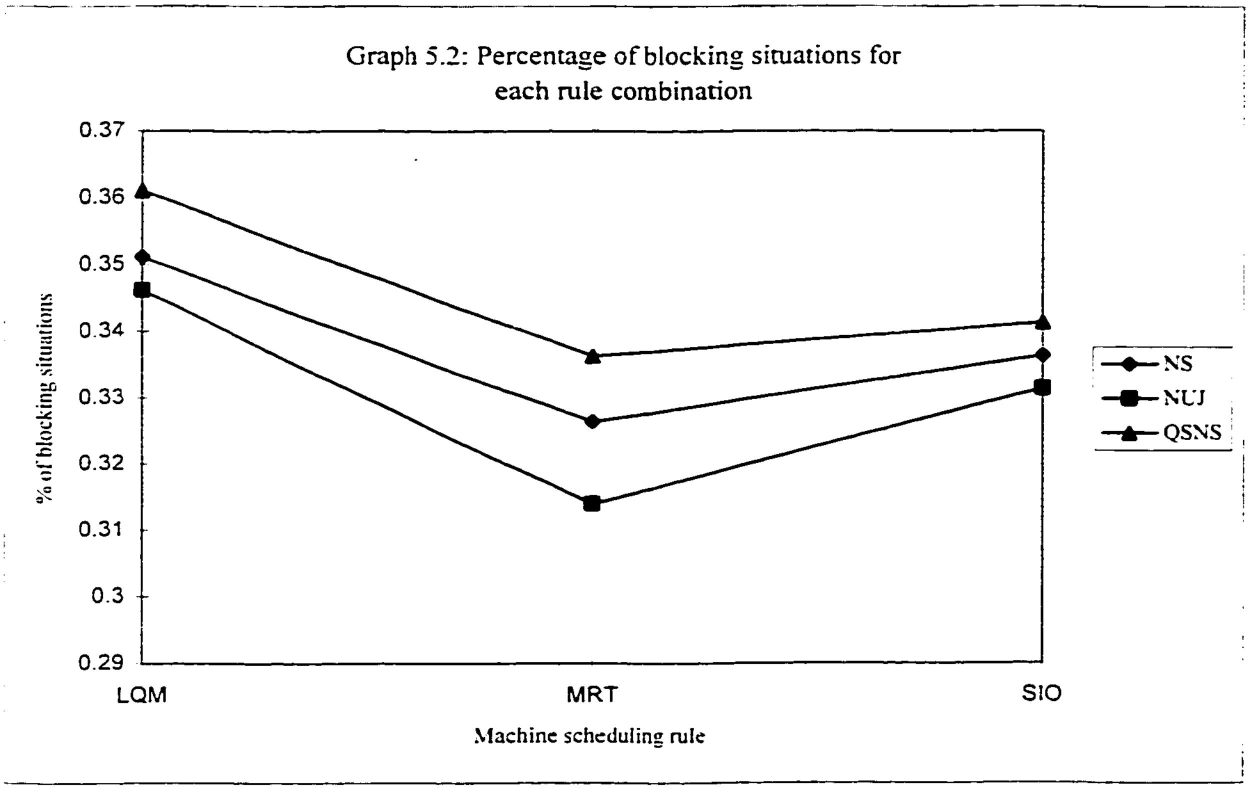
Rules	Performance Measures			
	FT	WIP	EL	AGV.UTZ
LQM-NS	74.49±1.39	13.82±0.31	0.34±0.003	87.68±0.46
LQM-NUJ	73.84±1.37	13.70±0.30	0.33±0.003	87.36±0.45
LQM-QSNS	75.98±1.41	14.00±0.31	0.34±0.003	87.85±0.47
MRT-NS	73.87±1.31	13.69±0.29	0.34±0.003	87.66±0.46
MRT-NUJ	73.24±1.30	13.57±0.29	0.33±0.003	87.35±0.45
MRT-QSNS	74.33±1.34	13.78±0.30	0.34±0.003	87.68±0.46
SIO-NS	72.91±1.26	13.50±0.28	0.34±0.003	87.77±0.46
SIO-NUJ	72.25±1.24	13.38±0.28	0.33±0.003	87.48±0.45
SIO-QSNS	73.31±1.29	13.59±0.29	0.34±0.003	87.79±0.46

Table 5.5: 95% Confidence Interval for each M/C-AGV rule averaged over 64 treatments.

shows the percentage of blocking situations experienced in seventy replications for each rule combination. This explains that MRT-NUJ handles job queuing-time better than the other rules. LQM rule performed poorly in this matter.

Overall performance of rules

Sometimes it may be necessary to decide on one machine scheduling and AGV dispatching rule that might perform well irrespective of the arrival time and distribution, nature of shop, tool copies and AGV speed. For this purpose a 95% confidence interval is determined for each machine and AGV scheduling rule averaged over the sixty-four treatment combinations. These values are shown in Table 5.5.


Graph 5.2: Percentage of blocking situations for each rule combination
0.37
0.36
0.35
0.34
0.33
0.32
0.31
0.3
0.29
% of blocking situations
LQM
MRT
SIO
Machine scheduling rule
NS
NUJ
QSNS

It can be seen that both SIO-NS and SIO-NUJ rules perform well in terms of flowtime and WIP measures. However, SIO-NUJ outperforms SIO-NS in EL ratio and AGV utilization. The 95% confidence-interval for each treatment and each rule is shown in Appendix-A.

Simultaneous study of machines and material handling systems

Decisions regarding selection of appropriate machine scheduling and AGV dispatching rules are important for an FMS user. From Appendix-C, it can be seen that in most cases selection of a scheduling rule for machines and AGVs are independent. However, in some cases the selection requires combined evaluation of machine scheduling and AGV dispatching rules. For example, in 5/U/F/Y/1/20 treatment combination, independent selection based on flowtime measure shows MRT and SIO rules for machines and NS and NUJ rules for AGV dispatching. However, MRT-NUJ and SIO-NS rule combinations yield best results. If machines and AGV sub-systems were to be studied separately, then it might happen that MRT-NS or SIO-NUJ could be recommended instead of MRT-NUJ and SIO-NS. Also for 5/U/J/N/1/15 treatment under flowtime criteria, both NS and NUJ AGV dispatching rules perform equally well but SIO-NUJ is alone recommended.

Chapter 6

Conclusion

This study addressed the FMS scheduling problem by evaluating the performance of different machine and AGV scheduling rules using a simulation model. Three machine scheduling rules and three AGV dispatching rules giving rise to nine rule combinations were tested in this study. Two of the three machine scheduling rules (LQM, MRT) are developed based on combinations of simple rules proposed in previous research, while the SIO rule is used as a benchmark for comparison purpose. Similarly, two new AGV dispatching rules (NUJ, QSNS) are proposed and NS rule is used as a benchmark.

6.1 Summary of Results

The results indicated that at high utilization rates, in which most FMS usually operate, the way that machines and AGVs are scheduled can significantly affect the system performance. Therefore, not only machines but also AGVs should be scheduled in the most effective way. Also, the choice of rules is found to be dependent on FMS operating condition as well as on the performance criteria chosen. The results can be summarized as follows:

1. The two newly tested factors, namely type of shop and bottleneck machine

are found to have significant effect on FMS performance.

2. Among the machine scheduling rules tested against the mean flowtime criterion, SIO appeared to be the best rule with NUJ AGV rule combination at high utilization rates. NUJ AGV rule significantly minimized the flowtime for the tool duplication cases. LQM rule performed well for the high inter-arrival time treatments.

3. With respect to variance of waiting times, LQM and MRT machine scheduling rules performed better than SIO. AGV dispatching rule showed no effect on variance of waiting times.

4. MRT-NUJ rule performed well in both average waiting time and variance of waiting times measures. MRT-NUJ rule has also shown to reduce the number of blockings during a simulation run.

5. Based on AGV operation, NUJ rule performed better than NS and QSNS rules in EL ratio, output queue and AGV utilization measures. LQM and MRT machine scheduling rules in combination with NUJ rule showed better operation of AGVs for the cases where there were no tool duplicates.

6.2 Application of Performance Based Selection of Rules to FMS Decision Maker

Selection of appropriate scheduling rules improves FMS performance. However, if an FMS user is concerned more on a particular performance measure than the others, then the classification of results based on selection criteria such as flowtime, consistency of output, and efficient operation of AGVs would be of use in the decision making process. Assume that the FMS decision-maker is faced with an FMS as follows: jobs of different varieties arriving to the shop in an uniform manner at high frequency; there are no tool duplicates; the AGVs are operated at high speed; and the load level on machines is slightly unbalanced. This situation is similar to 5/U/J/Y/1/20 treatment combination tested in the study. The ANOVA results show that SIO-NUJ performs well with respect to flowtime measure, MRT-NUJ with respect to consistency of output, and both LQM-NUJ and MRT-NUJ with respect to efficient operation of AGVs. The decision maker can make appropriate rule selection corresponding to the concerned performance criteria of importance. If all the measures matter to him equally then MRT-NUJ rule would be a good choice.

6.3 Suggestions for Future Research

Future work based on the initial insights provided in this research are listed below.

1. Since local buffer capacity is limited, there is a possibility that deadlock situation occurs. Therefore, deadlock avoidance and prevention algorithms can be incorporated to the resource allocation schemes.

2. Further development of robust rules that perform well in both congested and less congested environments.

3. To study the effect of varying the number of AGVs and machines on FMS performance.

4. To include routeing flexibility as a factor in the experimental design and study the performance of rules with or without alternative routeings.

5. Performance prediction for different FMS operating conditions by building a regression model.

6. Diagnostic technique based on residual analysis can be included as a part in the experimental design for model adequacy checking.

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Appendix A

-ANOVA Results: Effect of Machine and AGV Dispatching Rules on Performance Measures for the 64 Treatment Combinations.

Treatment	Rules	Performance Measures				
		FT	Var(WT)	WIP	EL	AGV.UTZ
5/E/F/N/1/15	M/C	0.2985	0.0218*	0.4181	0.8510	0.8281
	AGV	0.1315	0.9750	0.2811	0.0215*	0.0378*
5/E/F/N/1/20	M/C	0.1712	0.0036*	0.3160	0.0084*	0.8047
	AGV	0.8732	0.3433	0.9363	0.0000*	0.4168
5/E/F/N/2/15	M/C	0.5342	0.9162	0.6838	0.9436	0.9988
	AGV	0.0000*	0.0039*	0.0000*	0.0000*	0.0039*
5/E/F/N/2/20	M/C	0.4024	0.5956	0.6780	0.9918	0.9938
	AGV	0.5555	0.8936	0.7814	0.0000*	0.3675
5/E/F/Y/1/15	M/C	0.2829	0.0159*	0.4464	0.7302	0.6163
	AGV	0.3149	0.6925	0.5013	0.0106*	0.0308*
5/E/F/Y/1/20	M/C	0.4486	0.0001*	0.5170	0.5343	0.7921
	AGV	0.7858	0.8050	0.8940	0.0000*	0.3448
5/E/F/Y/2/15	M/C	0.4156	0.3400	0.5906	0.8914	0.9804
	AGV	0.0000*	0.4843	0.0001*	0.0013*	0.0080*
5/E/F/Y/2/20	M/C	0.3334	0.4749	0.5682	0.6577	0.9808
	AGV	0.8943	0.9541	0.9484	0.0000*	0.4343
5/E/J/N/1/15	M/C	0.0051*	0.0000*	0.0225*	0.6315	0.6189
	AGV	0.3436	0.8063	0.4564	0.0532	0.0831
5/E/J/N/1/20	M/C	0.0000*	0.0000*	0.0004*	0.0263*	0.7331
	AGV	0.7486	0.7386	0.8200	0.0156*	0.6476
5/E/J/N/2/15	M/C	0.6735	0.0192*	0.8067	0.9304	0.9801
	AGV	0.0000*	0.4885	0.0001*	0.0179*	0.0892
5/E/J/N/2/20	M/C	0.9367	0.0007*	0.9695	0.4655	0.9856
	AGV	0.8399	0.0007*	0.9268	0.0051*	0.6733
5/E/J/Y/1/15	M/C	0.0104*	0.0000*	0.0470*	0.9291	0.8675
	AGV	0.1682	0.3574	0.3030	0.0212*	0.8267
5/E/J/Y/1/20	M/C	0.0935	0.0000*	0.2025	0.0450*	0.8893
	AGV	0.9934	0.9818	0.9949	0.0038*	0.6099
5/E/J/Y/2/15	M/C	0.6962	0.6706	0.8373	0.9601	0.9763
	AGV	0.0000*	0.8703	0.0001*	0.0052*	0.0731
5/E/J/Y/2/20	M/C	0.9422	0.3781	0.9760	0.4829	0.9737
	AGV	0.9498	0.9765	0.9619	0.0013*	0.6563

Table 1: ANOVA Results: Rules affecting performance measures for TBA = 5 min and AD = exponential.

* Significant at 0.05 level.

Treatment	Rules	Performance Measures				
		FT	Var(WT)	WIP	EL	AGV.UTZ
5/U/F/N/1/15	M/C	0.0238*	0.0043*	0.0395*	0.2609	0.0000*
	AGV	0.0213*	0.5823	0.0525	0.0529	0.0000*
5/U/F/N/1/20	M/C	0.0042*	0.0000*	0.0089*	0.0138*	0.0438*
	AGV	0.6574	0.6469	0.7551	0.0000*	0.0000*
5/U/F/N/2/15	M/C	0.1149	0.0723	0.2165	0.9302	0.6562
	AGV	0.0000*	0.0004*	0.0000*	0.0009*	0.0000*
5/U/F/N/2/20	M/C	0.2836	0.0120*	0.4126	0.2343	0.6757
	AGV	0.3295	0.9293	0.4586	0.0000*	0.0000*
5/U/F/Y/1/15	M/C	0.0001*	0.0239*	0.0007*	0.2622	0.0005*
	AGV	0.2889	0.7407	0.3327	0.0311*	0.0000*
5/U/F/Y/1/20	M/C	0.0000*	0.0002*	0.0000*	0.0000*	0.0000*
	AGV	0.0003*	0.5668	0.0008*	0.0000*	0.0000*
5/U/F/Y/2/15	M/C	0.0192*	0.0523	0.0586	0.9827	0.6726
	AGV	0.0000*	0.2861	0.0000*	0.0033*	0.0000*
5/U/F/Y/2/20	M/C	0.0347*	0.0379*	0.0847	0.3292	0.6576
	AGV	0.4663	0.7163	0.6013	0.0000*	0.0000*
5/U/J/N/1/15	M/C	0.0000*	0.0000*	0.0000*	0.1009	0.0000*
	AGV	0.0390*	0.0580	0.0758	0.1573	0.0000*
5/U/J/N/1/20	M/C	0.0000*	0.0000*	0.0000*	0.0000*	0.0008*
	AGV	0.9845	0.5748	0.9868	0.0000*	0.0037*
5/U/J/N/2/15	M/C	0.2751	0.0867	0.4509	0.9574	0.8846
	AGV	0.0000*	0.9047	0.0001*	0.1089	0.0000*
5/U/J/N/2/20	M/C	0.7984	0.0077*	0.8887	0.2869	0.6189
	AGV	0.7336	0.8217	0.8277	0.0000*	0.0027*
5/U/J/Y/1/15	M/C	0.0000*	0.0000*	0.0002*	0.5826	0.0000*
	AGV	0.1069	0.3633	0.1437	0.0091*	0.0000*
5/U/J/Y/1/20	M/C	0.0000*	0.0000*	0.0000*	0.0000*	0.0050*
	AGV	0.9743	0.9427	0.9817	0.0001*	0.2129
5/U/J/Y/2/15	M/C	0.6664	0.7543	0.7694	0.8501	0.7531
	AGV	0.0008*	0.4116	0.0060*	0.2564	0.0000*
5/U/J/Y/2/20	M/C	0.9753	0.6338	0.9839	0.2658	0.6392
	AGV	0.7592	0.8679	0.8189	0.0000*	0.0061*

Table 2: ANOVA Results: Rules affecting performance measures for TBA = 5 min and AD = Uniform.

* Significant at 0.05 level.

Treatment	Rules	Performance Measures				
		FT	Var(WT)	WIP	EL	AGV.UTZ
6/E/F/N/1/15	M/C	0.0946	0.0049*	0.2912	0.5208	0.8968
	AGV	0.3674	0.2823	0.5518	0.0002*	0.4256
6/E/F/N/1/20	M/C	0.2538	0.0908	0.4287	0.0047*	0.7764
	AGV	0.7709	0.6667	0.8365	0.1982	0.9186
6/E/F/N/2/15	M/C	0.3472	0.8157	0.6608	0.7189	0.9898
	AGV	0.0029*	0.1956	0.1093	0.0000*	0.2308
6/E/F/N/2/20	M/C	0.4204	0.0104*	0.7303	0.1769	0.9486
	AGV	0.8431	0.9822	0.9448	0.0002*	0.8040
6/E/F/Y/1/15	M/C	0.1454	0.0967	0.3119	0.6461	0.9382
	AGV	0.8598	0.6002	0.9248	0.0041*	0.5547
6/E/F/Y/1/20	M/C	0.2132	0.0009*	0.4695	0.3215	0.9581
	AGV	0.9504	0.8591	0.9751	0.0102*	0.8826
6/E/F/Y/2/15	M/C	0.0321*	0.2723	0.2864	0.1964	0.8375
	AGV	0.0526	0.8891	0.3511	0.0000*	0.3356
6/E/F/Y/2/20	M/C	0.4944	0.3464	0.7717	0.4668	0.9931
	AGV	0.8538	0.9915	0.9465	0.0001*	0.7609
6/E/J/N/1/15	M/C	0.0109*	0.1021	0.0567	0.2636	0.8182
	AGV	0.7578	0.9476	0.8539	0.0392*	0.7027
6/E/J/N/1/20	M/C	0.0201*	0.0235*	0.0900	0.0005*	0.8067
	AGV	0.9353	0.8518	0.9604	0.4625	0.9481
6/E/J/N/2/15	M/C	0.2662	0.2675	0.6543	0.2907	0.9298
	AGV	0.6352	0.9240	0.8733	0.6486	0.9517
6/E/J/N/2/20	M/C	0.5449	0.1858	0.8480	0.8519	0.9917
	AGV	0.9483	0.9491	0.9848	0.0100*	0.8568
6/E/J/Y/1/15	M/C	0.0129*	0.0291*	0.0535	0.5869	0.8346
	AGV	0.8243	0.7884	0.8875	0.0177*	0.6305
6/E/J/Y/1/20	M/C	0.0239*	0.0695	0.1122	0.0991	0.9106
	AGV	0.9070	0.7023	0.9437	0.2444	0.9791
6/E/J/Y/2/15	M/C	0.6582	0.8983	0.8646	0.8583	0.9929
	AGV	0.0457*	0.8854	0.3134	0.0246*	0.5404
6/E/J/Y/2/20	M/C	0.9968	0.9301	0.9993	0.7327	0.9949
	AGV	0.7516	0.9974	0.9052	0.0014*	0.8290

Table 3: ANOVA Results: Rules affecting performance measures for TBA = 6 min and AD = exponential.

* Significant at 0.05 level.

Treatment	Rules	Performance Measures				
		FT	Var(WT)	WIP	EL	AGV.UTZ
6/U/F/N/1/15	M/C	0.0000*	0.0000*	0.0008*	0.0034*	0.0136*
	AGV	0.4534	0.2870	0.5176	0.0000*	0.0012*
6/U/F/N/1/20	M/C	0.0069*	0.0000*	0.0361*	0.0001*	0.0673
	AGV	0.9978	0.8850	0.9949	0.3014	0.7901
6/U/F/N/2/15	M/C	0.0848	0.8898	0.3323	0.1580	0.1731
	AGV	0.0017*	0.8414	0.0660	0.0000*	0.0000*
6/U/F/N/2/20	M/C	0.2322	0.0034*	0.5025	0.1498	0.8189
	AGV	0.9509	0.8263	0.9792	0.0067*	0.4411
6/U/F/Y/1/15	M/C	0.0002*	0.0529	0.0033*	0.0000*	0.0002*
	AGV	0.2315	0.7310	0.3637	0.0000*	0.0003*
6/U/F/Y/1/20	M/C	0.0093*	0.0003*	0.0374*	0.0000*	0.0893
	AGV	0.7067	0.1546	0.7964	0.4619	0.8896
6/U/F/Y/2/15	M/C	0.2090	0.5127	0.5273	0.9887	0.9923
	AGV	0.0006*	0.6598	0.0527	0.0000*	0.0000*
6/U/F/Y/2/20	M/C	0.1059	0.0019*	0.3285	0.4340	0.7340
	AGV	0.9564	0.8171	0.9729	0.0007*	0.3819
6/U/J/N/1/15	M/C	0.0000*	0.2036	0.0000*	0.0121*	0.1025
	AGV	0.8376	0.2492	0.8904	0.1998	0.2649
6/U/J/N/1/20	M/C	0.0000*	0.3579	0.0012*	0.0000*	0.0912
	AGV	0.9380	0.5938	0.9357	0.0292*	0.6657
6/U/J/N/2/15	M/C	0.5086	0.0352*	0.7761	0.3509	0.8245
	AGV	0.4045	0.4147	0.6753	0.0216*	0.1636
6/U/J/N/2/20	M/C	0.6511	0.0954	0.8176	0.8669	0.9962
	AGV	0.9917	0.7612	0.9924	0.8669	0.8637
6/U/J/Y/1/15	M/C	0.0000*	0.6028	0.0010*	0.0000*	0.0015*
	AGV	0.8490	0.9347	0.9004	0.0114*	0.1681
6/U/J/Y/1/20	M/C	0.0000*	0.0802	0.0008*	0.0000*	0.0346*
	AGV	0.7174	0.1196	0.8051	0.3423	0.8205
6/U/J/Y/2/15	M/C	0.2632	0.3683	0.5626	0.5432	0.8588
	AGV	0.1413	0.9204	0.4224	0.0000*	0.0027*
6/U/J/Y/2/20	M/C	0.4041	0.0522	0.6907	0.1651	0.8433
	AGV	0.9965	0.9926	0.9981	0.1651	0.6245

Table 4: ANOVA Results: Rules affecting performance measures for TBA = 6 min and AD = Uniform.

* Significant at 0.05 level.

Appendix B

-95% Confidence-Interval of Performance Measures

Treatment	Rules	Performance Measures			
		FT	WIP	EL	AGV.UTZ
5/E/F/N/1/15	LQM-NS	119.96±5.35	23.64±1.30	0.27±0.008	96.89±0.60
	LQM-NUJ	117.46±5.06	23.18±1.28	0.26±0.008	96.49±0.60
	LQM-QSNS	119.57±5.23	23.65±1.32	0.28±0.007	97.05±0.58
	MRT-NS	118.14±4.16	23.25±1.12	0.27±0.009	96.84±0.61
	MRT-NUJ	116.27±5.30	22.94±1.29	0.26±0.009	96.38±0.56
	MRT-QSNS	120.19±4.97	23.67±1.25	0.28±0.009	96.91±0.57
	SIO-NS	115.04±4.33	22.63±1.10	0.28±0.010	96.95±0.62
	SIO-NUJ	113.88±4.54	22.44±1.15	0.27±0.009	96.79±0.61
	SIO-QSNS	119.42±5.25	23.53±1.29	0.28±0.008	97.10±0.59
5/E/F/N/1/20	LQM-NS	106.43±5.04	20.98±1.24	0.33±0.003	86.97±1.00
	LQM-NUJ	106.02±4.04	20.91±1.04	0.32±0.003	86.59±0.97
	LQM-QSNS	107.22±4.96	21.09±1.17	0.33±0.003	86.98±0.98
	MRT-NS	103.91±4.08	20.45±1.03	0.33±0.003	87.00±1.00
	MRT-NUJ	103.80±3.87	20.48±1.00	0.32±0.004	86.49±0.95
	MRT-QSNS	104.75±4.72	20.63±1.13	0.33±0.003	86.89±0.98
	SIO-NS	103.49±3.79	20.38±0.99	0.34±0.003	87.16±1.00
	SIO-NUJ	103.41±4.07	20.35±0.98	0.33±0.004	86.72±0.90
	SIO-QSNS	103.78±4.34	20.44±1.07	0.34±0.004	87.20±0.96
5/E/F/N/2/15	LQM-NS	73.17±1.72	14.39±0.49	0.26±0.009	95.85±0.67
	LQM-NUJ	71.07±1.50	13.97±0.44	0.24±0.009	95.29±0.72
	LQM-QSNS	76.95±3.19	15.14±0.78	0.26±0.008	96.23±0.69
	MRT-NS	72.40±1.59	14.22±0.47	0.26±0.009	95.83±0.71
	MRT-NUJ	69.25±1.39	13.81±0.43	0.24±0.009	95.31±0.72
	MRT-QSNS	76.35±2.93	15.09±0.73	0.27±0.008	96.20±0.73
	SIO-NS	72.00±1.71	14.15±0.48	0.26±0.010	95.80±0.69
	SIO-NUJ	68.97±1.46	13.75±0.44	0.24±0.009	95.30±0.71
	SIO-QSNS	76.60±2.86	15.05±0.71	0.27±0.007	96.23±0.71
5/E/F/N/2/20	LQM-NS	62.11±1.29	12.22±0.39	0.33±0.004	86.69±1.08
	LQM-NUJ	61.66±1.27	12.13±0.39	0.31±0.004	86.20±1.05
	LQM-QSNS	62.35±1.35	12.26±0.40	0.33±0.004	86.69±1.05
	MRT-NS	61.64±1.32	12.12±0.39	0.33±0.004	86.69±1.02
	MRT-NUJ	61.27±1.33	12.05±0.39	0.31±0.004	86.21±1.02
	MRT-QSNS	61.72±1.31	12.14±0.38	0.33±0.004	86.74±1.01
	SIO-NS	61.56±1.35	12.11±0.40	0.33±0.004	86.67±1.04
	SIO-NUJ	61.10±1.24	12.03±0.39	0.31±0.004	86.18±1.03
	SIO-QSNS	61.49±1.30	12.09±0.39	0.33±0.004	86.66±1.04

Table 1: 95% Confidence Interval for TBA = 5 min.; AD = Exponential; Flowshop; Balanced

Treatment	Rules	Performance Measures			
		FT	WIP	EL	AGV.UTZ
5/E/F/Y/1/15	LQM-NS	124.66±6.51	24.57±1.58	0.28±0.008	96.93±0.58
	LQM-NUJ	120.63±5.14	23.77±1.27	0.26±0.008	96.52±0.56
	LQM-QSNS	125.67±6.78	24.74±1.59	0.28±0.008	97.04±0.58
	MRT-NS	120.63±5.49	23.82±1.38	0.27±0.009	96.78±0.58
	MRT-NUJ	120.55±5.13	23.76±1.28	0.26±0.008	96.34±0.59
	MRT-QSNS	123.27±5.35	24.25±1.31	0.28±0.008	96.96±0.56
	SIO-NS	120.09±5.28	23.65±1.34	0.28±0.009	97.01±0.56
	SIO-NUJ	119.00±5.54	23.47±1.33	0.27±0.008	96.58±0.60
	SIO-QSNS	121.37±5.96	23.91±1.45	0.28±0.008	97.18±0.59
5/E/F/Y/1/20	LQM-NS	109.94±5.13	21.69±1.26	0.33±0.003	86.92±0.88
	LQM-NUJ	108.40±4.58	21.41±1.19	0.32±0.004	86.51±0.92
	LQM-QSNS	109.64±5.27	21.66±1.27	0.33±0.003	87.02±0.97
	MRT-NS	108.48±4.89	21.38±1.17	0.33±0.004	86.94±0.96
	MRT-NUJ	107.59±4.74	21.22±1.19	0.32±0.004	86.52±0.91
	MRT-QSNS	108.29±4.53	21.32±1.16	0.33±0.003	87.03±0.97
	SIO-NS	107.92±4.44	21.20±1.16	0.34±0.004	87.23±0.89
	SIO-NUJ	106.50±4.66	20.97±1.18	0.33±0.003	86.75±0.94
	SIO-QSNS	106.52±4.75	20.99±1.20	0.33±0.004	87.12±0.88
5/E/F/Y/2/15	LQM-NS	75.55±2.18	14.84±0.60	0.26±0.009	95.92±0.69
	LQM-NUJ	73.33±2.01	14.40±0.56	0.25±0.009	95.38±0.68
	LQM-QSNS	78.88±3.05	15.48±0.77	0.26±0.009	96.22±0.69
	MRT-NS	74.27±2.04	14.58±0.58	0.26±0.009	95.94±0.69
	MRT-NUJ	71.57±1.99	14.24±0.56	0.25±0.009	95.44±0.68
	MRT-QSNS	77.37±2.73	15.17±0.71	0.26±0.009	96.16±0.66
	SIO-NS	74.27±2.12	14.58±0.59	0.26±0.009	95.94±0.68
	SIO-NUJ	71.31±1.91	14.19±0.55	0.25±0.009	95.41±0.69
	SIO-QSNS	78.42±3.24	15.39±0.81	0.27±0.009	96.31±0.65
5/E/F/Y/2/20	LQM-NS	64.73±1.88	12.71±0.52	0.33±0.003	86.80±1.08
	LQM-NUJ	64.52±1.96	12.66±0.54	0.32±0.004	86.33±1.02
	LQM-QSNS	64.83±1.89	12.73±0.53	0.33±0.004	86.86±1.05
	MRT-NS	63.93±1.75	12.54±0.50	0.33±0.004	86.76±1.05
	MRT-NUJ	63.66±1.74	12.49±0.49	0.31±0.004	86.34±1.05
	MRT-QSNS	63.99±1.79	12.55±0.50	0.33±0.004	86.74±1.07
	SIO-NS	63.83±1.82	12.52±0.51	0.32±0.004	86.69±1.03
	SIO-NUJ	63.53±1.79	12.47±0.51	0.31±0.004	86.29±1.06
	SIO-QSNS	63.83±1.72	12.53±0.49	0.33±0.004	86.78±1.01

Table 2: 95% Confidence Interval for TBA = 5 min.; AD = Exponential; Flowshop; Unbalanced.

Treatment	Rules	Performance Measures			
		FT	WIP	EL	AGV.UTZ
5/E/J/N/1/15	LQM-NS	123.81±5.54	24.40±1.32	0.27±0.009	96.75±0.56
	LQM-NUJ	123.89±6.09	24.41±1.47	0.27±0.008	96.44±0.58
	LQM-QSNS	125.29±5.89	24.67±1.39	0.28±0.009	96.87±0.55
	MRT-NS	120.71±4.93	23.78±1.21	0.27±0.009	96.59±0.57
	MRT-NUJ	120.81±5.49	23.79±1.32	0.27±0.009	96.22±0.57
	MRT-QSNS	124.33±6.44	24.51±1.43	0.28±0.008	96.74±0.57
	SIO-NS	117.74±4.25	23.18±1.06	0.27±0.009	96.77±0.61
	SIO-NUJ	115.13±5.07	22.64±1.18	0.27±0.009	96.43±0.63
	SIO-QSNS	119.29±5.71	23.50±1.33	0.28±0.009	96.97±0.58
5/E/J/N/1/20	LQM-NS	112.67±5.10	22.18±1.22	0.33±0.003	86.69±0.94
	LQM-NUJ	113.09±5.16	22.25±1.17	0.32±0.004	86.28±0.93
	LQM-QSNS	113.25±5.44	22.33±1.27	0.33±0.004	86.66±1.01
	MRT-NS	109.44±4.60	21.54±1.11	0.32±0.004	86.44±0.94
	MRT-NUJ	106.45±4.03	20.97±0.98	0.31±0.004	86.28±0.98
	MRT-QSNS	109.61±4.45	21.57±1.08	0.32±0.004	86.52±0.95
	SIO-NS	104.69±4.09	20.59±1.01	0.33±0.004	86.79±0.98
	SIO-NUJ	101.92±4.03	20.48±1.01	0.32±0.004	86.50±0.96
	SIO-QSNS	104.26±4.07	20.54±1.01	0.33±0.004	86.83±0.96
5/E/J/N/2/15	LQM-NS	72.77±1.71	14.31±0.50	0.25±0.009	95.50±0.74
	LQM-NUJ	71.29±1.52	14.01±0.46	0.24±0.009	95.21±0.73
	LQM-QSNS	75.74±2.58	14.88±0.65	0.26±0.008	95.88±0.69
	MRT-NS	72.24±1.62	14.19±0.48	0.26±0.010	95.68±0.74
	MRT-NUJ	69.81±1.55	13.91±0.47	0.25±0.009	95.25±0.76
	MRT-QSNS	75.27±2.27	14.79±0.59	0.26±0.009	95.83±0.72
	SIO-NS	72.03±1.57	14.13±0.47	0.25±0.009	95.58±0.71
	SIO-NUJ	69.73±1.53	13.59±0.46	0.24±0.009	95.24±0.75
	SIO-QSNS	75.26±2.52	14.78±0.64	0.26±0.008	95.86±0.71
5/E/J/N/2/20	LQM-NS	61.97±1.30	12.18±0.39	0.32±0.004	86.32±1.06
	LQM-NUJ	61.93±1.32	12.18±0.39	0.31±0.004	86.06±1.06
	LQM-QSNS	62.13±1.37	12.21±0.41	0.32±0.003	86.34±1.07
	MRT-NS	62.02±1.30	12.19±0.39	0.32±0.004	86.41±1.06
	MRT-NUJ	61.77±1.25	12.14±0.38	0.32±0.004	86.08±1.05
	MRT-QSNS	62.08±1.28	12.19±0.39	0.32±0.004	86.41±1.05
	SIO-NS	61.92±1.29	12.17±0.39	0.32±0.004	86.39±1.05
	SIO-NUJ	61.61±1.24	12.10±0.38	0.32±0.004	86.07±1.07
	SIO-QSNS	61.97±1.30	12.18±0.39	0.32±0.004	86.45±1.02

Table 3: 95% Confidence Interval for TBA = 5 min.; AD = Exponential; Jobshop; Balanced.

Treatment	Rules	Performance Measures			
		FT	WIP	EL	AGV.UTZ
5/E/J/Y/1/15	LQM-NS	124.42±5.91	24.47±1.39	0.27±0.009	96.80±0.59
	LQM-NUJ	123.77±6.10	24.41±1.43	0.27±0.008	96.48±0.56
	LQM-QSNS	126.28±6.39	24.87±1.51	0.28±0.008	96.81±0.58
	MRT-NS	122.06±5.37	24.02±1.30	0.27±0.009	96.74±0.59
	MRT-NUJ	120.67±5.14	23.74±1.23	0.26±0.009	96.34±0.59
	MRT-QSNS	125.55±6.83	24.73±1.57	0.28±0.008	96.87±0.58
	SIO-NS	119.81±5.08	23.26±1.25	0.27±0.009	96.82±0.62
	SIO-NUJ	116.00±4.89	22.84±1.22	0.26±0.009	96.53±0.58
	SIO-QSNS	120.88±5.23	23.80±1.27	0.28±0.007	96.95±0.59
5/E/J/Y/1/20	LQM-NS	111.79±4.77	22.02±1.18	0.33±0.003	86.77±0.92
	LQM-NUJ	111.84±4.89	22.03±1.22	0.32±0.004	86.39±0.95
	LQM-QSNS	110.83±5.28	21.84±1.25	0.33±0.003	86.71±0.99
	MRT-NS	109.63±4.76	21.60±1.18	0.33±0.003	86.65±0.96
	MRT-NUJ	110.45±5.36	21.71±1.26	0.32±0.004	86.41±0.98
	MRT-QSNS	110.53±4.93	21.78±1.20	0.33±0.003	86.69±0.96
	SIO-NS	107.80±4.69	21.22±1.15	0.33±0.004	86.86±0.97
	SIO-NUJ	106.59±4.50	20.98±1.09	0.33±0.003	86.52±0.95
	SIO-QSNS	107.87±4.69	21.24±1.12	0.34±0.004	86.88±0.99
5/E/J/Y/2/15	LQM-NS	74.99±1.89	14.54±0.54	0.26±0.009	95.77±0.71
	LQM-NUJ	72.24±1.78	14.19±0.51	0.25±0.009	95.38±0.71
	LQM-QSNS	77.01±2.66	15.14±0.68	0.26±0.008	96.10±0.71
	MRT-NS	74.64±1.89	14.48±0.53	0.26±0.009	95.78±0.73
	MRT-NUJ	71.12±1.69	14.17±0.49	0.25±0.009	95.47±0.71
	MRT-QSNS	77.25±2.54	15.18±0.65	0.26±0.009	96.17±0.69
	SIO-NS	74.20±1.79	14.39±0.52	0.26±0.009	95.80±0.73
	SIO-NUJ	71.09±1.70	14.17±0.49	0.25±0.009	95.51±0.72
	SIO-QSNS	76.07±2.41	14.95±0.63	0.26±0.008	95.99±0.69
5/E/J/Y/2/20	LQM-NS	63.35±1.63	12.46±0.46	0.32±0.004	86.53±1.04
	LQM-NUJ	63.27±1.48	12.44±0.43	0.31±0.004	86.15±1.00
	LQM-QSNS	63.42±1.66	12.48±0.46	0.32±0.004	86.57±1.04
	MRT-NS	63.49±1.52	12.49±0.44	0.32±0.004	86.57±1.02
	MRT-NUJ	63.45±1.53	12.47±0.45	0.32±0.005	86.31±1.00
	MRT-QSNS	63.72±1.57	12.53±0.45	0.33±0.004	86.64±1.03
	SIO-NS	63.54±1.58	12.49±0.46	0.32±0.004	86.58±1.05
	SIO-NUJ	63.38±1.53	12.46±0.45	0.32±0.003	86.32±1.08
	SIO-QSNS	63.54±1.57	12.49±0.45	0.33±0.004	86.59±1.03

Table 4: 95% Confidence Interval for TBA = 5 min.; AD = Exponential; Jobshop; Unbalanced.

Treatment	Rules	Performance Measures			
		FT	WIP	EL	AGV.UTZ
5/U/F/N/1/15	LQM-NS	113.64±3.42	22.76±0.77	0.27±0.004	99.01±0.07
	LQM-NUJ	111.22±3.50	22.30±0.78	0.27±0.004	98.72±0.08
	LQM-QSNS	112.83±2.78	22.59±0.62	0.27±0.004	99.10±0.08
	MRT-NS	113.26±2.90	22.67±0.66	0.27±0.004	98.98±0.06
	MRT-NUJ	109.79±3.07	21.99±0.68	0.27±0.004	98.67±0.07
	MRT-QSNS	112.98±2.92	22.63±0.66	0.27±0.004	98.99±0.08
	SIO-NS	110.41±2.37	22.08±0.55	0.27±0.005	99.16±0.07
	SIO-NUJ	107.60±2.56	21.51±0.57	0.27±0.004	98.89±0.08
	SIO-QSNS	110.75±2.93	22.17±0.68	0.28±0.005	99.16±0.06
5/U/F/N/1/20	LQM-NS	102.15±3.24	20.46±0.72	0.36±0.003	90.54±0.27
	LQM-NUJ	100.84±2.62	20.21±0.59	0.35±0.001	90.09±0.26
	LQM-QSNS	99.57±2.99	19.94±0.67	0.36±0.003	90.59±0.24
	MRT-NS	98.53±2.87	19.74±0.64	0.36±0.003	90.47±0.25
	MRT-NUJ	98.66±2.63	19.76±0.59	0.35±0.003	90.16±0.26
	MRT-QSNS	98.63±2.58	19.76±0.58	0.36±0.003	90.39±0.27
	SIO-NS	96.73±2.47	19.53±0.54	0.36±0.003	90.76±0.26
	SIO-NUJ	95.08±2.42	19.24±0.56	0.36±0.002	90.31±0.28
	SIO-QSNS	98.24±2.63	19.65±0.59	0.36±0.003	90.69±0.24
5/U/F/N/2/15	LQM-NS	64.58±0.77	12.93±0.19	0.28±0.005	99.24±0.06
	LQM-NUJ	62.82±0.80	12.58±0.20	0.27±0.004	98.88±0.08
	LQM-QSNS	64.75±0.91	12.96±0.22	0.28±0.004	99.23±0.07
	MRT-NS	64.00±0.87	12.81±0.21	0.28±0.005	99.19±0.08
	MRT-NUJ	62.39±0.79	12.49±0.19	0.27±0.004	98.88±0.08
	MRT-QSNS	64.21±0.85	12.85±0.21	0.28±0.005	99.22±0.07
	SIO-NS	63.85±0.84	12.78±0.21	0.28±0.005	99.21±0.06
	SIO-NUJ	62.23±0.74	12.46±0.19	0.27±0.005	98.87±0.08
	SIO-QSNS	64.14±0.98	12.84±0.24	0.28±0.004	99.21±0.08
5/U/F/N/2/20	LQM-NS	54.53±0.73	10.92±0.18	0.37±0.003	91.14±0.24
	LQM-NUJ	54.31±0.66	10.87±0.16	0.36±0.003	90.55±0.21
	LQM-QSNS	54.64±0.70	10.94±0.17	0.37±0.002	91.07±0.25
	MRT-NS	54.36±0.68	10.88±0.17	0.36±0.003	90.98±0.25
	MRT-NUJ	53.93±0.75	10.79±0.18	0.35±0.002	90.49±0.29
	MRT-QSNS	54.39±0.72	10.89±0.17	0.36±0.003	91.02±0.28
	SIO-NS	54.16±0.73	10.84±0.18	0.36±0.003	91.09±0.28
	SIO-NUJ	53.85±0.68	10.78±0.17	0.35±0.003	90.62±0.23
	SIO-QSNS	54.19±0.70	10.85±0.17	0.36±0.003	90.96±0.26

Table 5: 95% Confidence Interval for TBA = 5 min.; AD = Uniform; Flowshop; Balanced

Treatment	Rules	Performance Measures			
		FT	WIP	EL	AGV.UTZ
5/U/F/Y/1/15	LQM-NS	119.26±3.94	23.89±0.85	0.27±0.004	98.88±0.08
	LQM-NUJ	117.79±3.92	23.58±0.84	0.26±0.004	98.57±0.08
	LQM-QSNS	118.95±3.26	23.80±0.68	0.27±0.004	98.93±0.08
	MRT-NS	114.03±2.51	22.86±0.58	0.27±0.004	98.92±0.09
	MRT-NUJ	112.15±2.85	22.66±0.64	0.26±0.004	98.59±0.08
	MRT-QSNS	114.85±2.76	23.00±0.63	0.27±0.004	98.92±0.09
	SIO-NS	114.81±3.13	23.02±0.69	0.27±0.004	99.01±0.10
	SIO-NUJ	110.57±3.01	22.39±0.65	0.27±0.004	98.89±0.12
	SIO-QSNS	113.89±4.56	22.89±0.95	0.28±0.005	99.05±0.09
5/U/F/Y/1/20	LQM-NS	105.21±3.45	21.06±0.74	0.36±0.003	90.45±0.22
	LQM-NUJ	104.67±2.73	20.98±0.59	0.35±0.003	90.04±0.21
	LQM-QSNS	105.95±3.25	21.80±0.68	0.36±0.003	90.53±0.28
	MRT-NS	103.17±2.29	20.66±0.49	0.35±0.004	90.23±0.26
	MRT-NUJ	100.19±1.97	20.23±0.47	0.34±0.002	89.93±0.26
	MRT-QSNS	101.90±2.55	20.42±0.56	0.35±0.002	90.26±0.27
	SIO-NS	100.53±2.76	20.33±0.63	0.36±0.001	90.52±0.23
	SIO-NUJ	103.03±4.29	20.61±0.89	0.35±0.003	90.18±0.25
	SIO-QSNS	101.66±3.04	20.36±0.66	0.36±0.003	90.61±0.27
5/U/F/Y/2/15	LQM-NS	65.99±0.87	13.21±0.21	0.27±0.005	99.16±0.07
	LQM-NUJ	64.14±0.81	12.84±0.19	0.26±0.004	98.80±0.09
	LQM-QSNS	66.33±0.94	13.28±0.22	0.28±0.005	99.20±0.07
	MRT-NS	65.05±0.77	13.02±0.19	0.27±0.005	99.16±0.05
	MRT-NUJ	63.50±0.72	12.71±0.17	0.26±0.004	98.78±0.09
	MRT-QSNS	65.51±1.03	13.11±0.25	0.27±0.004	99.15±0.09
	SIO-NS	65.11±0.94	13.03±0.22	0.27±0.005	99.17±0.08
	SIO-NUJ	63.42±0.78	12.70±0.18	0.26±0.004	98.80±0.09
	SIO-QSNS	65.38±0.89	13.09±0.21	0.28±0.004	99.19±0.07
5/U/F/Y/2/20	LQM-NS	56.01±0.73	11.21±0.17	0.36±0.003	91.02±0.27
	LQM-NUJ	55.65±0.67	11.15±0.16	0.35±0.002	90.56±0.24
	LQM-QSNS	56.02±0.70	11.22±0.17	0.37±0.003	91.01±0.27
	MRT-NS	55.38±0.65	11.09±0.16	0.36±0.003	90.95±0.22
	MRT-NUJ	55.19±0.67	11.05±0.16	0.35±0.002	90.49±0.25
	MRT-QSNS	55.43±0.67	11.09±0.16	0.36±0.003	90.90±0.27
	SIO-NS	55.39±0.62	11.09±0.15	0.36±0.002	90.91±0.28
	SIO-NUJ	55.09±0.59	11.03±0.15	0.35±0.002	90.57±0.25
	SIO-QSNS	55.32±0.73	11.08±0.17	0.36±0.003	90.89±0.27

Table 6: 95% Confidence Interval for TBA = 5 min.; AD = Uniform; Flowshop; Unbalanced.

Treatment	Rules	Performance Measures			
		FT	WIP	EL	AGV.UTZ
5/U/J/N/1/15	LQM-NS	120.60±3.60	24.16±0.79	0.27±0.004	98.81±0.10
	LQM-NUJ	119.12±3.85	23.82±0.84	0.27±0.004	98.61±0.08
	LQM-QSNS	122.26±4.07	24.46±0.90	0.27±0.004	98.81±0.08
	MRT-NS	114.88±2.95	23.02±0.67	0.27±0.004	98.82±0.10
	MRT-NUJ	112.74±2.65	22.60±0.59	0.27±0.004	98.56±0.09
	MRT-QSNS	115.79±2.89	23.18±0.65	0.27±0.004	98.84±0.07
	SIO-NS	110.01±2.76	22.06±0.66	0.27±0.004	98.97±0.10
	SIO-NUJ	108.25±2.43	21.69±0.54	0.27±0.004	98.74±0.11
	SIO-QSNS	111.37±2.49	22.32±0.58	0.27±0.005	99.03±0.07
5/U/J/N/1/20	LQM-NS	109.03±3.01	21.86±0.66	0.35±0.003	89.68±0.29
	LQM-NUJ	108.98±3.99	21.86±0.87	0.34±0.003	89.49±0.27
	LQM-QSNS	109.24±3.46	21.89±0.78	0.35±0.003	89.86±0.28
	MRT-NS	102.57±2.79	20.53±0.61	0.35±0.002	89.93±0.28
	MRT-NUJ	102.36±2.49	20.49±0.56	0.34±0.002	89.45±0.25
	MRT-QSNS	101.74±2.67	20.37±0.60	0.35±0.002	89.79±0.29
	SIO-NS	99.02±1.92	19.84±0.49	0.36±0.002	90.23±0.28
	SIO-NUJ	98.79±2.51	19.79±0.58	0.35±0.003	90.00±0.29
	SIO-QSNS	99.14±1.79	19.86±0.44	0.35±0.003	90.07±0.26
5/U/J/N/2/15	LQM-NS	64.26±0.69	12.87±0.18	0.27±0.005	99.01±0.09
	LQM-NUJ	62.98±0.67	12.60±0.16	0.27±0.004	98.76±0.07
	LQM-QSNS	64.44±0.86	12.90±0.21	0.27±0.005	99.06±0.09
	MRT-NS	63.81±0.71	12.78±0.18	0.27±0.004	99.06±0.09
	MRT-NUJ	62.61±0.71	12.54±0.17	0.27±0.004	98.79±0.08
	MRT-QSNS	63.94±0.77	12.81±0.19	0.27±0.005	99.02±0.09
	SIO-NS	63.85±0.68	12.78±0.17	0.27±0.004	99.02±0.10
	SIO-NUJ	62.66±0.71	12.55±0.18	0.27±0.004	98.77±0.09
	SIO-QSNS	64.13±0.89	12.84±0.22	0.27±0.005	99.10±0.09
5/U/J/N/2/20	LQM-NS	54.87±0.60	10.99±0.15	0.36±0.002	90.54±0.24
	LQM-NUJ	54.63±0.65	10.94±0.16	0.35±0.002	90.11±0.29
	LQM-QSNS	54.84±0.57	10.98±0.15	0.36±0.003	90.48±0.23
	MRT-NS	54.63±0.62	10.94±0.15	0.36±0.003	90.36±0.28
	MRT-NUJ	54.59±0.59	10.94±0.15	0.35±0.002	90.07±0.29
	MRT-QSNS	54.73±0.61	10.96±0.15	0.36±0.002	90.39±0.26
	SIO-NS	54.71±0.66	10.96±0.16	0.36±0.002	90.46±0.28
	SIO-NUJ	54.51±0.65	10.92±0.16	0.35±0.003	90.16±0.27
	SIO-QSNS	54.68±0.65	10.95±0.16	0.36±0.003	90.38±0.30

Table 7: 95% Confidence Interval for TBA = 5 min.; AD = Uniform; Jobshop; Balanced.

Treatment	Rules	Performance Measures			
		FT	WIP	EL	AGV.UTZ
5/U/J/Y/1/15	LQM-NS	120.28±3.89	24.10±0.87	0.27±0.004	98.83±0.08
	LQM-NUJ	116.88±3.03	23.40±0.67	0.26±0.004	98.57±0.09
	LQM-QSNS	120.21±4.12	24.09±0.92	0.27±0.004	98.83±0.08
	MRT-NS	116.66±3.30	23.35±0.72	0.27±0.004	98.81±0.08
	MRT-NUJ	114.12±3.22	22.84±0.70	0.26±0.004	98.51±0.13
	MRT-QSNS	115.78±3.29	23.19±0.71	0.27±0.004	98.89±0.11
	SIO-NS	112.70±3.78	22.54±0.81	0.27±0.005	98.96±0.09
	SIO-NUJ	110.24±3.03	22.27±0.69	0.27±0.004	98.84±0.10
	SIO-QSNS	113.49±4.90	22.92±1.03	0.27±0.004	98.94±0.09
5/U/J/Y/1/20	LQM-NS	107.03±3.78	21.42±0.82	0.35±0.003	89.87±0.30
	LQM-NUJ	106.87±3.76	21.41±0.79	0.33±0.003	89.62±0.26
	LQM-QSNS	106.71±2.89	21.38±0.65	0.35±0.003	89.78±0.23
	MRT-NS	102.95±2.57	20.62±0.58	0.35±0.002	89.85±0.26
	MRT-NUJ	103.56±2.72	20.75±0.61	0.33±0.002	89.66±0.28
	MRT-QSNS	104.21±2.57	20.88±0.57	0.34±0.002	89.75±0.31
	SIO-NS	100.85±2.46	20.21±0.56	0.35±0.003	90.11±0.31
	SIO-NUJ	100.10±2.77	20.04±0.62	0.35±0.002	89.99±0.27
	SIO-QSNS	100.36±2.51	20.08±0.56	0.35±0.002	90.09±0.28
5/U/J/Y/2/15	LQM-NS	65.28±0.80	13.06±0.19	0.27±0.005	98.99±0.07
	LQM-NUJ	64.34±0.89	12.88±0.21	0.27±0.004	98.76±0.10
	LQM-QSNS	65.90±1.07	13.19±0.25	0.27±0.005	99.02±0.09
	MRT-NS	65.30±0.93	13.07±0.22	0.27±0.005	99.03±0.09
	MRT-NUJ	64.22±0.87	12.85±0.21	0.27±0.004	98.78±0.09
	MRT-QSNS	65.49±1.06	13.11±0.25	0.27±0.004	99.02±0.10
	SIO-NS	65.18±0.87	13.05±0.21	0.27±0.005	99.00±0.09
	SIO-NUJ	64.14±0.91	12.84±0.21	0.27±0.004	98.82±0.10
	SIO-QSNS	65.24±0.95	13.06±0.22	0.27±0.005	99.04±0.09
5/U/J/Y/2/20	LQM-NS	56.03±0.80	11.21±0.19	0.36±0.002	90.51±0.27
	LQM-NUJ	55.82±0.78	11.17±0.18	0.35±0.002	90.21±0.29
	LQM-QSNS	56.08±0.75	11.23±0.18	0.36±0.002	90.52±0.28
	MRT-NS	56.01±0.85	11.21±0.20	0.36±0.002	90.43±0.24
	MRT-NUJ	55.85±0.86	11.18±0.19	0.35±0.003	90.15±0.30
	MRT-QSNS	56.09±0.84	11.23±0.19	0.36±0.002	90.47±0.25
	SIO-NS	56.01±0.87	11.21±0.19	0.36±0.002	90.38±0.25
	SIO-NUJ	55.81±0.76	11.17±0.18	0.35±0.002	90.13±0.28
	SIO-QSNS	55.95±0.82	11.19±0.19	0.36±0.002	90.44±0.27

Table 8: 95% Confidence Interval for TBA = 5 min.; AD = Uniform; Jobshop; Unbalanced.

Treatment	Rules	Performance Measures			
		FT	WIP	EL	AGV.UTZ
6/E/F/N/1/15	LQM-NS	76.51±2.18	12.66±0.45	0.36±0.007	87.67±1.05
	LQM-NUJ	75.83±1.81	12.55±0.42	0.35±0.005	87.28±1.04
	LQM-QSNS	76.68±1.96	12.70±0.44	0.36±0.005	87.72±1.07
	MRT-NS	77.83±2.13	12.88±0.44	0.36±0.005	87.77±1.05
	MRT-NUJ	77.34±1.79	12.79±0.40	0.35±0.005	87.33±0.99
	MRT-QSNS	78.55±2.13	12.99±0.44	0.36±0.006	87.83±0.99
	SIO-NS	76.88±1.88	12.72±0.43	0.36±0.006	87.88±1.05
	SIO-NUJ	76.04±1.82	12.59±0.41	0.36±0.005	87.42±1.06
	SIO-QSNS	77.16±1.79	12.77±0.42	0.36±0.005	87.92±1.05
6/E/F/N/1/20	LQM-NS	69.99±1.85	11.60±0.42	0.34±0.002	74.24±0.99
	LQM-NUJ	69.32±1.53	11.46±0.35	0.34±0.003	74.12±1.04
	LQM-QSNS	69.96±1.85	11.58±0.42	0.35±0.003	74.31±1.03
	MRT-NS	70.62±1.84	11.69±0.41	0.34±0.003	74.27±1.06
	MRT-NUJ	70.32±1.69	11.64±0.39	0.34±0.004	74.13±1.07
	MRT-QSNS	70.23±1.72	11.63±0.40	0.34±0.003	74.18±1.06
	SIO-NS	69.43±1.94	11.49±0.39	0.35±0.003	74.50±1.10
	SIO-NUJ	68.94±1.59	11.39±0.35	0.35±0.003	74.34±1.07
	SIO-QSNS	69.37±1.94	11.47±0.39	0.35±0.004	74.54±1.12
6/E/F/N/2/15	LQM-NS	57.62±0.82	9.54±0.22	0.35±0.004	86.63±1.09
	LQM-NUJ	57.00±0.68	9.42±0.19	0.34±0.006	86.06±1.06
	LQM-QSNS	57.94±0.90	9.59±0.23	0.35±0.005	86.66±1.08
	MRT-NS	57.26±0.81	9.48±0.22	0.35±0.006	86.59±1.10
	MRT-NUJ	55.51±0.69	9.36±0.20	0.32±0.005	85.97±1.09
	MRT-QSNS	57.49±0.85	9.52±0.21	0.35±0.005	86.65±1.07
	SIO-NS	57.26±0.75	9.48±0.22	0.34±0.005	86.59±1.07
	SIO-NUJ	55.52±0.70	9.36±0.21	0.32±0.005	85.99±1.09
	SIO-QSNS	57.64±0.89	9.54±0.21	0.34±0.005	86.63±1.04
6/E/F/N/2/20	LQM-NS	50.47±0.61	8.36±0.18	0.34±0.003	74.05±1.14
	LQM-NUJ	50.44±0.66	8.35±0.19	0.34±0.003	73.76±1.11
	LQM-QSNS	50.50±0.62	8.36±0.18	0.34±0.003	74.04±1.13
	MRT-NS	50.31±0.60	8.33±0.18	0.34±0.003	73.88±1.11
	MRT-NUJ	50.08±0.56	8.29±0.17	0.33±0.003	73.66±1.12
	MRT-QSNS	50.27±0.59	8.32±0.18	0.34±0.004	73.93±1.11
	SIO-NS	50.25±0.59	8.32±0.17	0.34±0.003	73.94±1.11
	SIO-NUJ	50.12±0.63	8.29±0.18	0.33±0.003	73.69±1.14
	SIO-QSNS	50.20±0.59	8.31±0.17	0.34±0.003	73.89±1.11

Table 9: 95% Confidence Interval for TBA = 6 min.; AD = Exponential; Flowshop; Balanced.

Treatment	Rules	Performance Measures			
		FT	WIP	EL	AGV.UTZ
6/E/F/Y/1/15	LQM-NS	77.31±2.12	12.78±0.45	0.36±0.005	87.65±1.02
	LQM-NUJ	76.88±2.11	12.71±0.45	0.35±0.005	87.23±1.02
	LQM-QSNS	77.07±2.00	12.74±0.46	0.36±0.006	87.63±1.00
	MRT-NS	78.20±2.13	12.94±0.48	0.36±0.006	87.66±1.08
	MRT-NUJ	78.08±2.15	12.93±0.48	0.35±0.005	87.27±1.05
	MRT-QSNS	78.07±2.06	12.92±0.45	0.36±0.006	87.65±0.99
	SIO-NS	76.83±2.19	12.71±0.46	0.36±0.005	87.72±1.07
	SIO-NUJ	76.09±1.81	12.59±0.42	0.36±0.006	87.41±1.11
	SIO-QSNS	76.79±1.94	12.71±0.46	0.36±0.006	87.80±1.10
6/E/F/Y/1/20	LQM-NS	69.62±1.73	11.52±0.42	0.35±0.003	74.24±1.09
	LQM-NUJ	69.58±1.68	11.52±0.36	0.34±0.003	73.98±1.08
	LQM-QSNS	69.46±1.81	11.50±0.41	0.35±0.003	74.18±1.07
	MRT-NS	70.69±1.87	11.68±0.40	0.35±0.003	74.22±1.10
	MRT-NUJ	69.95±1.66	11.58±0.41	0.34±0.003	74.02±1.08
	MRT-QSNS	71.09±2.00	11.75±0.42	0.34±0.004	74.23±1.11
	SIO-NS	69.37±1.79	11.48±0.40	0.35±0.004	74.31±1.13
	SIO-NUJ	69.72±1.88	11.52±0.40	0.34±0.003	74.18±1.04
	SIO-QSNS	69.35±1.66	11.47±0.39	0.35±0.004	74.27±1.12
6/E/F/Y/2/15	LQM-NS	57.99±0.80	9.60±0.23	0.35±0.005	86.66±1.09
	LQM-NUJ	57.37±0.75	9.50±0.22	0.34±0.005	86.05±1.12
	LQM-QSNS	58.29±0.89	9.65±0.23	0.35±0.006	86.69±1.06
	MRT-NS	57.62±0.87	9.54±0.23	0.35±0.005	86.61±1.11
	MRT-NUJ	56.93±0.75	9.43±0.22	0.33±0.005	85.98±1.08
	MRT-QSNS	57.88±0.94	9.58±0.23	0.34±0.006	86.61±1.09
	SIO-NS	57.61±0.86	9.54±0.24	0.34±0.005	86.63±1.10
	SIO-NUJ	56.76±0.74	9.39±0.22	0.33±0.005	86.02±1.12
	SIO-QSNS	56.76±0.72	9.40±0.24	0.34±0.005	86.02±1.10
6/E/F/Y/2/20	LQM-NS	50.79±0.64	8.41±0.19	0.34±0.003	73.97±1.13
	LQM-NUJ	50.73±0.65	8.40±0.20	0.34±0.004	73.73±1.14
	LQM-QSNS	50.82±0.65	8.42±0.19	0.34±0.004	74.00±1.11
	MRT-NS	50.59±0.64	8.38±0.19	0.34±0.004	73.94±1.13
	MRT-NUJ	50.42±0.64	8.35±0.19	0.33±0.003	73.67±1.10
	MRT-QSNS	50.58±0.64	8.38±0.19	0.34±0.004	73.95±1.12
	SIO-NS	50.55±0.68	8.37±0.19	0.34±0.003	74.02±1.15
	SIO-NUJ	50.42±0.66	8.35±0.19	0.33±0.003	73.69±1.15
	SIO-QSNS	50.56±0.69	8.37±0.19	0.34±0.004	73.98±1.13

Table 10: 95% Confidence Interval for TBA = 6 min.; AD = Exponential; Flowshop; Unbalanced.

Treatment	Rules	Performance Measures			
		FT	WIP	EL	AGV.UTZ
6/E/J/N/1/15	LQM-NS	78.49±2.19	12.98±0.46	0.36±0.005	87.47±1.01
	LQM-NUJ	77.68±2.22	12.84±0.47	0.35±0.005	87.20±1.02
	LQM-QSNS	78.04±1.98	12.91±0.42	0.36±0.006	87.51±0.99
	MRT-NS	80.17±1.98	13.26±0.44	0.36±0.005	87.45±0.96
	MRT-NUJ	79.41±1.94	13.13±0.41	0.35±0.005	87.19±0.96
	MRT-QSNS	79.69±1.90	13.20±0.45	0.36±0.006	87.46±0.99
	SIO-NS	77.61±1.84	12.83±0.41	0.36±0.004	87.67±1.01
	SIO-NUJ	77.53±2.18	12.82±0.41	0.36±0.006	87.39±0.95
	SIO-QSNS	77.23±1.90	12.78±0.42	0.36±0.005	87.70±0.96
6/E/J/N/1/20	LQM-NS	70.77±1.88	11.70±0.40	0.34±0.003	74.05±1.01
	LQM-NUJ	71.25±1.94	11.78±0.38	0.33±0.002	74.01±1.04
	LQM-QSNS	71.04±1.85	11.75±0.39	0.34±0.003	74.08±1.01
	MRT-NS	72.23±1.58	11.95±0.38	0.34±0.003	74.05±1.03
	MRT-NUJ	72.37±1.68	11.98±0.36	0.33±0.002	73.92±1.02
	MRT-QSNS	72.64±1.82	12.02±0.38	0.34±0.003	74.05±1.04
	SIO-NS	70.69±1.59	11.69±0.38	0.34±0.003	74.27±1.04
	SIO-NUJ	70.35±1.59	11.64±0.35	0.34±0.003	74.16±0.99
	SIO-QSNS	70.75±1.66	11.70±0.37	0.35±0.003	74.33±1.03
6/E/J/N/2/15	LQM-NS	57.60±0.76	9.54±0.22	0.34±0.005	86.28±1.07
	LQM-NUJ	57.60±0.75	9.53±0.22	0.34±0.005	86.28±1.07
	LQM-QSNS	57.73±0.84	9.55±0.22	0.34±0.006	86.35±1.04
	MRT-NS	57.28±0.72	9.48±0.21	0.34±0.006	86.24±1.07
	MRT-NUJ	56.83±0.73	9.41±0.22	0.33±0.006	85.96±1.06
	MRT-QSNS	57.54±0.81	9.52±0.22	0.34±0.007	86.26±1.04
	SIO-NS	57.25±0.71	9.48±0.22	0.34±0.006	86.28±1.06
	SIO-NUJ	57.25±0.70	9.48±0.23	0.34±0.007	86.28±1.08
	SIO-QSNS	57.25±0.71	9.48±0.22	0.34±0.006	86.28±1.06
6/E/J/N/2/20	LQM-NS	50.76±0.56	8.40±0.18	0.34±0.005	73.79±1.12
	LQM-NUJ	50.71±0.55	8.39±0.18	0.33±0.003	73.56±1.06
	LQM-QSNS	50.77±0.57	8.40±0.18	0.34±0.005	73.82±1.12
	MRT-NS	50.56±0.58	8.37±0.18	0.34±0.004	73.78±1.07
	MRT-NUJ	50.51±0.54	8.36±0.18	0.34±0.003	73.65±1.06
	MRT-QSNS	50.57±0.59	8.37±0.19	0.34±0.004	73.78±1.06
	SIO-NS	50.58±0.57	8.37±0.18	0.34±0.004	73.77±1.05
	SIO-NUJ	50.48±0.59	8.36±0.19	0.33±0.003	73.53±1.07
	SIO-QSNS	50.53±0.55	8.36±0.18	0.34±0.004	73.75±1.04

Table 11: 95% Confidence Interval for TBA = 6 min.; AD = Exponential; Jobshop; Balanced.

Treatment	Rules	Performance Measures			
		FT	WIP	EL	AGV.UTZ
6/E/J/Y/1/15	LQM-NS	78.16±2.55	12.93±0.47	0.36±0.007	87.66±0.97
	LQM-NUJ	78.08±2.09	12.84±0.44	0.35±0.004	87.33±0.97
	LQM-QSNS	78.18±2.08	12.93±0.41	0.36±0.006	87.60±0.97
	MRT-NS	79.21±2.04	13.11±0.44	0.36±0.005	87.59±1.01
	MRT-NUJ	78.91±1.79	13.07±0.39	0.35±0.005	87.26±1.01
	MRT-QSNS	80.05±2.26	13.25±0.45	0.36±0.005	87.68±0.96
	SIO-NS	77.00±1.85	12.73±0.41	0.36±0.006	87.82±1.01
	SIO-NUJ	77.09±1.89	12.74±0.40	0.36±0.005	87.53±0.95
	SIO-QSNS	76.94±1.93	12.73±0.43	0.36±0.005	87.80±0.98
6/E/J/Y/1/20	LQM-NS	71.15±1.73	11.77±0.38	0.34±0.004	74.13±0.99
	LQM-NUJ	70.43±1.68	11.65±0.36	0.34±0.003	73.95±1.04
	LQM-QSNS	71.20±1.86	11.78±0.39	0.34±0.004	74.13±1.00
	MRT-NS	71.94±1.66	11.90±0.37	0.34±0.003	74.14±1.07
	MRT-NUJ	71.94±1.65	11.90±0.36	0.34±0.003	74.14±1.05
	MRT-QSNS	72.05±1.75	11.91±0.36	0.34±0.002	74.10±1.06
	SIO-NS	70.27±2.06	11.63±0.41	0.34±0.003	74.27±1.05
	SIO-NUJ	70.14±1.61	11.60±0.35	0.34±0.004	74.21±1.06
	SIO-QSNS	69.92±1.70	11.57±0.37	0.34±0.003	74.25±1.04
6/E/J/Y/2/15	LQM-NS	58.02±0.80	9.60±0.23	0.34±0.005	86.42±1.08
	LQM-NUJ	57.37±0.74	9.49±0.22	0.33±0.005	86.06±1.03
	LQM-QSNS	58.22±0.89	9.63±0.23	0.34±0.007	86.47±1.01
	MRT-NS	58.21±0.89	9.63±0.23	0.34±0.007	86.47±1.01
	MRT-NUJ	57.19±0.74	9.47±0.22	0.33±0.005	86.04±1.02
	MRT-QSNS	57.82±0.88	9.57±0.24	0.34±0.006	86.41±1.04
	SIO-NS	57.59±0.78	9.53±0.23	0.34±0.006	86.48±1.07
	SIO-NUJ	57.22±0.80	9.47±0.23	0.34±0.006	86.11±1.03
	SIO-QSNS	57.91±0.94	9.59±0.24	0.34±0.006	86.48±1.01
6/E/J/Y/2/20	LQM-NS	51.13±0.69	8.46±0.19	0.34±0.003	73.90±1.09
	LQM-NUJ	50.95±0.64	8.44±0.19	0.33±0.003	73.62±1.09
	LQM-QSNS	51.11±0.66	8.46±0.19	0.34±0.004	73.89±1.09
	MRT-NS	51.09±0.66	8.46±0.19	0.34±0.004	73.89±1.09
	MRT-NUJ	50.93±0.65	8.43±0.19	0.33±0.003	73.66±1.08
	MRT-QSNS	51.12±0.71	8.47±0.20	0.34±0.003	73.91±1.09
	SIO-NS	51.12±0.70	8.47±0.19	0.34±0.003	73.90±1.08
	SIO-NUJ	50.95±0.65	8.43±0.19	0.34±0.003	73.74±1.03
	SIO-QSNS	51.06±0.66	8.45±0.19	0.34±0.003	73.89±1.08

Table 12: 95% Confidence Interval for TBA = 6 min.; AD = Exponential; Jobshop; Unbalanced.

Treatment	Rules	Performance Measures			
		FT	WIP	EL	AGV.UTZ
6/U/F/N/1/15	LQM-NS	64.96±0.89	10.84±0.18	0.41±0.003	91.59±0.24
	LQM-NUJ	63.65±0.78	10.79±0.16	0.40±0.003	91.17±0.25
	LQM-QSNS	65.11±0.98	10.88±0.19	0.41±0.003	91.59±0.30
	MRT-NS	66.68±0.92	11.14±0.19	0.41±0.003	91.50±0.26
	MRT-NUJ	66.16±0.90	11.04±0.19	0.40±0.003	91.19±0.33
	MRT-QSNS	66.68±0.94	11.13±0.19	0.41±0.003	91.53±0.32
	SIO-NS	65.70±0.87	10.97±0.18	0.42±0.004	91.87±0.31
	SIO-NUJ	65.56±0.79	10.94±0.16	0.41±0.003	91.48±0.30
	SIO-QSNS	65.81±0.86	11.00±0.17	0.41±0.003	91.80±0.29
6/U/F/N/1/20	LQM-NS	58.60±0.90	9.78±0.18	0.37±0.003	76.27±0.35
	LQM-NUJ	58.59±0.89	9.78±0.18	0.37±0.003	76.27±0.34
	LQM-QSNS	58.59±0.90	9.79±0.18	0.37±0.003	76.25±0.35
	MRT-NS	59.63±0.84	9.95±0.17	0.37±0.003	76.42±0.37
	MRT-NUJ	59.60±0.78	9.95±0.16	0.37±0.003	76.29±0.38
	MRT-QSNS	59.65±0.83	9.95±0.17	0.37±0.003	76.43±0.37
	SIO-NS	58.85±0.86	9.82±0.17	0.38±0.003	76.61±0.32
	SIO-NUJ	58.93±0.84	9.84±0.17	0.37±0.003	76.49±0.31
	SIO-QSNS	58.89±0.86	9.83±0.17	0.38±0.003	76.62±0.41
6/U/F/N/2/15	LQM-NS	50.28±0.30	8.40±0.08	0.42±0.004	92.10±0.27
	LQM-NUJ	49.79±0.32	8.31±0.08	0.40±0.003	91.26±0.29
	LQM-QSNS	50.30±0.29	8.40±0.08	0.42±0.004	92.14±0.27
	MRT-NS	50.13±0.32	8.37±0.08	0.42±0.003	92.12±0.29
	MRT-NUJ	49.73±0.29	8.30±0.08	0.41±0.003	91.55±0.28
	MRT-QSNS	50.03±0.30	8.30±0.07	0.41±0.003	91.55±0.29
	SIO-NS	50.10±0.27	8.36±0.07	0.42±0.004	92.14±0.24
	SIO-NUJ	49.73±0.33	8.30±0.08	0.41±0.004	91.57±0.27
	SIO-QSNS	50.04±0.27	8.35±0.07	0.42±0.004	92.06±0.25
6/U/F/N/2/20	LQM-NS	44.00±0.29	7.35±0.07	0.38±0.002	77.00±0.35
	LQM-NUJ	43.96±0.26	7.34±0.06	0.37±0.002	76.85±0.31
	LQM-QSNS	43.99±0.29	7.35±0.07	0.38±0.002	76.98±0.34
	MRT-NS	43.83±0.25	7.32±0.07	0.38±0.002	76.98±0.39
	MRT-NUJ	43.81±0.23	7.32±0.06	0.38±0.002	76.78±0.37
	MRT-QSNS	43.84±0.25	7.32±0.07	0.38±0.003	76.96±0.38
	SIO-NS	43.87±0.23	7.32±0.06	0.39±0.003	77.03±0.36
	SIO-NUJ	43.84±0.28	7.32±0.07	0.38±0.001	76.90±0.35
	SIO-QSNS	43.86±0.23	7.32±0.06	0.39±0.003	77.04±0.38

Table 13: 95% Confidence Interval for TBA = 6 min.; AD = Uniform; Flowshop; Balanced.

Treatment	Rules	Performance Measures			
		FT	WIP	EL	AGV.UTZ
6/U/F/Y/1/15	LQM-NS	64.95±0.77	10.84±0.17	0.41±0.003	91.53±0.28
	LQM-NUJ	64.57±0.76	10.77±0.15	0.40±0.003	91.09±0.32
	LQM-QSNS	64.57±0.76	10.77±0.15	0.40±0.003	91.09±0.32
	MRT-NS	66.17±0.81	11.05±0.17	0.41±0.003	91.51±0.29
	MRT-NUJ	65.55±0.87	10.94±0.18	0.40±0.003	90.98±0.26
	MRT-QSNS	66.31±0.89	11.07±0.18	0.41±0.004	91.40±0.25
	SIO-NS	65.51±0.84	10.94±0.17	0.42±0.003	91.83±0.27
	SIO-NUJ	64.89±0.79	10.83±0.16	0.41±0.004	91.44±0.24
	SIO-QSNS	65.13±0.88	10.88±0.18	0.42±0.003	91.71±0.30
6/U/F/Y/1/20	LQM-NS	58.19±0.90	9.71±0.18	0.37±0.004	76.27±0.34
	LQM-NUJ	58.08±0.86	9.69±0.17	0.36±0.002	76.09±0.37
	LQM-QSNS	58.17±0.90	9.71±0.18	0.37±0.003	76.25±0.36
	MRT-NS	59.19±0.68	9.88±0.14	0.37±0.003	76.33±0.37
	MRT-NUJ	59.16±0.78	9.88±0.16	0.37±0.002	76.27±0.36
	MRT-QSNS	59.06±0.71	9.86±0.14	0.37±0.003	76.33±0.37
	SIO-NS	58.94±0.95	9.84±0.18	0.38±0.003	76.47±0.35
	SIO-NUJ	58.32±0.78	9.74±0.16	0.38±0.003	76.54±0.31
	SIO-QSNS	58.96±0.85	9.84±0.17	0.38±0.003	76.50±0.34
6/U/F/Y/2/15	LQM-NS	50.38±0.31	8.41±0.08	0.42±0.003	92.00±0.30
	LQM-NUJ	49.95±0.28	8.34±0.07	0.40±0.003	91.41±0.26
	LQM-QSNS	50.38±0.32	8.41±0.08	0.42±0.003	92.00±0.27
	MRT-NS	50.14±0.28	8.37±0.08	0.42±0.004	91.94±0.28
	MRT-NUJ	49.79±0.31	8.32±0.08	0.40±0.003	91.52±0.28
	MRT-QSNS	50.19±0.29	8.38±0.08	0.42±0.004	91.99±0.28
	SIO-NS	50.17±0.30	8.38±0.08	0.42±0.004	91.99±0.28
	SIO-NUJ	49.82±0.32	8.32±0.08	0.40±0.003	91.50±0.27
	SIO-QSNS	50.27±0.35	8.39±0.09	0.42±0.003	91.97±0.25
6/U/F/Y/2/20	LQM-NS	44.18±0.26	7.38±0.07	0.38±0.003	77.03±0.37
	LQM-NUJ	44.14±0.28	7.37±0.07	0.38±0.003	76.83±0.38
	LQM-QSNS	44.16±0.26	7.38±0.07	0.38±0.003	77.04±0.36
	MRT-NS	43.97±0.30	7.34±0.07	0.38±0.002	76.89±0.36
	MRT-NUJ	43.92±0.27	7.33±0.07	0.37±0.003	76.77±0.42
	MRT-QSNS	43.97±0.30	7.34±0.07	0.38±0.002	76.90±0.37
	SIO-NS	43.98±0.29	7.34±0.07	0.38±0.003	76.96±0.37
	SIO-NUJ	43.96±0.24	7.34±0.06	0.37±0.003	76.77±0.36
	SIO-QSNS	43.97±0.29	7.34±0.07	0.38±0.003	76.97±0.37

Table 14: 95% Confidence Interval for TBA = 6 min.; AD = Uniform; Flowshop; Unbalanced.

Treatment	Rules	Performance Measures			
		FT	WIP	EL	AGV.UTZ
6/U/J/N/1/15	LQM-NS	67.01±1.17	11.19±0.24	0.40±0.003	90.92±0.29
	LQM-NUJ	67.11±1.13	11.20±0.23	0.39±0.002	90.66±0.34
	LQM-QSNS	66.97±1.09	11.17±0.22	0.40±0.003	91.03±0.28
	MRT-NS	69.38±1.05	11.59±0.22	0.40±0.003	90.95±0.33
	MRT-NUJ	69.38±1.05	11.59±0.22	0.40±0.003	90.94±0.34
	MRT-QSNS	69.13±1.20	11.54±0.24	0.40±0.003	91.00±0.33
	SIO-NS	67.33±0.92	11.25±0.20	0.41±0.002	91.20±0.35
	SIO-NUJ	67.25±0.98	11.23±0.21	0.40±0.003	91.01±0.34
	SIO-QSNS	67.00±0.98	11.19±0.19	0.40±0.004	91.19±0.31
6/U/J/N/1/20	LQM-NS	60.79±1.10	10.15±0.21	0.36±0.002	75.81±0.34
	LQM-NUJ	60.78±1.04	10.15±0.21	0.35±0.002	75.61±0.36
	LQM-QSNS	60.80±1.09	10.16±0.21	0.36±0.002	75.81±0.34
	MRT-NS	63.34±0.89	11.42±0.19	0.36±0.002	75.86±0.36
	MRT-NUJ	63.26±0.77	11.39±0.16	0.36±0.002	75.79±0.34
	MRT-QSNS	63.35±0.88	11.42±0.18	0.36±0.002	75.90±0.35
	SIO-NS	61.10±0.95	10.20±0.19	0.37±0.002	76.04±0.32
	SIO-NUJ	60.85±0.86	10.15±0.18	0.37±0.002	76.01±0.31
	SIO-QSNS	61.10±0.95	10.20±0.19	0.37±0.002	76.04±0.32
6/U/J/N/2/15	LQM-NS	50.71±0.39	8.47±0.10	0.41±0.003	91.44±0.31
	LQM-NUJ	50.38±0.36	8.41±0.09	0.40±0.003	91.09±0.33
	LQM-QSNS	50.64±0.34	8.45±0.09	0.41±0.003	91.27±0.29
	MRT-NS	50.49±0.32	8.43±0.09	0.41±0.003	91.34±0.31
	MRT-NUJ	50.28±0.36	8.40±0.09	0.40±0.004	91.06±0.29
	MRT-QSNS	50.50±0.37	8.43±0.09	0.41±0.004	91.37±0.28
	SIO-NS	50.52±0.33	8.44±0.09	0.41±0.003	91.32±0.30
	SIO-NUJ	50.52±0.33	8.44±0.09	0.41±0.003	91.32±0.31
	SIO-QSNS	50.43±0.34	8.42±0.09	0.41±0.003	91.34±0.31
6/U/J/N/2/20	LQM-NS	44.70±0.34	7.46±0.08	0.37±0.003	76.37±0.41
	LQM-NUJ	44.70±0.29	7.46±0.07	0.37±0.003	76.33±0.37
	LQM-QSNS	44.69±0.34	7.46±0.08	0.37±0.003	76.34±0.39
	MRT-NS	44.58±0.31	7.45±0.08	0.37±0.003	76.41±0.41
	MRT-NUJ	44.59±0.31	7.44±0.08	0.37±0.001	76.30±0.33
	MRT-QSNS	44.59±0.30	7.44±0.08	0.37±0.003	76.30±0.35
	SIO-NS	44.63±0.30	7.45±0.08	0.37±0.002	76.38±0.34
	SIO-NUJ	44.58±0.35	7.44±0.08	0.37±0.002	76.29±0.39
	SIO-QSNS	44.64±0.29	7.45±0.08	0.37±0.002	76.38±0.34

Table 15: 95% Confidence Interval for TBA = 6 min.; AD = Uniform; Jobshop; Balanced.

Treatment	Rules	Performance Measures			
		FT	WIP	EL	AGV.UTZ
6/U/J/Y/1/15	LQM-NS	66.51±0.91	11.11±0.20	0.40±0.003	91.11±0.30
	LQM-NUJ	66.29±1.11	11.07±0.22	0.39±0.003	90.80±0.32
	LQM-QSNS	66.53±1.02	11.12±0.21	0.40±0.002	91.02±0.35
	MRT-NS	68.29±1.03	11.41±0.21	0.40±0.003	90.91±0.31
	MRT-NUJ	68.27±1.00	11.40±0.20	0.39±0.003	90.79±0.29
	MRT-QSNS	68.17±1.04	11.39±0.22	0.40±0.003	90.93±0.31
	SIO-NS	67.27±0.99	11.23±0.21	0.41±0.003	91.42±0.31
	SIO-NUJ	66.96±0.99	11.16±0.21	0.40±0.003	91.18±0.31
	SIO-QSNS	66.91±1.03	11.17±0.21	0.41±0.002	91.32±0.33
6/U/J/Y/1/20	LQM-NS	60.13±1.08	10.04±0.21	0.36±0.003	75.74±0.35
	LQM-NUJ	60.82±1.14	10.15±0.22	0.36±0.003	75.76±0.37
	LQM-QSNS	60.12±1.08	10.04±0.21	0.36±0.003	75.74±0.35
	MRT-NS	62.06±1.01	10.36±0.21	0.37±0.002	75.90±0.26
	MRT-NUJ	61.76±0.99	10.31±0.21	0.37±0.002	75.85±0.36
	MRT-QSNS	62.02±1.01	10.35±0.21	0.37±0.003	75.88±0.29
	SIO-NS	60.21±0.94	10.05±0.19	0.37±0.002	76.13±0.38
	SIO-NUJ	60.64±0.93	10.12±0.19	0.37±0.003	76.02±0.35
	SIO-QSNS	60.23±0.92	10.06±0.18	0.37±0.002	76.12±0.38
6/U/J/Y/2/15	LQM-NS	50.89±0.31	8.50±0.08	0.41±0.003	91.43±0.29
	LQM-NUJ	50.58±0.32	8.45±0.08	0.40±0.003	91.07±0.27
	LQM-QSNS	50.84±0.36	8.49±0.09	0.41±0.003	91.50±0.29
	MRT-NS	50.74±0.32	8.47±0.08	0.41±0.003	91.42±0.30
	MRT-NUJ	50.51±0.36	8.43±0.09	0.40±0.003	91.06±0.28
	MRT-QSNS	50.66±0.38	8.46±0.09	0.41±0.003	91.38±0.32
	SIO-NS	50.66±0.31	8.46±0.08	0.41±0.003	91.38±0.27
	SIO-NUJ	50.44±0.32	8.42±0.08	0.40±0.003	91.08±0.33
	SIO-QSNS	50.58±0.34	8.45±0.08	0.41±0.003	91.38±0.28
6/U/J/Y/2/20	LQM-NS	44.90±0.26	7.50±0.07	0.38±0.002	76.52±0.36
	LQM-NUJ	44.86±0.25	7.48±0.07	0.37±0.002	76.29±0.36
	LQM-QSNS	44.90±0.26	7.49±0.07	0.37±0.002	76.51±0.34
	MRT-NS	44.79±0.29	7.47±0.07	0.37±0.003	76.44±0.39
	MRT-NUJ	44.77±0.28	7.48±0.07	0.37±0.003	76.36±0.38
	MRT-QSNS	44.77±0.29	7.48±0.07	0.37±0.003	76.44±0.39
	SIO-NS	44.74±0.29	7.47±0.07	0.37±0.003	76.37±0.39
	SIO-NUJ	44.77±0.28	7.48±0.07	0.37±0.002	76.32±0.35
	SIO-QSNS	44.74±0.29	7.47±0.08	0.37±0.003	76.38±0.40

Table 16: 95% Confidence Interval for TBA = 6 min.; AD = Uniform; Jobshop; Unbalanced.

Appendix C

-Best Combination of Machine and AGV Dispatching Rules for the 64 Treatments against Flowtime, Consistency of Output and Efficient Operation of AGVs.

Treatment Combinations	M/C Scheduling Rule	AGV Dispatching Rule	M/C-AGV Rule
5/E/F/N/1/15			
5/E/F/N/1/20			
5/E/F/N/2/15		NUJ	MRT-NUJ, SIO-NUJ
5/E/F/N/2/20			
5/E/F/Y/1/15			
5/E/F/Y/1/20			
5/E/F/Y/2/15		NUJ	MRT-NUJ, SIO-NUJ
5/E/F/Y/2/20			
5/E/J/N/1/15	SIO		SIO-NS, SIO-NUJ
5/E/J/N/1/20	SIO		SIO-NUJ
5/E/J/N/2/15		NUJ	MRT-NUJ, SIO-NUJ
5/E/J/N/2/20			
5/E/J/Y/1/15	SIO		SIO-NUJ
5/E/J/Y/1/20			
5/E/J/Y/2/15		NUJ	MRT-NUJ, SIO-NUJ
5/E/J/Y/2/20			
5/U/F/N/1/15	SIO	NUJ	SIO-NUJ
5/U/F/N/1/20	SIO		SIO-NS, SIO-NUJ
5/U/F/N/2/15		NUJ	MRT-NUJ, SIO-NUJ
5/U/F/N/2/20			
5/U/F/Y/1/15	MRT, SIO		MRT-NUJ, SIO-NUJ
5/U/F/Y/1/20	MRT, SIO	NS, NUJ	MRT-NUJ, SIO-NS
5/U/F/Y/2/15	MRT, SIO	NUJ	MRT-NUJ, SIO-NUJ
5/U/F/Y/2/20	MRT, SIO		MRT-NUJ, SIO-NUJ
5/U/J/N/1/15	SIO	NS, NUJ	SIO-NUJ
5/U/J/N/1/20	SIO		SIO-NS, SIO-NUJ, SIO-QSNS
5/U/J/N/2/15		NUJ	MRT-NUJ, SIO-NUJ
5/U/J/N/2/20			
5/U/J/Y/1/15	SIO		SIO-NUJ
5/U/J/Y/1/20	SIO		SIO-NS, SIO-NUJ, SIO-QSNS
5/U/J/Y/2/15		NUJ	MRT-NUJ, SIO-NUJ
5/U/J/Y/2/20			

Table 1: Best combination of rules based on flowtime criteria for TBA = 5 min.

Treatment Combinations	M/C Scheduling Rule	AGV Dispatching Rule	M/C-AGV Rule
6/E/F/N/1/15			
6/E/F/N/1/20			
6/E/F/N/2/15		NUJ	MRT-NUJ, SIO-NUJ
6/E/F/N/2/20			
6/E/F/Y/1/15			
6/E/F/Y/1/20			
6/E/F/Y/2/15	SIO		SIO-NUJ
6/E/F/Y/2/20			
6/E/J/N/1/15	SIO		SIO-NS, SIO-NUJ, SIO-QSNS
6/E/J/N/1/20	SIO, LQM		SIO-NS, SIO-NUJ
6/E/J/N/2/15			
6/E/J/N/2/20			
6/E/J/Y/1/15	SIO		SIO-NS, SIO-NUJ, SIO-QSNS
6/E/J/Y/1/20	SIO		SIO-NUJ
6/E/J/Y/2/15		NUJ	SIO-NUJ
6/E/J/Y/2/20			
6/U/F/N/1/15	LQM		LQM-NUJ
6/U/F/N/1/20	LQM		LQM-NS, LQM-NUJ, LQM-QSNS
6/U/F/N/2/15		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
6/U/F/N/2/20			
6/U/F/Y/1/15	LQM		LQM-NUJ, LQM-QSNS
6/U/F/Y/1/20	LQM		LQM-NUJ
6/U/F/Y/2/15		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
6/U/F/Y/2/20			
6/U/J/N/1/15	LQM,SIO		LQM-NS, LQM-NUJ, LQM-QSNS
6/U/J/N/1/20	LQM,SIO		LQM-NS, LQM-NUJ, LQM-QSNS
6/U/J/N/2/15			
6/U/J/N/2/20			
6/U/J/Y/1/15	LQM		LQM-NUJ
6/U/J/Y/1/20	LQM, SIO		LQM-NS, LQM-QSNS, SIO-NS, SIO-QSNS
6/U/J/Y/2/15			
6/U/J/Y/2/20			

Table 2: Best combination of rules based on flowtime criteria for TBA = 6 min.

Treatment Combinations	M/C Scheduling Rule	AGV Dispatching Rule	M/C-AGV Rule
5/E/F/N/1/15	LQM		LQM-QSNS
5/E/F/N/1/20	LQM		LQM-NS, LQM-NUJ
5/E/F/N/2/15		QSNS	LQM-QSNS, SIO-QSNS
5/E/F/N/2/20			
5/E/F/Y/1/15	LQM		LQM-NUJ
5/E/F/Y/1/20	LQM		LQM-NUJ, LQM-QSNS
5/E/F/Y/2/15			
5/E/F/Y/2/20			
5/E/J/N/1/15	MRT		MRT-NS, MRT-QSNS
5/E/J/N/1/20	MRT		MRT-NUJ, MRT-QSNS
5/E/J/N/2/15	LQM		LQM-QSNS
5/E/J/N/2/20	LQM		LQM-NS, LQM-NUJ
5/E/J/Y/1/15	MRT		MRT-NS, MRT-NUJ
5/E/J/Y/1/20	MRT		MRT-NS, MRT-NUJ, MRT-QSNS
5/E/J/Y/2/15			
5/E/J/Y/2/20			
5/U/F/N/1/15	LQM		LQM-NUJ, LQM-QSNS
5/U/F/N/1/20	LQM		LQM-NUJ, LQM-QSNS
5/U/F/N/2/15		NUJ	LQM-NUJ
5/U/F/N/2/20	LQM		LQM-NUJ, LQM-QSNS
5/U/F/Y/1/15	MRT		MRT-NS
5/U/F/Y/1/20	LQM, MRT		LQM-NS, MRT-NS
5/U/F/Y/2/15			
5/U/F/Y/2/20	LQM		LQM-NS, LQM-QSNS
5/U/J/N/1/15	MRT		MRT-NUJ
5/U/J/N/1/20	MRT		MRT-QSNS
5/U/J/N/2/15			
5/U/J/N/2/20	LQM		LQM-QSNS
5/U/J/Y/1/15	MRT		MRT-NS, MRT-NUJ
5/U/J/Y/1/20	MRT		MRT-NS, MRT-NUJ, MRT-QSNS
5/U/J/Y/2/15			
5/U/J/Y/2/20			

Table 3: Best combination of rules based on consistency of output for TBA = 5 min.

Treatment Combinations	M/C Scheduling Rule	AGV Dispatching Rule	M/C-AGV Rule
6/E/F/N/1/15	LQM, MRT		LQM-NS, LQM-NUJ
6/E/F/N/1/20			
6/E/F/N/2/15			
6/E/F/N/2/20	LQM		LQM-NS
6/E/F/Y/1/15			
6/E/F/Y/1/20	LQM, MRT		LQM-NS
6/E/F/Y/2/15			
6/E/F/Y/2/20			
6/E/J/N/1/15			
6/E/J/N/1/20	MRT		MRT-NS, MRT-NUJ
6/E/J/N/2/15			
6/E/J/N/2/20			
6/E/J/Y/1/15	MRT, SIO		SIO-NS
6/E/J/Y/1/20			
6/E/J/Y/2/15			
6/E/J/Y/2/20			
6/U/F/N/1/15	LQM, MRT		LQM-NS, MRT-NS
6/U/F/N/1/20	LQM, MRT		MRT-NUJ, MRT-QSNS
6/U/F/N/2/15			
6/U/F/N/2/20	LQM		LQM-NUJ
6/U/F/Y/1/15			
6/U/F/Y/1/20	MRT		MRT-NUJ
6/U/F/Y/2/15			
6/U/F/Y/2/20	LQM		LQM-NUJ
6/U/J/N/1/15			
6/U/J/N/1/20			
6/U/J/N/2/15	LQM		LQM-NS, LQM-QSNS
6/U/J/N/2/20			
6/U/J/Y/1/15			
6/U/J/Y/1/20			
6/U/J/Y/2/15			
6/U/J/Y/2/20			

Table 4: Best combination of rules based on consistency of output for TBA = 6 min.

Treatment Combinations	M/C Scheduling Rule	AGV Dispatching Rule	M/C-AGV Rule
5/E/F/N/1/15		NUJ	LQM-NUJ, MRT-NUJ
5/E/F/N/1/20	LQM, MRT	NUJ	LQM-NUJ, MRT-NUJ
5/E/F/N/2/15		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
5/E/F/N/2/20		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
5/E/F/Y/1/15		NUJ	MRT-NUJ
5/E/F/Y/1/20		NUJ	LQM-NUJ, MRT-NUJ
5/E/F/Y/2/15		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
5/E/F/Y/2/20		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
5/E/J/N/1/15			
5/E/J/N/1/20	MRT	NUJ	MRT-NUJ
5/E/J/N/2/15		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
5/E/J/N/2/20		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
5/E/J/Y/1/15		NUJ	MRT-NUJ, SIO-NUJ
5/E/J/Y/1/20	LQM, MRT	NUJ	LQM-NUJ, MRT-NUJ
5/E/J/Y/2/15		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
5/E/J/Y/2/20		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
5/U/F/N/1/15	MRT	NUJ	MRT-NUJ
5/U/F/N/1/20	LQM, MRT	NUJ	LQM-NUJ, MRT-NUJ
5/U/F/N/2/15		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
5/U/F/N/2/20		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
5/U/F/Y/1/15	LQM, MRT	NUJ	LQM-NUJ, MRT-NUJ
5/U/F/Y/1/20	LQM, MRT	NUJ	LQM-NUJ, MRT-NUJ
5/U/F/Y/2/15		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
5/U/F/Y/2/20		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
5/U/J/N/1/15	LQM, MRT	NUJ	LQM-NUJ, MRT-NUJ
5/U/J/N/1/20	LQM, MRT	NUJ	LQM-NUJ, MRT-NUJ
5/U/J/N/2/15		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
5/U/J/N/2/20		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
5/U/J/Y/1/15	LQM, MRT	NUJ	LQM-NUJ, MRT-NUJ
5/U/J/Y/1/20	LQM, MRT	NUJ, QSNS	LQM-NUJ, MRT-NUJ
5/U/J/Y/2/15		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
5/U/J/Y/2/20		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ

Table 5: Best combination of rules based on efficient operation of AGVs for TBA = 5 min.

Treatment Combinations	M/C Scheduling Rule	AGV Dispatching Rule	M/C-AGV Rule
6/E/F/N/1/15		NUJ	LQM-NUJ, MRT-NUJ
6/E/F/N/1/20	LQM, MRT		LQM-NUJ, MRT-NUJ
6/E/F/N/2/15		NUJ	MRT-NUJ, SIO-NUJ
6/E/F/N/2/20		NUJ	MRT-NUJ, SIO-NUJ
6/E/F/Y/1/15		NUJ	LQM-NUJ, MRT-NUJ
6/E/F/Y/1/20		NUJ	LQM-NUJ, MRT-NUJ
6/E/F/Y/2/15		NUJ	MRT-NUJ, SIO-NUJ
6/E/F/Y/2/20		NUJ	MRT-NUJ, SIO-NUJ
6/E/J/N/1/15		NUJ	LQM-NUJ, MRT-NUJ
6/E/J/N/1/20	LQM, MRT		MRT-NUJ
6/E/J/N/2/15			
6/E/J/N/2/20		NUJ	LQM-NUJ, SIO-NUJ
6/E/J/Y/1/15		NUJ	LQM-NUJ, MRT-NUJ
6/E/J/Y/1/20			
6/E/J/Y/2/15		NUJ	LQM-NUJ, MRT-NUJ
6/E/J/Y/2/20		NUJ	LQM-NUJ, MRT-NUJ
6/U/F/N/1/15	LQM, MRT	NUJ	LQM-NUJ, MRT-NUJ
6/U/F/N/1/20	LQM, MRT		LQM-NUJ, MRT-NUJ
6/U/F/N/2/15		NUJ	LQM-NUJ
6/U/F/N/2/20		NUJ	LQM-NUJ, MRT-NUJ
6/U/F/Y/1/15	LQM, MRT	NUJ	LQM-NUJ, MRT-NUJ
6/U/F/Y/1/20	LQM, MRT		LQM-NUJ
6/U/F/Y/2/15		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
6/U/F/Y/2/20		NUJ	MRT-NUJ, SIO-NUJ
6/U/J/N/1/15	LQM		LQM-NUJ
6/U/J/N/1/20	LQM	NUJ	LQM-NUJ
6/U/J/N/2/15		NUJ	LQM-NUJ
6/U/J/N/2/20			
6/U/J/Y/1/15	LQM, MRT	NUJ	MRT-NUJ
6/U/J/Y/1/20	LQM		LQM-NS, LQM-NUJ, LQM-QSNS
6/U/J/Y/2/15		NUJ	LQM-NUJ, MRT-NUJ, SIO-NUJ
6/U/J/Y/2/20			

Table 6: Best combination of rules based on efficient operation of AGVs for TBA = 6 min.