SCHEDULING OF A COMPUTER INTEGRATED MANUFACTURING SYSTEM: A SIMULATION STUDY

Daryoosh BagherzadehYazdi

A Thesis

In

The Department

Of

Mechanical and Industrial Engineering

Presented in Partial Fulfillment of the Requirements
For
the Degree of Master of Applied Science
at
Concordia University
Montreal, Quebec, Canada

August 2006

Library and
Archives Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 978-0-494-34608-2
Our file Notre référence
ISBN: 978-0-494-34608-2

NOTICE:
The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:
L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

ABSTRACT

SCHEDULING OF A COMPUTER INTEGRATED MANUFACTURING SYSTEM: A SIMULATION STUDY

Daryoosh BagherzadehYazdi

In recent years Computer Integrated Manufacturing (CIM) systems are increasingly being used in the manufacturing for their advantages of flexibility, quality, reduced labor and inventory cost. CIM systems are consisting of a number of computer-controlled machines and material handling devices integrated with ERP (Enterprise Resource Planning) and supporting systems.

Production scheduling problem is one of the main area of research of CIM Systems since with a proper scheduling, the utilization of resources is optimized and orders are produced on time which improves the shop performance and associated cost benefits.

In general terms, the scheduling problem is defined as the allocation of resources, machinery or people, to accomplish specific tasks over a certain time-period such that the desired performance of the system is maximized. In many situations, production scheduling is done by the use of dispatching rules due to their effectiveness and ease of use. Dispatching rules are simple algorithms that use various priority attributes and relevant information concerning the availability status of resources in prioritizing the jobs waiting for processing.

The target of this study is to research the effect of selected scheduling dispatching rules on the performance of an actual CIM System located in the Mechanical and Industrial Engineering Department using different performance measures and to compare the results with the literature. To achieve this objective, a computer simulation model of the existing CIM system based on the control logic that describes the operation of the system is developed to test the performance of different scheduling rules with respect to mean flow time, Machine Efficiency and Total Run Time as performance measures.

The Design of Experiments (D.O.E.) method is used to set up runs for the experimental study of combinations of number of factors in various levels that influence the performance of the selected dispatching rules. Furthermore, ANOVA analysis of the variance was adapted to evaluate and analyze the relative effectiveness of the dispatching rules for each set of experiments based on the performance measures.

Based on the assumptions of this study, the experimental work performed suggests that the system performs much better considering the Machine Efficiency when the initial part release is maximum and the buffer size is minimum. Furthermore, considering the Average Flow Time, the system performs much better when the selected dispatching rule is either Earliest Due Date (EDD) or Shortest Process Time (SPT) with buffer size of five and initial part release of eight.

ACKNOWLEDGMENTS

I would like to thank with all my heart several people for their valuable encouragement, contribution, guidance, and assistance.

This thesis could not have been successfully completed without the support and encouragement of my fiancé, Salomeh Ahmadi, who stood by me to the completion of my study. I would like to take this opportunity to express my outmost appreciation for her endless care.

I would also like to express my gratitude to my advisors, Dr. Gerard Gouw and Dr. Nadia Bhuiyan for their guidance, advice and patience throughout this research.

I also express my appreciation to the CIM laboratory support staff, especially Mr. Gilles Huard, whose co-work and assistance were extremely helpful and precious.

Lastly, I would like to express a full heart of thankfulness to my parents. Their great support and patience have enabled me to complete this journey. I would not have been able continue my education without their moral and financial support. They always reached out to help me during the most difficult times.

TABLE OF THE CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Background

In the modern industrial setting, considering the tight competitive market, efficiency and superior performance are critical factors for companies to address. One of the approaches that advanced companies have taken in this regard is to increase the level of automation and computerization of their production system.[1, 2, 3, 4] The approaches used in this regard are Flexible Manufacturing Systems (FMS) and computer integrated manufacturing (CIM) systems. CIM systems are defined as the systems that "focus upon the computer as the center of control of the entire factory. This approach does not stop at computerization of the fabrication and assembly processes, but also encompasses information flow for production control, quality, maintenance, material handling, and inventory control in a totally integrated system"[5] where FMS are the systems that "takes advantage of the flexibility of the robots, NC machine tools, industrial logic controllers and microprocessors in creating an overall flexible system"[5]

Flexible Manufacturing Systems are increasingly being used in the manufacturing for their advantages of flexibility, quality, reduced labor and inventory cost in the era of continues improvements and frequent turnaround initiatives. However the main disadvantage of the Flexible Manufacturing Systems is the high initial investment requirement. For this reason it is of utmost importance for firms to ensure the economical justification to acquire these systems. This fact makes it attractive to conduct research in this area.

Production scheduling problem is one of the main area of research of Flexible Manufacturing Systems. In general terms, the scheduling problem can be described as follows: each production run consists of a set of jobs to be produced; each job has one or more operations which have to be processed on specified machines. The objective is to come up with the best production sequence for the jobs by assigning the available resources within the existing constraints such that the desired performance of the system is maximized [6].

The scheduling performance is usually evaluated based on certain criteria that can be classified in two general areas, meeting the due date of the ordered products and increasing the productivity of the system.

In many situations, production scheduling is done by the use of dispatching rules due to their effectiveness and ease of use. Dispatching rules are predefined rules that prioritize the jobs waiting for processing. As Conway defined[7] "A priority rule can be considered to operate by assigning, at the time that a selection must be made from a queue, a numerical value called a 'priority' to each of the jobs waiting in the particular queue, and then by selecting the job with the minimum value of priority". However, many studies have shown that system performance varies to a great degree for different shop environments and thus no dispatching rule has been found to be optimal for all planning and scheduling problems.[8] Furthermore, the performance of scheduling rules depends on the performance criteria under consideration and also the arrangement of the production system. The body of literature in this area is sometimes contradictory since the experimental settings and assumptions of these studies are not the same. Consequently, for each FMS there has to be a separate scheduling study to find the best dispatching rule to accommodate the desired measure of performance.

The effects of dispatching rules are normally studied with the use of computer simulation models. Computer simulation models provide the possibility to compare different dispatching rules and test their effects on shop operation performance.

1.2. Scope of the Research

The target of this study is to evaluate the performance of selected dispatching rules for different operation on the existing CIM facility using a simulation model against different performance measures and to compare the results with the literature.

The existing Flexible Manufacturing System under study consists of four workstations around a closed conveyor loop for part transportation among workstations. The existing work stations are as follow:

- An AS/RS Station (Automated Storage and Retrieval System) supplies raw materials to the system, stores parts in intermediate stages of production, and holds finished products using its robot.
- A Machining Station, where materials are shaped. There are two CNC machines (a Mill and a Lathe) in the system.

- A Laser Engraver Station
- An Assembly and Quality Control (QC) Station for assembly and inspection of parts using machine vision

Note that the laser engraver and the Assembly and QC station are not part of the simulation study.

Furthermore, each machine station and the QC station have a serving robot and a buffer area to hold jobs that are waiting to be processed. Once a part is released to the system by the AS/RS based on the processes it visits different machines and equipments in the system.

Scheduling rules prioritize these jobs on a machine. It is possible to assign different priority dispatching rules to each machine in the system, however since the interest of this research is to evaluate the performance of each dispatching rule separately, for each simulation run same dispatching rule is assigned to all the equipments in the system.

1.3. Research Approach

The effect of different dispatching rules is studied through the following methodology:

- Creating a simulation model of the existing CIM system based on the control logic that describes the operation of the system. In this regard ARENA simulator software is used for modeling the CIM system.
- Using the Design of Experiments (D.O.E.) method to set up runs for the experimental study of combinations of number of environment factors in various levels that influence the performance of the selected dispatching rules on the existing CIM system based on the performance measures of interest as the output.
- Executing the simulation runs created by the D.O.E on the created simulation model and collecting the results.
- Evaluating and analyzing the performance of the dispatching rules for each set of experiments based on the performance measures through ANOVA (analysis of the variance) statistical analysis.
- Comparing the results from the study with the results from the literature review.

1.4. Organization of the Thesis

The remainder of this thesis is organized as follows:

Chapter 2 provides a detailed survey of the scheduling problems, their classification and the method used to address them with the main focus is in the area of the priority dispatching rules.

Chapter 3 provides an overview of the existing Flexible Manufacturing System in the mechanical engineering department including its layout, control system, communication network and programming.

Chapter 4 covers the design of the experiments to evaluate the performance of the rules by using both simulation model and the real system. In this regard the components of the method including the Control Factors, Assumptions, Experimental Conditions and The Performance Measures of interest are presented.

Chapter 5 presents and discusses the results of the experiments for the simulation model and the real system.

Chapter 6 presents concluding remarks, the highlights of the research and recommendations for future research.

2. SCHEDULING PROBLEM FUNDAMENTALS

2.1. Introduction

The production scheduling problem is one of the main areas of research of Flexible Manufacturing Systems. In general terms, the scheduling problem can be described as follows: given a set of required tasks, what is the best way to assign the available resources to the tasks, within the existing constraints that would maximize the desired performance of the system.

In this regard the resources are usually the processing machines and transportation units such as conveyor, AGVs (Automated Guided Vehicle), forklifts or robots. The tasks are the processes that have to be conducted on the raw materials to produce the final product. The performance measures are the aspects of the production system which normally are or can be translated to some form of monetary measure such as: Production cost, Flow time, Production consistency, Job quality, Machine and tool utilization, Average in-process inventory, Average lateness, etc.

Thus, a mechanism is required to make decision on the priority of the tasks and create the sequence of the activities in the FMS. These activities normally include the following:

- Selection of the next part to be processed by the machines when the machine becomes free
- Selection of the next part to be released into the system
- Selection of the next part to be loaded on a transportation system

Mathematically, for a scheduling problem of a shop with *m* machine that are going to process n jobs, the number of possible sequences is calculated as follows[9]:

$$N = (n1)!\,(n2)!\,\dots\,(nm)! \tag{2.1}$$

where n_p is the number of operations to be performed on machine p.

However, only some of the sequences are feasible which should be technologically feasible and yet optimize the performance measure. Nevertheless, complete listing of all the feasible solutions to identify the optimal one is not practical. This is the reason that the majority of the scheduling problems falls into a large class of intractable numerical problems known as *NP*-Hard (*NP* stands for non deterministic polynomial) due to the factorial explosion.[9] This is the main reason that number of different methods and approaches has been developed to address the scheduling problem of FMSs.

2.2. Aspects of Scheduling Problems in Manufacturing

Scheduling problems can be classified base on different dimensions. Jones and Rabelo [10] categorized different aspect of scheduling problems as follows:

2.2.1. Manufacturing Environment

In this category, manufacturing systems are categorized into open and closed shops. In an open shop, each job could have a different routing and production is conducted according to the customers' orders. The number of routings for a job is fixed in closed shops and an arriving job can follow through one of the routings.

2.2.2. Process Complexity

Process complexity depends on the number of workstations and processing steps of the production process. This can be further categorized as:

- One stage, one process
- One stage, multiple processes
- Multistage, flow shop
- Multistage, job shop

The first two categories consist of only one processing step that should be carried out either on a single resource or multiple resources. The last two categories consist of several stages and tasks for each job that need to be executed by the resources. The difference between flow shop and job shop lays in the fact that in the flow shop problem all jobs have a common route, where in the job shop different routes and resources may be chosen.

2.2.3. Scheduling Criteria

Scheduling criteria are the same as performance measures such as total tardiness, number of late jobs, system/resource utilization, in-process inventory, production rate, etc. Evidently it is impossible to satisfy all these measures at the same time.

2.2.4. Parameters Variability

This factor refers to the degree of uncertainty of the scheduling problem. The problem is deterministic if the degree of uncertainty in the system is low. In another words the parameters of interest have low variance. At the other hand, stochastic problems are the ones with high level of uncertainty in the system's parameters.

2.2.5. Scheduling Environment

The final category groups the problems into static and dynamic. Static scheduling problems are the ones where all the information with regards to the jobs and resources is available at the beginning and does not change in time. In dynamic problems, the information and thus the characteristics of the system changes over time.

Figure 2.1 summarizes the scheduling problems classifications.

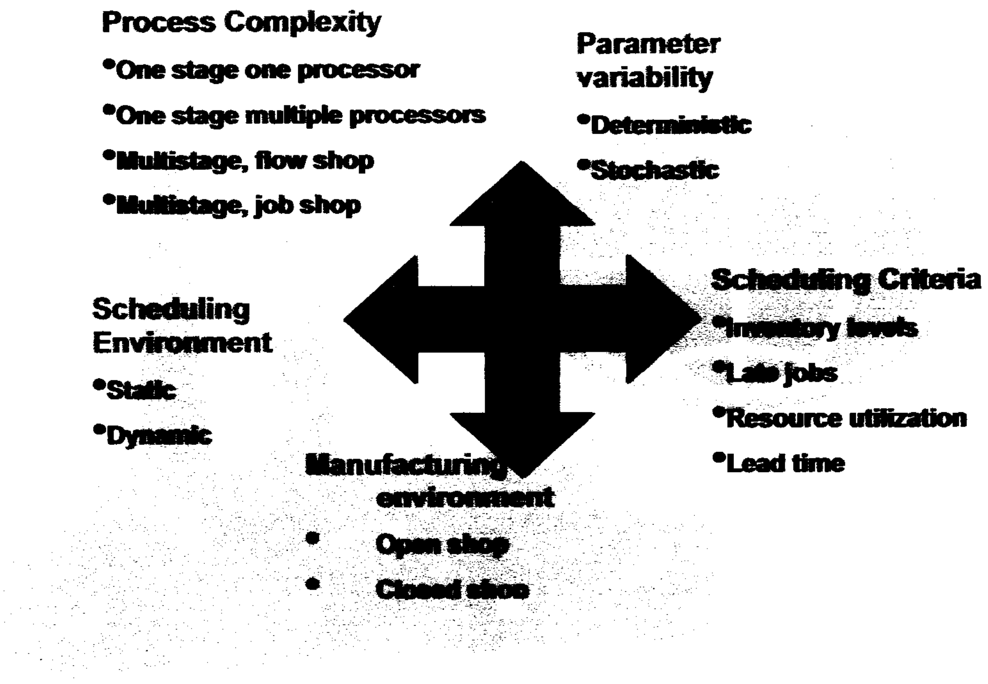


Figure 2.1: Scheduling Problems Criteria [11]

2.3. Solution Methods

Solutions to FMS operations problems can be classified into the following classes: [6, 10, 12, 13]

2.3.1. Mathematical Methods

Linear Programming is the first mathematical approach that has been utilized to solve the scheduling problems. In this method, by defining an objective function with appropriate constraints, it is possible to find the optimal solution in cases where the size of the problem is relatively small.[14, 15, 16, 17, 18]

Other methodologies that have been used in this area include: stochastic optimization, Monte Carlo simulation, queuing theory, and Integer Programming.[19]

2.3.2. Neural Networks Techniques

Neural network techniques have been developed based on the way the brain functions. Basically this technique organizes rules and data into networks of neurons that are competing among themselves. The simplicity, ability for distributed processing, learning and generalization are advantages of this approach. Jain and Meeran [9] reviewed major works on solving scheduling problems using neural networks.

2.3.3. Artificial Intelligence and Expert Systems

The next approach in solving scheduling problems is expert systems (ES). These systems normally consist of three components; the knowledge base where the required knowledge for solving the problem is stored and it creates a model of the shop, the inference engine where the decisions are made and the user interface. Normally this method is used in conjunction with simulation systems to generate the schedules. The advantages of this method include the possibility of generating more complex heuristics than the simple dispatching rules, possibility of customization and flexibility of the system where the complexity of building, verifying and changing the models are the main disadvantages. Metaxiotis et al. [20] reviewed the studies in the area of ES in production planning and scheduling.

2.3.4. Fuzzy Logic

Scheduling problems for manufacturing systems are essentially multi-criteria, thus it is essential to be able to make compromises among different criteria of interest. The fuzzy method is a good alternative for this purpose. Furthermore fuzzy logic theory can address the uncertainty in production systems by fuzzy numbers. This approach normally is integrated with other methodologies. For example, Wang et al. [21] studied the application of the fuzzy method in conjunction with dispatching rules where the fuzzy approach provides a means to combine different dispatching rules in order to achieve better performance.

2.3.5. Neighborhood Search Methods

The basic principle of these techniques is based on the fact that they continue to evaluate schedules until there is no improvement in the desired performance measure. The techniques that fall into this category include simulated annealing, Tabu search and genetic algorithms.[12]

2.3.6. Dispatching Rules

Dispatching rules have been used in the last decades to address scheduling problems for their simplicity and ease of use. [22, 23, 24] Dispatching rules are simple algorithms that have been developed to control the production sequences. The terms dispatching rule, sequencing rule, or scheduling rule are often used interchangeably.

The effects of dispatching rules are normally studied with the use of computer simulation models. The reason for using the simulation models is evident. First, it is almost impossible to test all the available dispatching rules on the physical system due to the required time frame and associated cost. Second, without testing alternative rules, there is no way to predict how they will affect the system's behavior. Computer simulation models have made it feasible to quickly compare alternative dispatching rules and test their effects on shop operation performance.

2.4. Dispatching Rules' Definition and Classification

Dispatching rules can be classified into different categories based on different factors. The most complete categorization of the dispatching rules is done by Wu [25] who categorized the dispatching rules into several classes as follows:

Class 1 consists of simple priority rules. This class can further be categorized into the following sub-classes:

- Process-time based rules
- Due-date based rules
- Rules that are neither process-time based nor due-date based

Class 2 consists of the combinational rules which are created from the simple rules in the first class.

Finally, Class 3 dispatching rules are the Weight Priority Index rules. In this category, couples of factors are taken into consideration at the same time where weights are assigned to these factors based on their relative importance.

Although combination dispatching rules (combining second and third class) are proposed to produce better results, their efficiency comes with a price. In combination rules, the weighting parameter needs to be specified. Finding the optimal value depends on the situation and requires significant effort and in majority of cases the added value of the combination rules is not large enough to justify the effort compared to the simple priority rules.

Furthermore, the dispatching rules are also classified as either static or dynamic, based on the moment in time that scheduling decisions are made. [8] With static rules, priority decisions are made in advance and remain the same throughout the operation. With dynamic rules, however, the priorities of the job might change in time.

In the following, some of the most well-known dispatching rules will be introduced. In this regard the following notation will be used to define these rules. [8, 26]

$\boldsymbol{T}$	Scheduling horizon (total available production time)
$\boldsymbol{t}$	Time at which a decision is to be made
$\boldsymbol{n}$	Number of jobs in the shop
$\boldsymbol{i}$	Job index
$\boldsymbol{j}$	Operation index
$\boldsymbol{j(t)}$	Imminent operation of job i, i.e., all operations $1 \leq j < j(t)$
$\boldsymbol{P_{i,j}}$	The processing time for the jth operation of the ith job
$\boldsymbol{TO_i}$	Total number of operations on the ith job $(1 \leq j \leq TO_i)$
$\boldsymbol{TP_i}$	Total processing time of the ith job $(\sum_{j=1}^{TOi} p_{i,j})$
$\boldsymbol{RO_i(t)}$	Remaining number of operations on the ith job
$\boldsymbol{RP_i(t)}$	Remaining processing time on the ith job
$\boldsymbol{R_{i,j}}$	The time at which the ith job becomes ready for its jth operation
$\boldsymbol{R_{i,1}}$	The time at which the ith job arrived at the shop
$\boldsymbol{C_i}$	The time at which the ith job is completed and leaves the system

d_i	The due date of the *i*th job
L_i	The lateness of the *i*th job $(L_i = C_i - d_i)$
T_i	The tardiness of the *i*th job ($T_i = \max(0, L_i)$)
F_i	Flow time (the amount of time that job I spends in the system $(F_i = C_i - {}_{i.1})$)
$S_i(t)$	Slack (difference between due date, the arrival time and the total processing time of the part $(S_i = d_i - R_{i.1} - TP_i)$)
$N_{i,j}(t)$	The set of jobs in the queue corresponding to the *j*th operation of the *i*th job at time *t*
$Z_i(t)$	The priority of job *i* at time *t*. Priority is given to the job with the minimum or maximum of $Z_i(t)$
$X_{i,j}$	A random number, uniformly distributed between zero and one, assigned to the *j*th operation of ith job
C	A penalty function, assigned to the *j*th operation of ith job
WT_i	Sum of expected waiting times for the job's uncompleted operations

The following is a sample list of the most famous dispatching rules with their description [8, 26, 27]:

RANDOM	Select the job which has the smallest value of a random priority at the time of arrival to a queue. The priority index is given as follows: select minimum $Z_i(t)$ where $Z_i(t) = X_{i,j}$
EDD	Select the job which has the earliest due date (EDD). This rule is often used for its simplicity of implementation. This rule performs well with respect to minimizing maximum tardiness and variance of tardiness in the single-machine scheduling problem. The priority index is given as follows: select minimum $Z_i(t)$ where $Z_i(t) = d_i$
SIO	Select the job with the shortest imminent operation time (SIO). The priority index is given as follows: select minimum $Z_i(t)$ where $Z_i(t) = P_{i,j(t)}$

LIO	Select the job with the longest imminent operation time (LIO). The priority index is given as follows: select minimum $Z_i(t)$ where $Z_i(t)= P_{i,j(t)}$
SPT	Select the job with the shortest processing time (SPT). The priority index is given as follows: select minimum $Z_i(t)$ where $Z_i(t) = TP_i$ This rule is effective in minimizing mean flow time and mean tardiness under highly loaded shop floor conditions.
LPT	Select the job with the longest processing time (LPT). The priority index is given as follows: select maximum $Z_i(t)$ where $Z_i(t) = TP_i$
SRPT	Select the job with the shortest remaining processing time (SRPT). The priority index is given as follows: select minimum $Z_i(t)$ where $Z_i(t)=RP_i(t)$
LRPT	select the job with the longest remaining processing time (LRPT). The priority index is given as follows: select maximum $Z_i(t)$ where $Z_i(t) = RP_i(t)$
SDT	Select the job with the smallest ratio obtained by dividing the processing time of the imminent operation by the total processing time for the part. The priority index is given as follows: select minimum $Z_i(t)$ where $Z_i(t) = P_{i,j}(t)/T\,P_i$
SMT	Select the job with the smallest value obtained by multiplying the processing time of the imminent operation by the total processing time for the part. The priority index is given as follows: select minimum $Z_i(t)$ where $Z_i(t) = P_{i,j(t)}\,TP_i$
LDT	Select the job with the largest ratio obtained by dividing the processing time of the imminent operation by the total processing time for the part. The priority index is given as follows: select maximum $Z_i(t)$ where $Z_i(t) = P_{i,j(t)}/TP_i$
LMT	Select the job with the largest value obtained by multiplying the processing time of the imminent operation by the total processing

	time for the part. The priority index is given as follows select maximum $Z_i(t)$ where $Z_i(t) = P_{i,j(t)} \cdot TP_i$
FRO	Select the job with the fewest number of remaining operations (FRO). The priority index is given as follows: select minimum $Z_i(t)$ where $Z_i(t)=RO_i(t)$
MRO	Select the job with the largest number of remaining operations. The priority index is given as follows: select maximum $Z_i(t)$ where $Z_i(t)=RO_i(t)$
FIFO	Select the job according to first in, first out (FIFO). The job that has entered the queue the earliest is chosen for loading. The priority index is given as follows: select minimum $Z_i(t)$ where $Z_i(t) = R_{i,j}$ for $i \in N_{i,j}(t)$ This rule is often used as a bench-mark. The FIFO rule is an effective rule for minimizing the maximum flow time and variance of flow time.
FASFO	Select the job according to first at shop, first out (FASFO). The job with the earliest arrival time in the shop is chosen. The priority index is given as follows: select minimum $Z_i(t)$ where $Z_i(t)=R_{i,1}$ for $i \in N_{i,j}(t)$
SLACK	Select the job with the least amount of slack. The priority index is given as follows: select minimum $Z_i(t)$ where $Z_i(t) = S_i(t)$
SLACK/RO	Select the job with the smallest ratio of slack time to the number of remaining operations (slack-per-operation). This rule is often used as bench-mark for evaluating the rules with respect to the tardiness-related measures of performance. The priority index is given as follows: select minimum $Z_i(t)$ where $Z_i(t) = \begin{cases} Si(t)/ROi(t)) & \text{if } si \geq 0 \\ Si(t) \times ROi(t) & \text{if } si < 0 \end{cases}$

SSLACK/RO Select the job with the smallest ratio of static slack time to the number of remaining operations. The priority index is given as follows:

select minimum $Z_i(t)$ where $Z_i(t) = S_i(t)/ RO_i(t)$

SLACK/TP Select the job with the smallest ratio of the job slack time to the total processing time. The priority index is given as follows:

select minimum $Z_i(t)$ where $Z_i(t) = S_i(t)/TP_i$

SLACK/RP Select the job with the smallest ratio of the job slack time to the remaining processing time. The priority index is given as follows:

select minimum $Z_i(t)$ where $Z_i(t) = S_i(t)/RP_i(t)$

COVERT (cost over time) Select the job with the smallest ratio of the computed penalty function, c_i to the process time of the j_{th} operation of job i.

c_i depends on the slack of job i, S_i, and the sum of expected waiting times for the job's uncompleted operations, WT_i. Mathematically, the priority index $Z_i(t)$ is given as follows:

select maximum $Z_i(t)$ where $Z_i(t) = c_i/P_{ij}$

$$\text{where } c_i = \begin{cases} (WT_i - S_i(t))/WT_i & \text{if } 0 \le S_i(t) < WT_i \\ 0 & \text{if } S_i(t) \ge WT_i \\ 1 & \text{if } S_i(t) < 0 \end{cases}$$

This rule is effective to reduce job tardiness

In general process-time based rules perform better under a high level of shop congestion, while due date based rules perform better under light level of congestion. [26, 28] However the choice of a dispatching rule depends on the performance measure of interest and its specific aspect (mean, variance, maximization or minimization).

2.5. Performance Measures

To study the effect of the dispatching rules on the FMS, normally the measures of performance of the system are monitored. A sample list of performance measures is as follows: average lateness, flow time, production cost, production consistency, job quality, job priority, machine and tool utilization, average work-in-process and average waiting time per part.

However, the most used performance measures in the scheduling studies are lateness, flow time and tardiness which can be defined as follows: [28]

Flow time (F_i)	The amount of time job i spends in the system.
Lateness (L_i)	The amount of time by which the completion time of job i exceeds its due date. Lateness may be negative, indicating an early completion.
Tardiness (T_i)	The positive lateness of a job: $(T_i=\max(0, L_i))$

In general the main interests have been improving a shop's productivity while meeting the due dates. In this regard, minimization of mean flow time would reduce in process inventory. However no rule has been found to perform well and improves all performance measures. Thus the choice of dispatching rule depends on the performance measure that is intended to be improved also the characteristic of the system under study.

2.6. Elements Affecting the Dispatching Rules' Performance

A number of different factors are identified which affect the performance of the dispatching rules and thus it is important to use the same setting in the experiment once the dispatching rules are being compared. Furthermore, there are factors that seem to affect the outcome of the experiment but in fact their effects are minimal or they do not have any effect all together. In what follows, some of the main factors in this regard are introduced.

2.6.1. Method of Assigning Due Date

Conway [26] in his investigation of priority dispatching rules introduced a new dimension in measuring the effect of the dispatching rules of the system's performance. He looked at the way the job due dates are set. In his experiments, he defines four methods of assigning due date to the jobs in the following where:

I	Job index
j	Operation index

d_i	The due date of the *i*th job
$R_{i,1}$	The time at which the *i*th job arrived at the shop
$P_{i,j}$	The processing time for the *j*th operation of the *i*th job
TO_i	Total number of operations on the *i*th job $(1 \leq j \leq TO_i)$
X_i	A random number, uniformly distributed between zero and one, assigned to the ith job

Internally Determined

In this method, the production facility itself is responsible for assigning due dates.

- Total work content (TWK): the time between job's arrival and the due date is proportional to the total work required to be executed on the job. In his experiment, Conway [26] defined this method with the following equation:

  $$d_i = R_{i,1} + 9 \,.\, \textstyle\sum_j P_{i,j} \text{ (for j=1,TO}_\text{i}\text{)} \tag{2.2}$$

- Number of operations (NOP): due date assignment is proportional to the total number of operations required by the job

  In his experiment, Conway [26] defined this method with the following equation:

  $$d_i = R_{i,1} + 8.663.TO_i \tag{2.3}$$

Externally Determined

- Constant lead time (CON): due dates are set based on the job's arrival time and a constant lead time.

  In his experiment, Conway [26] defined this method with the following equation:

  $$d_i = R_{i,1} + 78.7985 \tag{2.4}$$

- Random (RAN): the due date is set by the customer

  In his experiment, Conway [26] defined this method with the following equation:

  $$d_i = R_{i,1} + 157.597 \,.\, X_i \tag{2.5}$$

Conway [26] compared the performance of FIFO, SPT and EDD dispatching rules for each of the four modes based on the proportion of jobs with positive lateness. He found that the performance of all rules was rather sensitive to the method of due date setting; however SPT was the least sensitive and performed the best by its lower proportion of the tardy jobs.

2.6.2. Workload

In studying the effect of shop load on the performance of dispatching rules, Conway et al [29] used three level of congestion in his simulated manufacturing shop and compared the percentages of tardy jobs in each utilization level for the FIFO and SPT dispatching rules. It was observed that the performance of a given rule reduces when utilization is increased. From the results it can be concluded that when shop loads are quite heavy the SPT rule is preferable.

2.6.3. Size of the Shop

Despite the fact that in real life the manufacturing shops potentially have many machines, the shop models studied in the literature usually have a small number of machines, typically between six to twelve [28]. This fact is based on the study by Baker and Dzielinski [30] in their experiments with dispatching rules in shops of various sizes. They found that the size of the shop does not affect the performance of the dispatching rules considerably and that a shop with about nine machines adequately characterizes the complexity of large systems. This finding is useful because it is easer to simulate smaller systems and generalize the resulting conclusions.

2.6.4. Sample Size

Many scheduling problems have been studied using simulation models. The simulations are typically run for a specified period of time and statistics on the mean and variance of the performance measure(s) of interest are collected. There may be incomplete jobs at the end of each simulation run. Because the incomplete jobs are usually excluded from the analysis, the collected data may not reflect the complete picture of the dispatching rules' performance. This effect is known as censored data.

Conway [26] suggests the following solution to eliminate the effect of *censored* data Run the simulation system to completion of 10,000 jobs. Eliminate the first four hundred jobs to allow the system to become stable. Discard the last nine hundred jobs. The calculations are thus based on 8,700 jobs.

2.6.5. Job Arrival

There has not been any specific study reporting the effect of distribution of job arrival in FMSs. Normally in the studies on job shops in the literature, exponential or Erlang distributions have been taken as the candidate distribution. [31]

In the following chapter a review of the literature on the performed studies of the dispatching rules' problem is presented.

3. DISPATCHING RULES STUDIES

3.1. Introduction

As was pointed out in the previous chapter, dispatching rules have been used in the last decades to address scheduling problems for their simplicity and ease of use. Dispatching rules are simple algorithms that have been developed to control the production sequences where their performance depends on the performance criteria under consideration and also on the arrangement of the production system.

The body of literature in this area is sometimes contradictory since the experimental settings and assumptions of these studies are often not the same. Consequently, for each FMS there has to be a separate scheduling study to find the best dispatching rule to accommodate the desired measure of performance.

In general, there are two main performance objective categories that dispatching rules should improve, namely to increase productivity and to meet the due date of the job orders. In the following, the literature directly related to these two aspects of production shops will be reviewed.

3.1.1. Reducing Mean Flow Time

The most common productivity performance measure of production shops is mean job flow time. It has been found that SPT minimizes mean job flow time among other simple dispatching rules.

Conway [7] considered a shop with nine machine groups each with a single machine. In this experiment, he reported results for over 30 dispatching rules. He used four different performance measures in studying the effect of dispatching rules as follow:

1. Work Remaining: The sum of the processing times of all operations not yet completed or in process for all jobs in the shop.

2. Total Work Content: The sum of the processing times of all operations of all jobs in the shop.

3. Work Completed: The sum of the processing times of all completed operations of all jobs in the shop. Work Completed is equal to Total Work Content less Work Remaining.

4. Imminent Operation Work Content: The sum of the processing times of the particular operations for which jobs are waiting in queue.

In total, Conway [7] tested 16 different priority dispatching rules and concluded that the SPT rule performs relatively better than all other rules in general with respect to average job lateness and in-process-inventory for the four methods of due date assignment as described earlier. He stated that "SPT performance under every measure was very good, it was an important factor in each of the rules that exhibit are 'best' performance under some measure, and it is simpler and, easier to implement than the rules that surpass it in performance. It surely should be considered the 'standard' in scheduling research, against which candidate procedures must demonstrate their virtue". This is especially true where minimization of mean flow time is the goal. The SPT rule reduces mean flow time with following method: by giving priority to the jobs with short process times, it accelerates the progress of production of jobs at the expense of some jobs with long processing time. This way, in total the average flow time is reduced, but jobs with long processing time face long waiting times.

3.1.2. Meeting Due Dates

When dealing with meeting job due dates, the performance measure which is usually used in the literature is mean job tardiness. However other lateness and tardiness performance measures have also been used such as job lateness and production cost.
In general terms, job lateness is the difference between the job completion and its due date. Furthermore, tardiness is the positive lateness. However it is not only the mean of the performance measure but also its variance that accounts for good performance.

A simulation study by Conway [26] studied the jobs' tardiness as a performance measure with the use of a simulated production shop and the results of the simulation runs with use of number of different priority rules were compared. The following conclusions were made from the experiment:

- The mean shop time is directly proportional to the mean number of jobs in the shop
- FIFO rule resulted in a large proportion of tardy jobs

- SPT rule got a small proportion of tardy jobs because of its low lateness mean that offsets the high lateness variance.
- EDD rule produced a lower variance of job lateness than FIFO or SPT in all the methods of due date assignment.
- Overall, it concluded that the SPT priority rule exhibited the best performance of all the rules tested with less sensitivity to the degree of congestion in the shop.

3.1.3. Other Studies

Montazeri and Van Wassenhove [8] have also studied the effectiveness of the scheduling rules for various system performance measures using a discrete event simulator. Their system consisted of three machine families, three load/unload stations, three carriers, and 11 work in process buffer positions. Eleven different part types produced by the system and the weekly production of the system were 199 parts. It was assumed that raw material for the parts is readily available. They assigned the same priority rule in every run for all decision points in the system in order to be able to study the pure effect of each dispatching rule separately. The decision points in the system included:

- Select next part to be processed by the machines.
- Select next part to be moved in the system.
- Select next part to be loaded on carrier from a facility.

They concluded that the SPT priority rule was the second best priority rule for the system under study in terms of average waiting time. No single scheduling rule was found to improve both average and variance of a job's waiting times. They also concluded that SPT based rules minimize average waiting times and LPT (Longest Process Time) based rules maximize machine utilization. Finally, no single scheduling rule was found to be the winner on all performance measures. They suggested that it is up to the user to choose the scheduling rules based on the performance measure that needs to be improved.

Persi et al [32] have proposed a hierarchical approach in addressing the problem of improving machine utilization in flexible manufacturing system. They decomposed the problem into four hierarchically arranged simpler sub-problems and solved it separately to come up with a solution for the whole problem. The proposed sub-problems are as follows:

1. Batching: partitioning the required parts by the production plan into subsets of parts
2. Batch sequencing: the most appropriate sequence of the batches
3. Batch linking: the transition from each batch to the next
4. Scheduling parts within each batch

They used a simulation model of an FMS cell with three machining centers and a washer. Each machine had an input/output buffer for parts. Pallets carrying parts moved automatically. The performance of ten scheduling rules including FIFO, SRPT, RAND, SIO and EDD was evaluated according to two different criteria: the ratio between batch workloads and the corresponding schedule duration (δ), a measure of the work-in-process (WIP). For each part, the due date calculated by the TWK method. They concluded that EDD provided low idle times and high values for δ and considered the best dispatching rule where the other rules showed a good performance in only one of the two considered criteria.

Choi et al [33] described the use of a physical simulator as opposed to computer simulation as an analysis tool in the evaluation of scheduling dispatching rules in an FMS. The use of a real model has a number of advantages including realism and better visual observation of problems. They modeled an actual FMS which consisted of an automatic storage/ retrieval system (AS/RS), a parallel machine center structure including six identical numerically controlled (NC) machining centers, one turning cell including a robot, two vertical NC lathes, a washing station and overhead conveyors.

They studied the performance of seven dispatching rules including Random, FIFO and SPT based on six performance measures including actual system effectiveness, total traveling time of parts, actual production output, total manufacturing throughput time, work-in-process inventory and total production lateness. Each set was simulated for 140 hours of real time. They concluded that the RANDOM rules had high values of actual system effectiveness and low values of production lateness where the SPT had high values of the actual production output, low throughput time and low work-in-process inventory. However no rule was found to be best for all performance measures.

Horng and Chou [34] studied the performance of dispatching rules in open shops in comparison to job shop with the use of computer simulation. They considered mean flow time, maximum flow time, variance of flow time, proportion of tardy jobs, mean tardiness, maximum tardiness, and variance of tardiness as performance measures. They ran each simulation for the completion of 2500 job and discarded the first 500 jobs to let the system reach steady state. Twenty simulation replicates were made for each run and the total work-content (TWK) method (see section 2.6.1) is used in calculating due date. Furthermore, two FMSs with five and ten machines and two levels of shop utilization of 80% and 95% were used. It was concluded that when using the average flow time as the performance measure, SPT is the best job dispatching rule except when the number of machine is 5 and utilization rate is high. Additionally, if considering the proportion of tardy jobs, SPT is the best for most. In general it was found that the choice of the dispatching rule is influenced by factors such as, due-date, process time distribution and utilization at each station.

In addition to the analysis of job-dispatching rules in an open shop, they also studied the best job dispatching rule for a job shop and a flow shop with similar system configuration. The results show that if considering the same performance criterion, the best dispatching rule for one system is not necessary the same for the others with the same system configurations. However in general SPT was one of the best rules in reducing the percentage of tardy jobs and minimizing the mean flow time.

The objective of the study conducted by Co et al [35] was to investigate the effect of queue length on five dispatching rules;

- First In, First Out (FIFO)
- Shortest Processing Time (SPT)
- Least Work Remaining (LWKR): highest priority is given to the job having the least total processing time for all operation yet not performed
- Total Work (TWK): highest priority is given to the job having the least total processing time for all operations
- Next Queue Length (NXQL): highest priority is given to the job where the direct successor operation station has the shortest queue.

In this regard they considered mean flow time as the performance measure and used three sets of 2, 4 and 6 job types, four sets of machine stations (5, 7, 10 and 15) and four levels of machine utilization including *(2/3)m, m, 2m, 5m,* where *m* is the number of stations in the system. They used twelve simulation replications for each dispatching rule, with more than 600 finished parts for each simulation run. It was found that the SPT rule is the best dispatching rule, when the number of jobs in the system is less than or equal to the number of stations.

Chan et al. [36] used a simulation model of a FMS to study the possibility of minimization of three performance measures at the same time. To this end, the system was designed in such a way that the dispatching rule will be changed dynamically. Based on the value of the performance measure at the time, the next dispatching rule is selected to improve the worst measure.

The FMS used included five machine workstations and one loading/unloading station. The system had a central buffer area to hold in process jobs. Two AGVs were used for transporting the parts. The job arrival time was set to be exponentially distributed, the due date was set based on the TWK method and mean flow time, mean tardiness and mean earliness performance measures were considered along with 14 dispatching rules including FIFO, SPT and EDD. Each simulation run consisted of 2200 job completion where the first 200 jobs were discarded.

For the experiment without machine breakdown, it was concluded that the best dispatching rule to minimize mean flow time of the jobs is SPT. In addition, the best dispatching rule to get minimum mean tardiness is EDD. Other results showed that this method gives a better overall performance compared to the isolated simple dispatching rule assignment.

Veral [37] studied the possibility of setting reliable static due-dates through operation flow time analysis in an unbalanced, multi-machine job shop with six machines. Three different dispatching rules were used, FIFO (First Come, First Serve), SI* (modification to SPT where it separates late jobs from normal ones and prioritizes each subset according to the SPT rule) and MDD (Modified Due-Date; modifies the internal due-date of a job to its earliest possible completion time if it is already late) with three different levels of shop tightness. Proportion of tardy jobs, maximum tardiness and machine utilization were among other considered performance measures. Each simulation run consisted of 6000 job completions where the data related to the first 2000 jobs were discarded and each simulation run replicated 30 times. It was concluded that the proposed methodology was effective under all levels of due-date tightness, and for all performance measures at the same time and that it is not affected by tightness of due-dates. This study showed the advantages of using static job information as opposed to dynamic shop information in setting due-dates.

Shanker and Tzen [31] studied the two interdependent aspects of scheduling problems in an FMS: loading and sequencing. They used a simulation model of four machines and studied heuristic and sequential loading methods and four dispatching rules; FIFO (First In, First Out), SPT (Shortest Processing Time first), LPT (Longest Processing Time first) and MOPR (Most Operations Remaining first). Each job assumed to have between one to three operations and each processing time uniformly was distributed between 6 to 30 minutes. Each simulation run was eight hours and total of ten runs was executed. It was mentioned that due to constraints on computer time, a steady state termination criterion was not used. In conclusion, the SPT was considered the best rule on average.

Rajendran and Holthaus [27] conducted a comparative study on the performance of dispatching rules in dynamic flow shops and job shops with and without missing operations. Along with ten dispatching rules (including SPT, EDD and FIFO) three new dispatching rules were proposed. Mean flow time, maximum flow time, variance of flow time, proportion of tardy jobs, mean tardiness, maximum tardiness and variance of tardiness were the considered as performance measures. A system of ten machines was considered. The jobs' process times ranged from 1 to 49. The TWK method of due date setting was used. The job arrivals were exponentially distributed. In all, three due-date settings and four different utilization level were considered. In each run, the shop is continuously loaded with job-orders to completion of 2000 jobs and the first 500 jobs were discarded. Each simulation setting was replicated 20 times. It was concluded that for flow shop, the SPT is one of the best rules to reduce mean flow time where the performances of the SPT rule was also satisfactory in job shop. In all, it was observed that the performance of dispatching rules is influenced by the routing of jobs and shop floor configurations.

3.2. Other Scheduling Problem Studies

Scheduling problems occurs in different settings and in variety of conditions. The following presents some categories of scheduling problems that have been extensively studied.

3.2.1. Scheduling Research Involving Setup Considerations

The greater part of literature on scheduling problems considers the setup as insignificant or at most, part of the job's processing time. Although this assumption makes the analysis of the problem easier, in some cases where the setup time is significant, the generated solutions would not be the optimal especially when the setup time is not equal for all jobs. System setup includes activities such as adjusting tools, positioning process material in storage, tooling cleanup, setting the required jigs and fixtures and inspecting materials.

Allahverdi et al. [38], reviewed all the published research papers related to static shop scheduling problems involving setup consideration at length. They classified the scheduling problems into batch and non-batch, sequence-independent and sequence dependent setup and categorized the papers according to the shop environments of single machine, parallel machine, flow shops and job shops. "Setup is sequence-dependent if its duration (cost) depends on both the current and the immediately preceding job, and is sequence-independent if its duration (cost) depends only on the current job to be processed. Furthermore, a batch setup problem occurs when part types are grouped into batches (or product families) and a (major) setup time is incurred when switching between part types belonging to different batches, and, a (minor) setup is incurred for switching between part types within batches (i.e. from the same product families). In other words, a major setup time depends only on the batch being switched to, and the minor setup time depends only on the part type being switched to" [38].

3.2.2. No Wait Scheduling

No wait scheduling problems are a category of scheduling problems in which the production of jobs must be executed without any interruption or delay. As result in this production method, no intermediate buffer or storage area is available. As an example, this production method can be observed in steel production to acquire desired material characteristics. Furthermore, lack of storage area in the shop environment is another reason to use this method of production. Candar [39] has reviewed the conducted research on this type of scheduling problems and presented a brief tabulated summary based on the computational complexity of the researched problem.

3.2.3. Buffer and Dead-Lock

The next series of problems study the effect of buffer and storage location in the production system. A side problem that relates to this category is dead-lock problems. Dead-lock is the technical term for the phenomenon that happens in a production system when it is brought to a halt due to excessive production load and lack of handling and delivering resources. The majority of the papers in this field study the problem are conducted using the analytical method. Lawley et al. [40] developed and define the criteria for real-time FMS deadlock-handling and then provide guidelines for developing strategies satisfying these criteria that guarantees deadlock-free buffer space allocation for FMSs.

3.2.4. Reactive Problems

The last series of scheduling problems are called reactive and cope with unexpected events such as machine breakdowns, tool failures, order cancellation and due date changes. Sabuncuoglu and Bayiz [41] have reviewed the literature in this area and categorized them in three main divisions: environment, schedule generation and implementation of reactive policies that define the characteristics of the problems. They then studied several scheduling policies under machine breakdown in a classical job shop in four different sizes. They observed that the relative performances of the scheduling methods are not affected by the systems size; rather they are more affected by the system load. Furthermore, they noticed that the distribution of the load in the system has significant impact on the performance of the scheduling methods. In this case, when the load across the machines is not uniform, they observed that the off-line scheduling method performs better than on-line dispatching rules.

3.2.5. Assembly Shops

The majority of the studies in the domain of scheduling problems have been done by considering shops producing simple products. However Mohanansundaram et al. [23] studied the scheduling problem in assembly job shops. This category of problems is more complicated than the problem associated with shops producing simple products since in assembly operations, all the lower levels should be available (processed) to be able to process the higher-level part. This issue adds a new dimension of co-ordination to the scheduling problem that does not exist in the scheduling problems associated with simple parts.

In their study, they considered an open shop configuration with nine work centers, each having two identical machines. Job arrivals were distributed exponentially. The due-date is set base on the TWK method. Two levels of machine utilization (80 and 90%) are tested and the maximum and standard deviation of flow time and production delay of jobs are considered as performance measures. The simulation run for each setting was replicated 20 times and each run covered 1250 job completions. The fist 250 jobs were discarded to allow the system reaches steady state and data from jobs 251 to 1250 were collected for statistical computations. They proposed new dispatching rules and it was found that the proposed rules were effective base on the performance measures under consideration.

3.3. Summary

From the reviewed literature, it can be concluded that due-date based rules (e.g. EDD) perform better under light load conditions while process-time based rules (e.g. SPT) perform better in heavy load conditions. Furthermore, the main advantage of due-date-based rules over processing-time-based rules is smaller variance of job lateness, and often smaller number of tardy jobs. Finally, the FIFO rule, a rule that is neither process-time based nor due-date based, has been found to perform worse than processing-time rules and due date rules with respect to both the mean and variance of most measurement criteria. FIFO performs similar to the random rule; however it produces a lower variance of performance measures. As a result, the FIFO rule can be used as reference for studying the performance of dispatching rules so that any rule to be considered effective should perform better than random selection and thus better than FIFO.

Thus according to the reviewed literature the overall best simple dispatching rules among all other simple rules in order of their performance are SPT, EDD and FIFO. However the selections of a "best" priority rule depend on factors such as: "Method of due date setting", "Tightness of the due dates", "Level of shop load" and "Type of shop". As result it is extremely difficult to generalize the conclusions of a simulation study.

In this regard in the remaining of this thesis the above conclusion is rechecked and revisited for a specific system, the existing CIM system in the Mechanical Engineering Department of Concordia University.

4. SYSTEM DESCRIPTION

4.1. System Overview

Typically, an FMS is able to produce a range of different products where the traditional product assembly lines normally produce a high volume of a limited number of products. FMSs are normally automated where a central control system controls a number of CNC machines connected by a material handling system, usually automated guided vehicles (AGVs), or a conveyor system.

The existing FMS under study consists of four workstations around a closed conveyor loop for part transportation among workstations as shown in Figure 4.1.

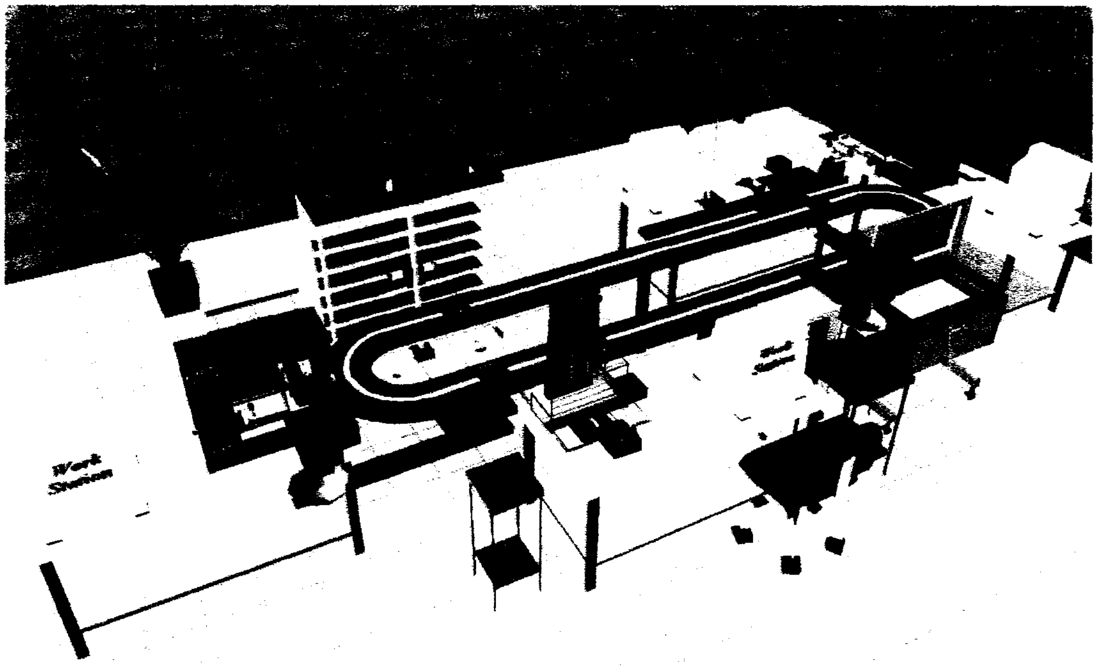


Figure 4.1: Layout of the Existing FMS

The work stations are as follows:

- An Automated Storage and Retrieval System Station (AS/RS), which is an automatic warehouse which supplies raw materials to the system, stores parts in intermediate stages of production, and holds finished products with its Cartesian robot.

- Machining Stations, where materials are shaped. There are three machining stations in the system; a CNC station with a mill, and a lathe CNC and a laser engraver station.
- An Assembly and Quality Control Station (QC) for assembly and inspection of parts using machine vision.

Furthermore, each machining station and the QC station have a serving robot and a buffer area to hold all jobs to be processed. The CNC station's buffer has the capacity of four parts and the laser engraver and QC stations' buffers each have the capacity of two parts. Each part type has a unique template to mount the part. Also, the conveyor system has six pallets where the templates (with mounted parts) are being placed on for transportation among stations. The shop floor control system (SFCS) monitors the location of the parts either separately, when they are being processed at a station, or in conjunction with a template when they are on pallets, in ASRS or in a buffer location.. A more detailed description of the FMS's equipment is presented in Appendix A.

4.2. The Control System for the Shop Floor Production Cell

A shop floor control system (SFCS) is responsible for control and monitoring of activities on the shop floor. The SFCS communicates with equipment controllers via the workstation controller to send tasks and receive progress status. The equipment controller is connected with devices, such as conveyors and robots, and controls them according to the instructions from the SFCS. The SFCS of the existing system is OpenCIM which is ready made control software from Intelitek Inc. OpenCIM is an educational SFCS which provides the principles of automated production using robotics, computers, and CNC machines. It also allows searching for optimal production techniques by experimenting with different production strategies. OpenCIM provides a realistic, expandable environment through interfaces to the shop equipments. [42]

The various manufacturing functions exist on three hierarchical levels. The topology of the SFCS of the existing FMS is shown in the following figure.

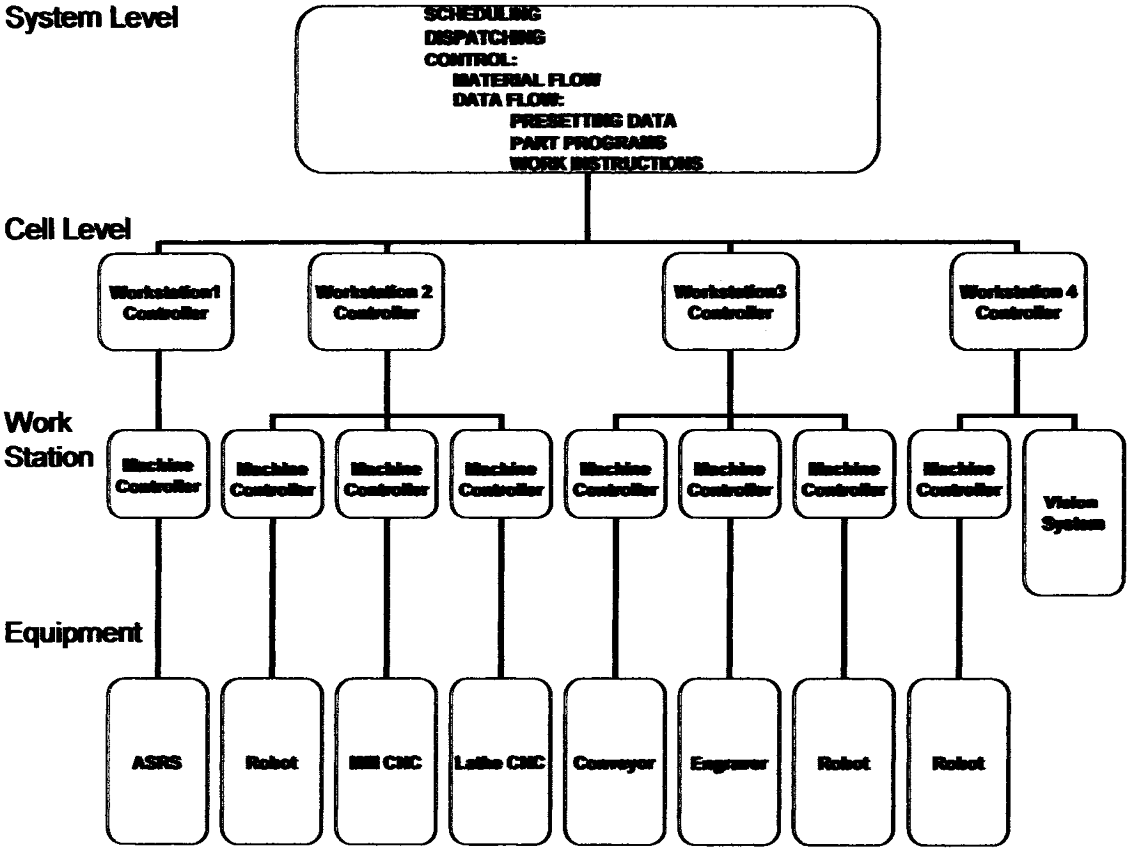


Figure 4.2: Topology of the SFCS of the Existing FMS

The *System (Cell)* level coordinates and monitors the activities at the shop floor. The input to a shop floor control system is the production order. The production order should be transformed into a production plan at the System level where orders are divided into jobs, which are set into a production plan. A job is a unit of work which is sent to a workstation. Machine capacity, production due dates and operation processing times are the basis for production planning. Consequently, production schedules are prepared as a task list containing the sequential execution of different jobs and also the sequence of executable tasks for each job.

In general the functions performed by the system level can be summarized as follows:

- Generate the production plan
- Release the jobs to the different workstations
- Download processing instructions to the relevant workstation

- Monitor the operations, detect errors and generate reports
- Control and monitor material flow such as pallets and work pieces between stations
- Synchronize processes

The *Workstation* level is the next level in SFCS. This level consists of a workstation manager PC, equipment controllers and related equipment. At this level the parts are processed. The workstation manager communicates with the equipment by their related controllers. The process that takes place is either single operations or a combination of operations in which the workstation manager has to coordinate the actions between the different units/equipments in the system. In this regard, the related programs are loaded to the equipment controllers by the workstation manager by way of the related device driver. These device drivers are interface programs designed to communicate messages between the workstation manager and the controllers of the devices connected to the workstation.

The Workstation Manager runs concurrently separate device drivers for each connected device. The device drivers perform the following functions:

- Translate cell controller commands into instructions understood by device controllers
- Translate status information from device controllers into system messages and vise versa.
- Download process programs to equipment controllers

All device drivers have a control panel for sending commands and viewing status information, error messages, and responses from the device. The following device drivers exist in the existing FMS: *CNC Device Driver*, *Robotic Device Driver* and *PLC Device Driver*.

Finally, the lowest level is called the *Equipment* level. On this level machining and other operations are executed. A graphical presentation of the activities of the different level of SFCS is shown in the following figure.

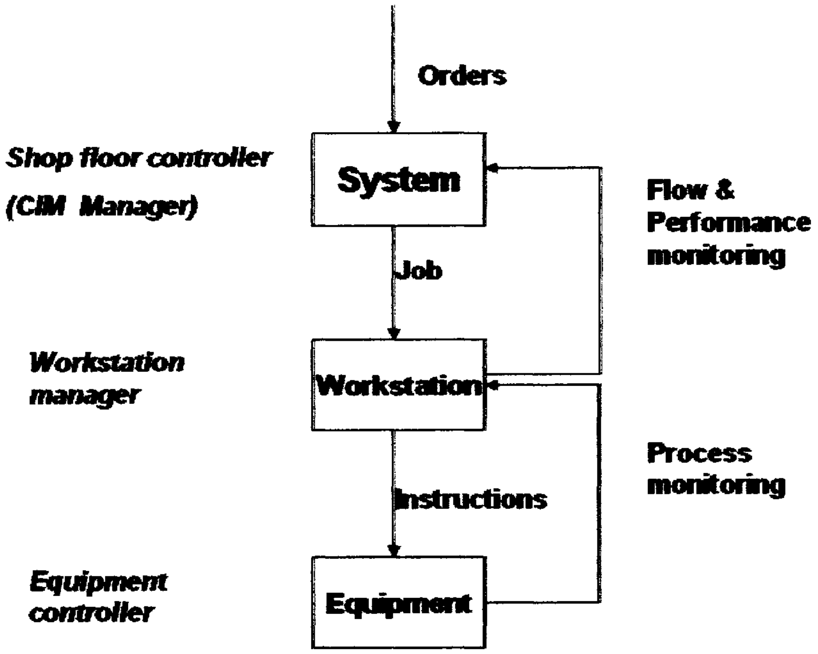


Figure 4.3: Hierarchical Control Levels in a Shop Floor Production System

4.3. SFCS Communication Process

The SFCS manages the production process by creating a task list which includes a sequence of tasks scheduled to occur.

Initially, the SFCS creates the production plan based on the received orders, products tree and machine and process specification. Based on the production plan, the cell controller generates tasks and inserts them into a task list. When the production cycle starts, the cell controller downloads the inserted task in the task list to the corresponding equipment controllers sequentially. Furthermore, the cell controller receives the status of the downloaded task from the equipment controllers and monitors its progress. Finally the cell controller deletes the finished tasks from the task list. In general the cell controller is not concerned with how the functions are performed at the workstation level; the workstation controller controls the execution of the jobs by communicating with the equipment.

A graphical representation of the SFCS automatic functions in relation to the manual inputs and presetting data is presented in the following figure.

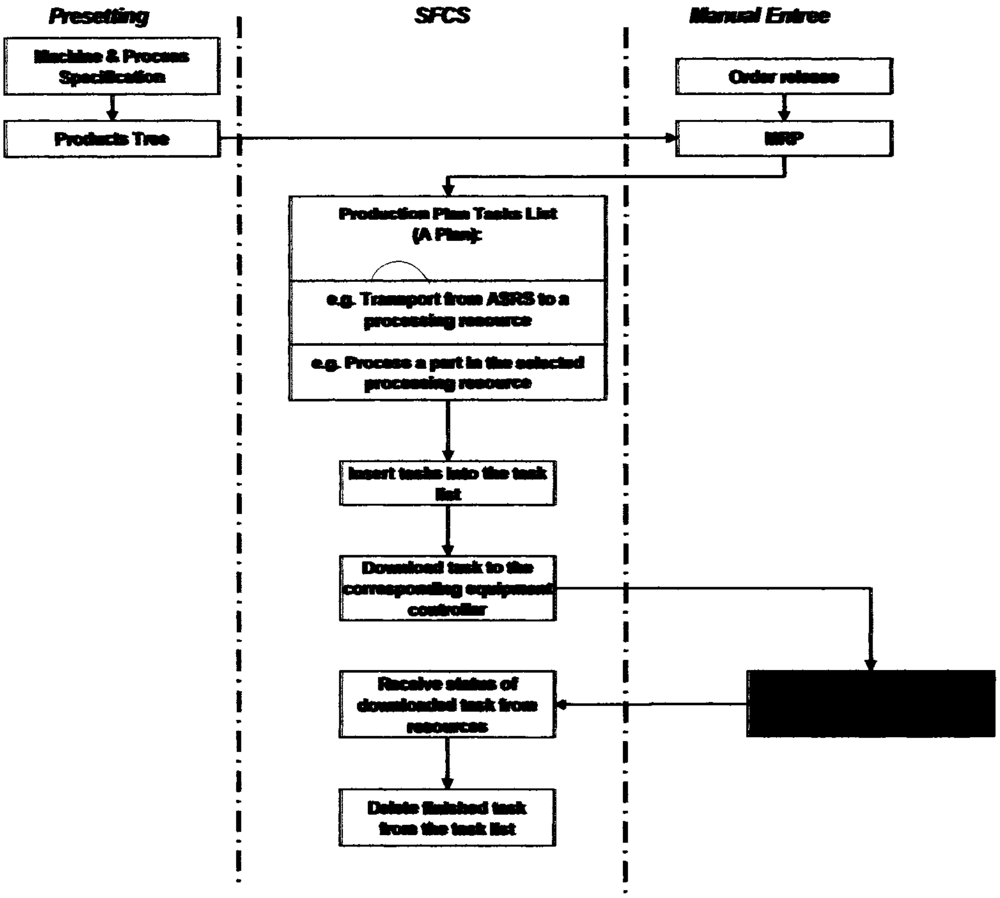


Figure 4.4: Automatic Functions, Manual Inputs and Presetting Data Relations of SFCS

4.4. Part Movement In the System

Whenever a pallet goes to a station, the conveyor device driver stops the pallet, identifies it by checking the unique pallet's magnet arrangement at its back and decides if the pallet/part is required at the station (contains a part that needs to be processed in that station), and if so, it notifies the cell controller. Consequently the template with the part is picked by the robot and is placed on the buffer. In general when the cell controller needs a part at a workstation, it sends a command to the related device driver in the workstation. The cell controller then waits for the device driver to inform it that the pallet with the part has arrived. The pallet is kept at the station by the device driver until the release message is sent by the cell controller. The release message is sent when the handling robot clears the conveyor space and has sent the clear signal.

Since each machine in the system can only process one part at a time, when there is more that one job in the system that needs to be processed by a particular machine, a queue will be made in the related buffer. Next, when the machine becomes free, the serving robot will select the next part to be processed based on a specified dispatching rule. When the buffer is full, any new part will remain in the conveyor system until a free spot on the workstation's buffer becomes available. Evidently, since the number of pallets is limited, too many jobs' arrivals from the AS/RS will saturate the system since no more space will be available to hold the new parts.

4.5. Robotic Programming

When teaching a robot to perform a new task, it needs to have a robotic program. The OpenCIM cell controller uses a strategy called pick-and-place to handle parts in a workstation. This strategy is adopted to reduce the required number of programs for part transfer among locations. For this purpose, each device and location in the station has its own Put and Get programs so whenever the robot gets an instruction from OpenCIM to pick a part from a location (e.g. a buffer or CNC machine) the related Get program will be triggered. The same way, when a robot should place a part in a specific location, the related Put program will be triggered. This way instead of writing individual programs to move a part between two locations, it is only required to write two programs per location and thus significantly reduce the number of necessary programs.

When OpenCIM sends a command to a robot device driver it contains a set of parameters. These parameters include a sequence number generated by the OpenCIM for each command, the ID of the device at the source location where the part/template will be picked up by the robot, the Index parameter for a source device that has multiple locations that specifies in which location the robot will find the part/template, the device ID of the target location where the part/template will be placed by the robot, the Index parameter for a target device and the part's ID number that the robot handles. By way of these parameters, OpenCIM is able to command and control the robot. [42]

For each part type in the system, there are separate instructions for each robot as how to handle (grab and release) the part.

A standard procedure for teaching a robot to grab and release a part is as follows [42]:

1. Use a teach pendant (a portable terminal for operating and controlling the axes of the robot) to train the robot how to move and grasp the part/template.
2. Put the source and target locations' coordinates in the appropriate array.
3. Specify the proper commands for robot movement in the GET and PUT programs.

4.6. CNC Programming

The programming and control of the NC machines are done by way of G-Code control programs. The Control Program is normally written in the control interface program.

To run an NC program the following steps have to be taken:

1. Open the NC program
2. Select tool for verification
3. Verify the program by using Tool path verification and checking for programming errors before actually running the part program on the CNC machine
4. Dry run the program with no stock mounted to ensure that the tool does not move to undesirable area and damage the machine and/or part
5. Finally, mount the part and run the program

4.7. The Control Logic

In order to be able to run the simulation experiments, it is necessary to model the CIM system. The system described in previous sections along with the various scheduling rules was modeled using Arena software. The first step in modeling the system is to provide the simulation modeling logic structure. In this regard, the simulation logic at the AS/RS in Figure 4.5 and the simulation logic at the CNC processing work stations for each part type is showed in Figure 4.6.

For each queue in the system, there is a priority selection routine which calculates the priorities of the parts/jobs in the queue based on the selected priority dispatching rule (in the case of the CNC workstation) or the predefined part selection table (in the case of the AS/RS).

It the case of the AS/RS (Figure 4.1), the pallets on the conveyor are stopped once they reach the AS/RS workstation and each is checked to see if it has a finished part to be stored in the AS/RS or if it is empty. In the first case, the location for the part in the AS/RS is identified and the part is put in that location. In the latter case, it is checked to see if a raw material should be released to the system, then the part is selected base on the predefined tabulated routine. Finally the selected part is picked and put on the pallet on the conveyor. At the end of the both scenarios, the pallet is released.

In the case of the CNC processing workstation (Figure 4.1), at the arrival of the pallet to the station, it is checked to see if it contains a part. If it does, it is verified if that part should be processed in this workstation. In the case that the part needs to be processed, it is checked to see if the required resources are available, including robot and buffer. If the resources are available, the part is picked and put on the buffer. Subsequently, the part is added to the job list. The simulator maintains a job list which contains the parts that need to be processed or released. Then, it is checked if a robot is available to handle the part. If a robot is available, the priority calculation routine is called to choose a part in the queue for the processing. Next, it is checked to see if the part needs to be processed by the other CNC machine or should be released to the system. Finally, the finished part is added to the finished parts job list to be released to the conveyor system.

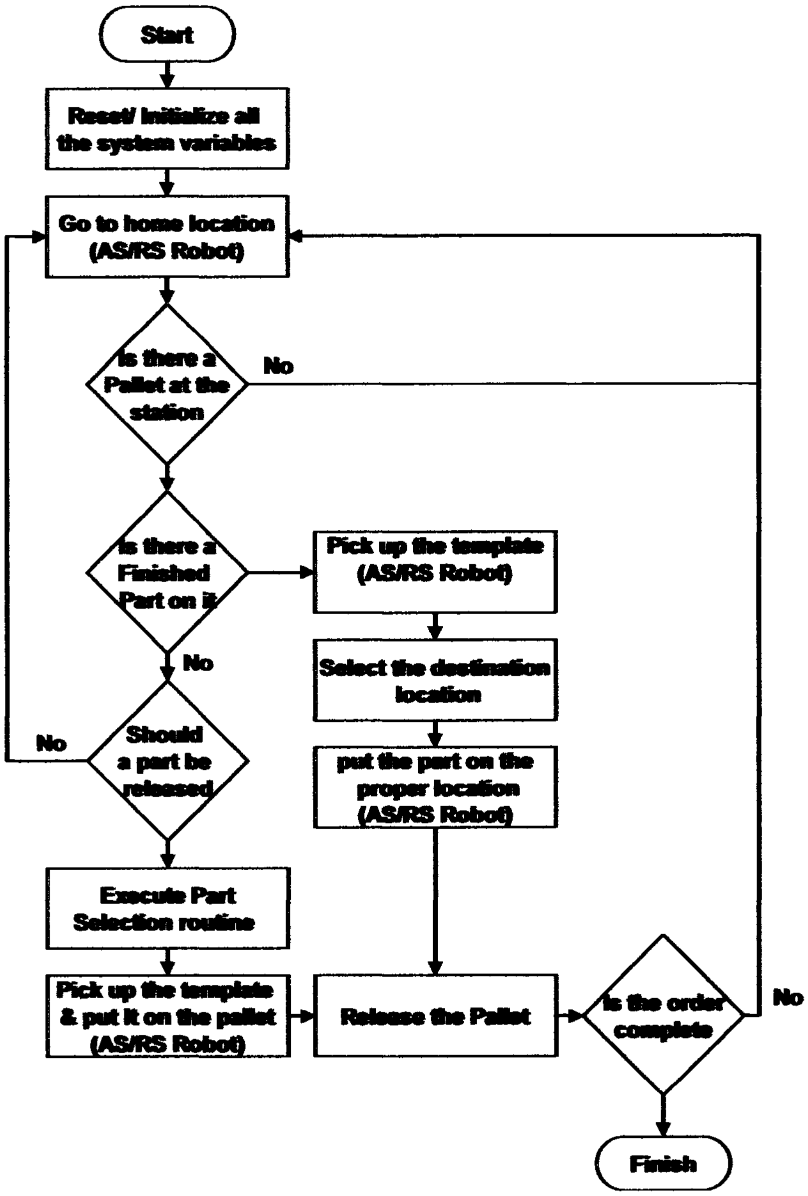


Figure 4.5: Control Logic for the AS/RS Work Station

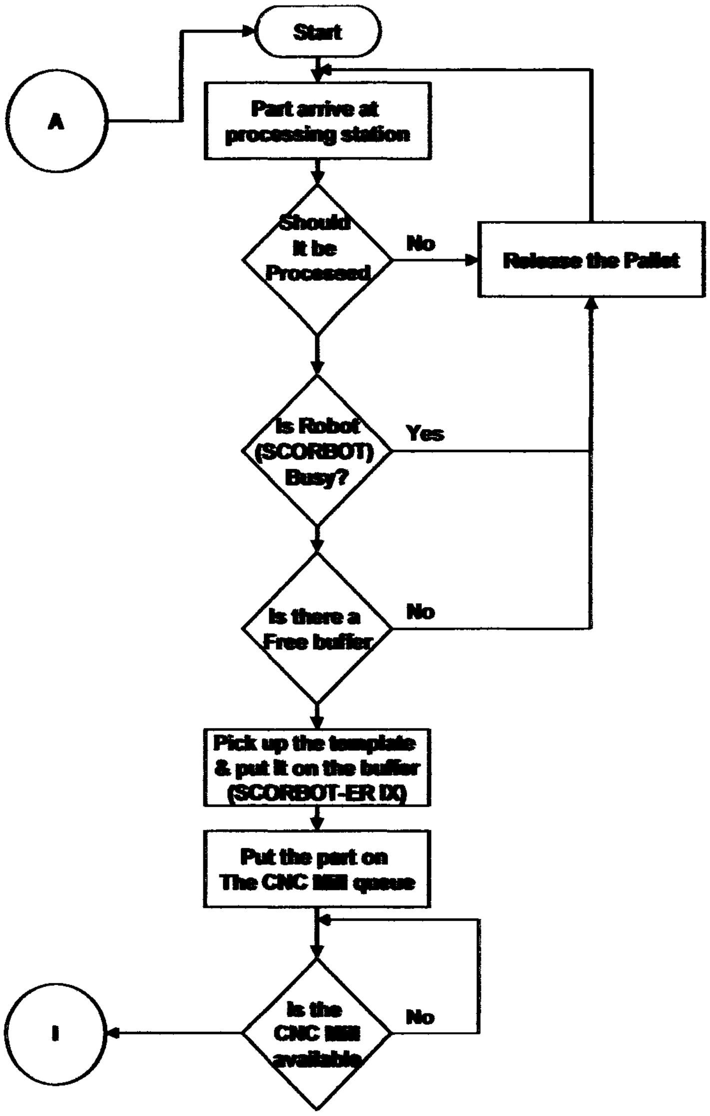


Figure 4.6: Control Logic for Parts

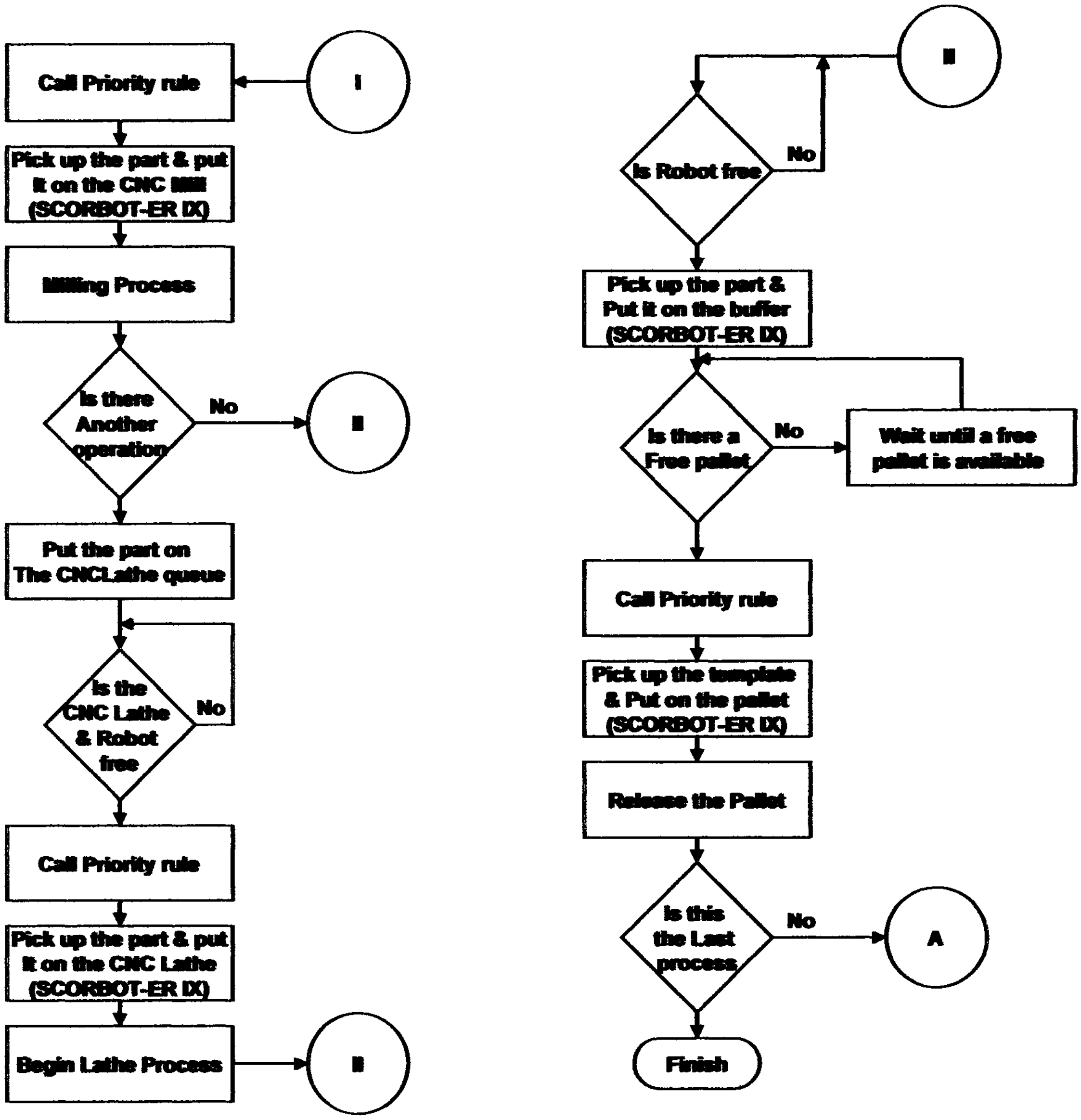


Figure 4.6: Control Logic for Parts (continued)

When a robot puts a part in the CNC machine, the robot's movements are coordinated with the CNC machine.

Communication between the CNC machine and robot is by high or low signals (I/O connection). The following figure describes a typical robot and CNC machine interaction:

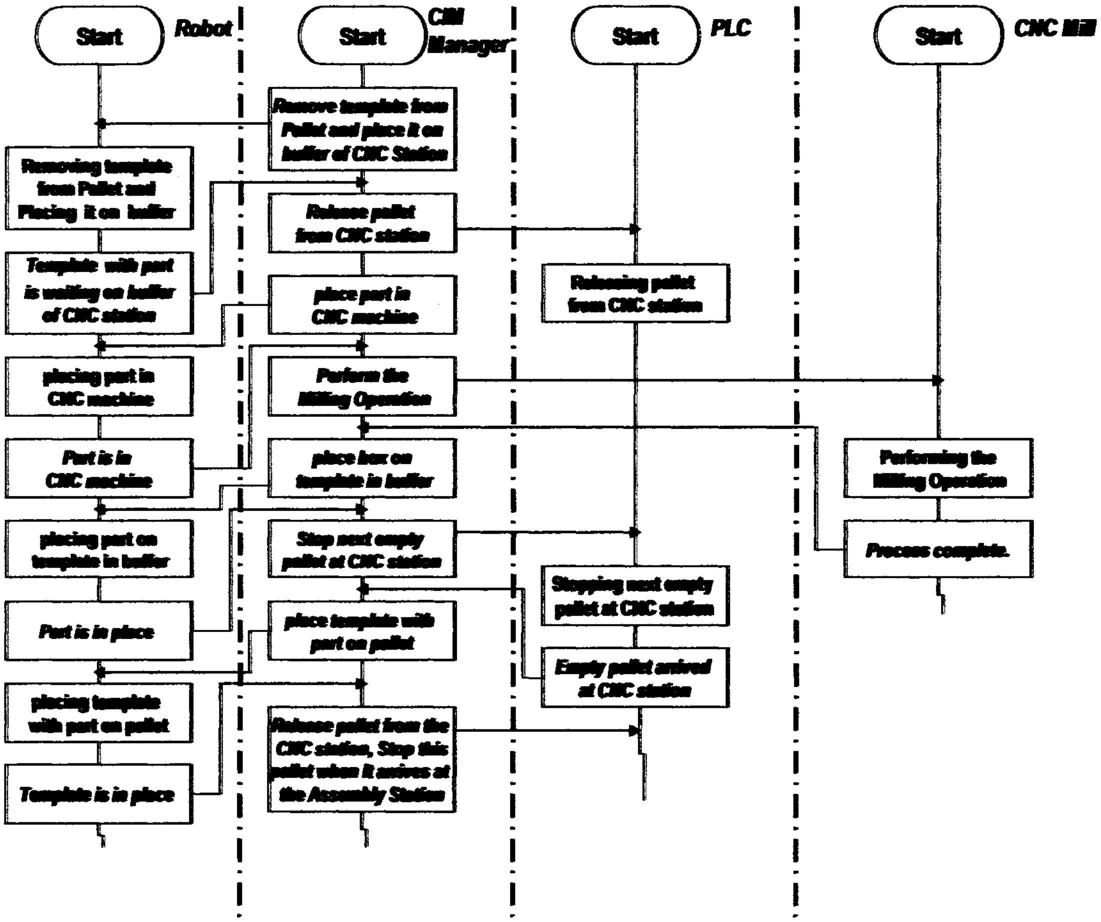


Figure 4.7: Equipment Interaction in the SFCS

5. DESIGN OF EXPERIMENTS AND FORMULATION

5.1. Introduction

Design of Experiments (D.O.E.) is a structured approach in experimentation used to identify the significance of selected variables (factors) on the performance of the system under study. In this approach the required set of experimental runs is created based on the combinations of factors and the levels of these factors. The experiments are performed by measuring the performance measures of the system under study, while changing the values of other factors in the system. The point is to evaluate the impact of these changes.

An experimental design approach is employed for three main reasons. First, experimental design enables to decide which particular configuration of factors to run, so that the information regarding the performance of the system can be reached with the minimum number of runs. Secondly, experimental design provides the tool for determining which factors or which combination of factor levels have significant effects on the performance of the system. Finally, full or fractional factorial design of experiments is the only statistical means of studying the interaction effects between two or more factors.

The D.O.E. method requires necessary inputs to create the experimental runs. Therefore information regarding the number of different alternative dispatching rules, the number of the independent factors which are affecting the manufacturing performance and the levels of these factors must be specified. Furthermore, for the purpose of the statistical analysis of the results, the number of replications for each experimental setting is required.

The total number of runs required for a Full Factorial D.O.E. is derived from the formula:

$$\textit{Total runs} = p \times m_1^{n1} \times m_2^{n2} \times m_3^{n3} \times \dots \times m_j^{nj} \qquad (5.1)$$

where, n = the factors under consideration,

m = the specified level for the factor,

j = number of the factors under consideration and

p = the number of replications.

5.2. Control Factors and Experimental Runs

In order to study the characteristics of the FMS and its production performance, it is necessary to find the factors which affect the system's performance. In order to avoid the significant increase in the number of simulation runs, the experiment must be designed carefully. Thus only the factors that have a significant effect on the performance of the system should be taken into consideration. In general, these factors can be classified into two categories: controllable or design factors, and uncontrollable factors. Some examples of uncontrollable factors include number of machines, part mix, number of buffers etc.

The main design factors of interest to this study in the existing CIM system are defined dispatching rules. These rules are mainly used by the handling robots in the system to perform material-handling tasks according to the production plan. They include:

- First-come First-served (FIFO)
- Earliest Due Date (EDD)
- Shortest Processing Time (SPT)

These rules are well known sequencing algorithms which have been shown to be effective in specific production systems settings and/or used as a reference.

Two other factors are also considered in this study. The first factor is the system load (initial number of released parts), which is treated as an experimental factor to study the FMS for different levels of system congestion. The release time of each additional part from the AS/RS is not set in terms of time intervals, but rather in terms of the work (part) progress. An additional part is released to the system only when the previous part exits the system or reaches a specified stage in its production process. Thus the increase or decrease in the system utilization is set by the number of initial parts released into the system. The second factor is the number of buffers in the system. These factors are included in the experiment because they introduce variability in the CIM system. The introduction of variability into the system is important since the effectiveness of the dispatching rule should be proven under different conditions. Furthermore, these factors have also been used in similar studies that enable a comparison of the findings of the experiments with the literature in this field.

Three levels of the two factors, presented in the following table are suggested. These levels will allow the number of the total required simulation runs to remain in a feasible execution level and thus to be able to employ full factorial set-up of experiments.

Table 5.1: Factor-level of The Experiment

Levels	**Factors for the experimental set-up**	
	Number of initially released parts	*Number of buffers in the system*
1	3	3
2	8	4
3	12	5

The first level of the *Number of initially released parts* factor is set to three since it is required to have a lineup of jobs, needed to be processed in the system to be able to see the effect of the dispatching rules. Furthermore, upon constructing the simulation model it was discovered that a deadlock may occur in the system depending on the number of buffers in the system and the number of initially released parts. It was discovered that the maximum number of parts released should not exceed the number of available buffers plus nine. Under these circumstances, the minimum number of buffers is set at three and consequently the maximum number of released parts as twelve. This level of maximum number of parts released also helps to keep each real production run in a manageable time frame. The second level of part release is chosen to be a number between the first and last level (8).

The *number of buffers in the system* factor also has three levels. The first level is chosen to be three, as discussed above. Furthermore, since the main workstation under study in the existing system is the CNC and since this workstation has four buffers, the second level of buffers is set to four. The maximum level of this factor is set at five.

Since the study uses two factors with three levels of severity along with 3 different scheduling dispatching rules, a 3 x 3 x 3 = 27 full factorial D.O.E. set-up (Equation 4.1) is formulated to evaluate the performance of the system under study. The combination of factor levels can be provided by any of the available commercial statistical software packages since it is essential to run a complete randomized experimental design. Randomization is important in any experimental design when it is uncertain that every major influence on the system has been included in the experiment. Even when all major influences have been identified and included in the experiment, unplanned complications can bias the results of an experiment. Thus, when comparisons are made among levels of a factor, randomization will tend to cancel the bias effect and the true factor effect will remain. [43] The set-up of the runs is presented in Table 5.2.

To analyze the significance of the output of the D.O.E., analysis of variance (ANOVA) is conducted. In order to be able to perform an ANOVA analysis, at least two replications of each experiment are required, however to obtain more reliable values of the performance metrics, more replications are required. Kelton and Low [44] and Schmeiser [45] recommend ten replications, which was used in this study as well. Thus, for each dispatching rule and all the factor-level combinations, a single simulation run is replicated 10 times in the simulation model. Hence the number of total experiment treatments will amount to 270 (27 conditions * 10 experiment replications).

Table 5.2: Set-up of the Experimental Design Runs

RUN No.	Dispatching Rule	Number of initially released parts	Number of buffers in the system
1	FIFO	3	3
2	FIFO	3	4
3	FIFO	3	5
4	FIFO	8	3
5	FIFO	8	4
6	FIFO	8	5
7	FIFO	12	3
8	FIFO	12	4
9	FIFO	12	5
10	EDD	3	3
11	EDD	3	4
12	EDD	3	5
13	EDD	8	3
14	EDD	8	4
15	EDD	8	5
16	EDD	12	3
17	EDD	12	4
18	EDD	12	5
19	SPT	3	3
20	SPT	3	4
21	SPT	3	5
22	SPT	8	3
23	SPT	8	4
24	SPT	8	5
25	SPT	12	3
26	SPT	12	4
27	SPT	12	5

5.3. Production Batch Size

The number of produced parts for each production cycle run is 12 jobs. Each production batch contains different part types. In this study, each production run consisted of three different part types. In order to be able to use the EDD based dispatching rule it is necessary to have different parts with different due dates in each production cycle so that when the EDD dispatching rule is selected as the priority rule, it gives the priority to a part having the earliest due date.

5.4. Characteristics of the System

In this study, the existing FMS is regarded as a flow shop. However, several features which differentiate this system from the "standard" flow shop, as studied by Conway [7, 26, 29] and other researchers [8, 32,33, 34] are:

1. Job inter-arrival time: The arrival of new parts to the system (release of additional part from the AS/RS) is set in terms of the progress of jobs in the system and not base on some form of time distribution. An additional part is released when the previous part exits the system or reaches a certain stage in the production process. This method is unlike the other research studies where the arrival of a new part is based on a certain time interval and usually treated as a system input parameter.
2. System work load: By defining the Initial Quantity of the released parts to the system in the manufacturing order form in the OpenCIM control software, the number of parts to be released from the AS/RS when production begins is defined. This is the only variable that can be used to manipulate the system work load. Thus the increase or decrease in the system utilization is set by the number of initial parts released into the system. It should be noted that as the simulation runs showed, the maximum number of parts that can be released to the system without creating a deadlock for the system is less than 19. Thus this variable is set between the minimum of 3 (in order to have a queue of parts waiting to be processed in the system) and 18. Consequently there is no possibility to set the work load of the system to a predetermined percentage like other research studies.

5.5. Assumptions

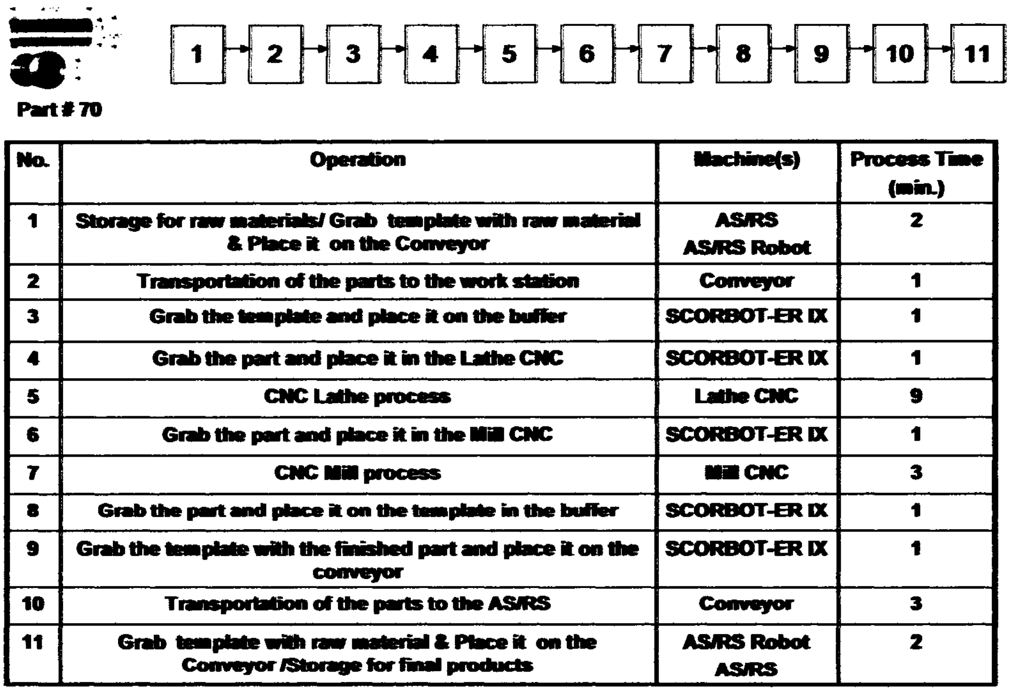
The following assumptions for the setup of the experiments for the existing CIM system are considered:

1. All the operations will be performed based on the designed G-Code program where operation times at the CNC stations are fixed.
2. The time required for tool changes is considered negligible with the help of an automatic tool changer (ATC).
3. Due dates for each part type in each order are known.
4. All the raw materials are available at the beginning of each production cycle and thus there are no inter-arrival times for raw materials.
5. The raw material is the same for every product and comes in as cylinder type plastics.
6. Priority ordering of parts is equal and is set to one (the highest priority).
7. Once an operation has begun, it should be completed before starting the next operation (the processing of only one operation on a given machine at a given instant is allowed).
8. The resource requirements are predetermined and there are no alternatives.
9. No machine breakdowns or tool failures are considered in order to simplify the problem.
10. The study does not include preventing blocking situations. However this effect may occur in the course of the experiment.

5.6. Experimental Conditions

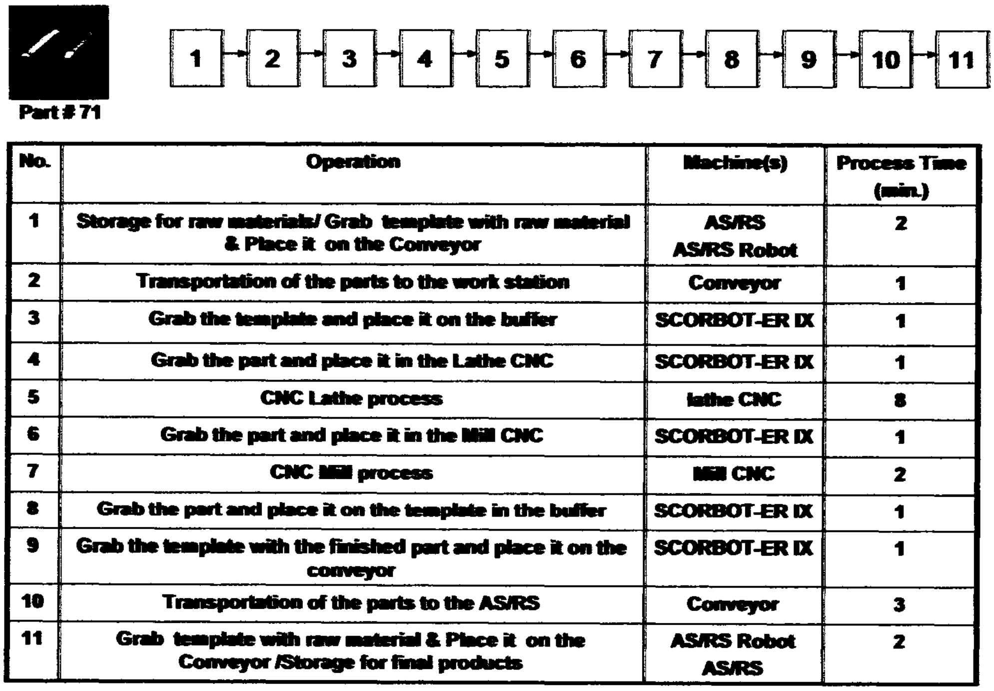
5.6.1. Parts to be Produced

Three part types are produced in this system and their processing sequence is such that each job has two operations and each operation is done by a different machine. Processing time for each operation is assumed to be between two to ten minutes. Each of the part types follows a similar processing route as illustrated in the following figures and each production batch consists of equal numbers of each part.



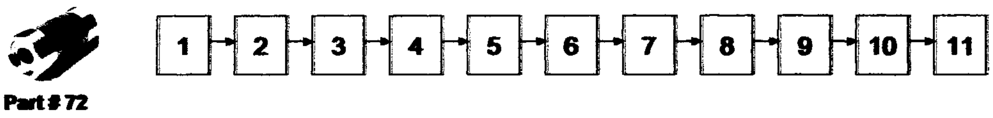
No.	Operation	Machine(s)	Process Time (min.)
1	Storage for raw materials/ Grab template with raw material & Place it on the Conveyor	AS/RS AS/RS Robot	2
2	Transportation of the parts to the work station	Conveyor	1
3	Grab the template and place it on the buffer	SCORBOT-ER IX	1
4	Grab the part and place it in the Lathe CNC	SCORBOT-ER IX	1
5	CNC Lathe process	Lathe CNC	9
6	Grab the part and place it in the Mill CNC	SCORBOT-ER IX	1
7	CNC Mill process	Mill CNC	3
8	Grab the part and place it on the template in the buffer	SCORBOT-ER IX	1
9	Grab the template with the finished part and place it on the conveyor	SCORBOT-ER IX	1
10	Transportation of the parts to the AS/RS	Conveyor	3
11	Grab template with raw material & Place it on the Conveyor /Storage for final products	AS/RS Robot AS/RS	2

Figure 5.1: Part #70's Processing Route



No.	Operation	Machine(s)	Process Time (min.)
1	Storage for raw materials/ Grab template with raw material & Place it on the Conveyor	AS/RS AS/RS Robot	2
2	Transportation of the parts to the work station	Conveyor	1
3	Grab the template and place it on the buffer	SCORBOT-ER IX	1
4	Grab the part and place it in the Lathe CNC	SCORBOT-ER IX	1
5	CNC Lathe process	lathe CNC	8
6	Grab the part and place it in the Mill CNC	SCORBOT-ER IX	1
7	CNC Mill process	Mill CNC	2
8	Grab the part and place it on the template in the buffer	SCORBOT-ER IX	1
9	Grab the template with the finished part and place it on the conveyor	SCORBOT-ER IX	1
10	Transportation of the parts to the AS/RS	Conveyor	3
11	Grab template with raw material & Place it on the Conveyor /Storage for final products	AS/RS Robot AS/RS	2

Figure 5.2: Part #71's Processing Route



No.	Operation	Machine(s)	Process Time (min.)
1	Storage for raw materials/ Grab template with raw material & Place it on the Conveyor	AS/RS AS/RS Robot	2
2	Transportation of the parts to the work station	Conveyor	1
3	Grab the template and place it on the buffer	SCORBOT-ER IX	1
4	Grab the part and place it in the Mill CNC	SCORBOT-ER IX	1
5	CNC Mill process	Mill CNC	3.5
6	Grab the part and place it in the Lathe CNC	SCORBOT-ER IX	1
7	CNC Lathe process	Lathe CNC	10
8	Grab the part and place it on the template in the buffer	SCORBOT-ER IX	1
9	Grab the template with the finished part and place it on the conveyor	SCORBOT-ER IX	1
10	Transportation of the parts to the AS/RS	Conveyor	3
11	Grab template with raw material & Place it on the Conveyor /Storage for final products	AS/RS Robot AS/RS	2

Figure 5.3: Part #72's Processing Route

5.6.2. Due Date Setting

Due dates can be set either externally or internally. When due dates are set externally, the scheduling system function is to arrange and prioritize the production plan to accommodate the predefined date. Internally set due dates, however, drive from the production load, manufacturing capacity and type of jobs being produced in the system. In the existing system the due dates are considered to be set externally and thus the production plan is arranged to meet the deadline.

Furthermore, in order to be able to use the due date based scheduling dispatching rule (EDD), it is essential to have different due dates for different part types in each production run cycle. Therefore, the following table will be used as the production order reference for each production run.

Table 5.3: Production Order for Production Runs

Order No.	*Part Type*	*Order Date*	*Due Date Priority*
1	70	1	3
2	71	1	2
3	72	1	4

This due date arrangement will be the same for all experimental run settings.

5.6.3. Transportation Time

It can be expected that the utilization of machines is relatively low due to the fact that the total expected transportation time is rather significant compared to the total expected processing time for parts. The following table shows the approximate transportation times between workstations in the existing FMS.

Table 5.4: Transportation Time Between Work Stations

Location	*Next Location*	
	WS1: AS/RS*	*WS2*: CNCs*
WS1: AS/RS	0 min	1 min
WS2: CNCs	3 min	0 min

*Work station 1

**Work station 2

5.7. The Performance Measures

The effectiveness of the dispatching rules can be compared using the system on the basis of performance criteria. In general, the following performance criteria have been observed in the existing literature in this field: criteria based on due date, criteria based on flow time, criteria based on in-process parts. The performance measures used in the current experiment are outlined as follows [42]:

Total Run Time: The time period of the manufacturing cycle.

Machine Efficiency: The efficiency of each machine in the system. It is defined as the total process time divided by the total manufacturing time of the machine.

Average Flow Time: The average time that it takes to manufacture a product.

5.8. Summary

In this chapter the Design of Experiments and its formulation is reviewed. As it was indicated, Design of Experiments is an experimentation method adopted to identify the significance of the used factors on the performance of the system under study. The experiments are performed by measuring the performance measures of the system under study, while changing the values of other factors in the system. Consequently, the main design factors for this study indicated along with the factor's level, full factorial set-up, characteristics of the system under study and assumptions used for the setup of the experiments. Furthermore, the method of due date setting, the number of part types and their processing sequence, the transportation time among workstations and adopted performance measures were described.

6. THE SIMULATION MODEL

6.1. Introduction

The complex interaction of modern production and manufacturing systems on the one hand and the high capital costs on the other hand requires good system performance to justify their use. Modeling and analysis are important tools to achieve these goals, however the complexity of modern production systems makes the use of analytical tools more difficult, thus discrete-event simulation remains a tool that is used extensively to analyze and improve manufacturing systems' performance.

There are two main types of simulation, *terminating* and *steady*-state [46, 47]. In the *terminating* simulation the model specifies the starting and stopping conditions of each run based on the behavior of the target system and the way it operates. A *steady-state* simulation, on the other hand, is one in which the outputs of the simulation are estimated in the long run. In this case, the initial conditions for the simulation do not matter where normally a warm-up period is defined to eliminate the effect of the starting condition on the output results.

This study simulate the existing FMS where we have a limited production capacity, therefore terminating simulation method is used. The simulation carried out using Arena software.

6.2. Model Overview

Raw materials are stored in the AS/RS station. Upon start of the production cycle, according to the initial part release number setup, raw material parts are taken from the AS/RS and put on the conveyor's pallet by way of the AS/RS serving robot. The conveyor then delivers the raw material to workstation 1. The parts are now taken from the conveyor and put on the workstation 1 buffer by the robot serving that station. The raw material is then selected from the queue, based on the selected dispatching rule to be processed at the CNC Lathe. Upon completion of this operation, the partially finished parts are moved to the CNC Mill for the final machining operation. The robot now puts the finished product back on the workstation 1 buffer. Finally the robot places the finished product on a pallet and the conveyor delivers it back to the AS/RS station for final storage. A diagrammatic representation of these tasks is presented in the following figure:

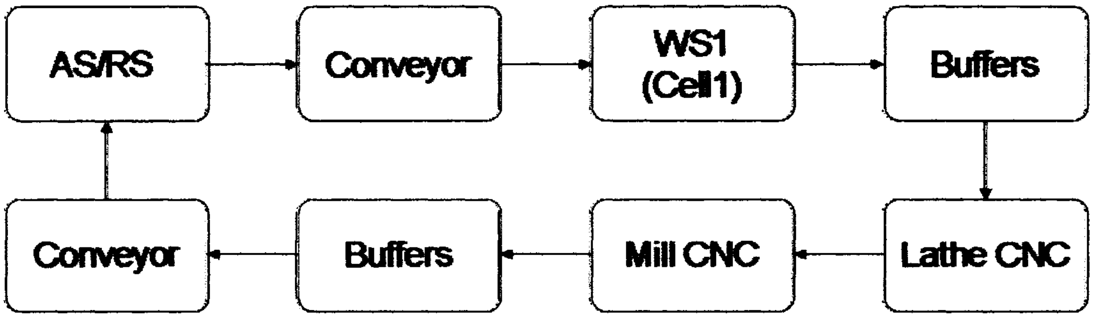


Figure 6.1: Part Flow in the System

A detailed description of the components is given in the following section.

6.3. Detailed Model Description

6.3.1. The AS/RS Station

The load/unload station (AS/RS) is the entrance and exit of the simulation model. Figure 6.2 shows the block diagram of AS/RS station. At the beginning entities are created which represent the parts in the system. The Create module is used to generate arrivals of raw material starting at time zero of the simulation run. Three separate Create modules exist in the AS/RS, each representing one part type and each creates an equal number of entities.

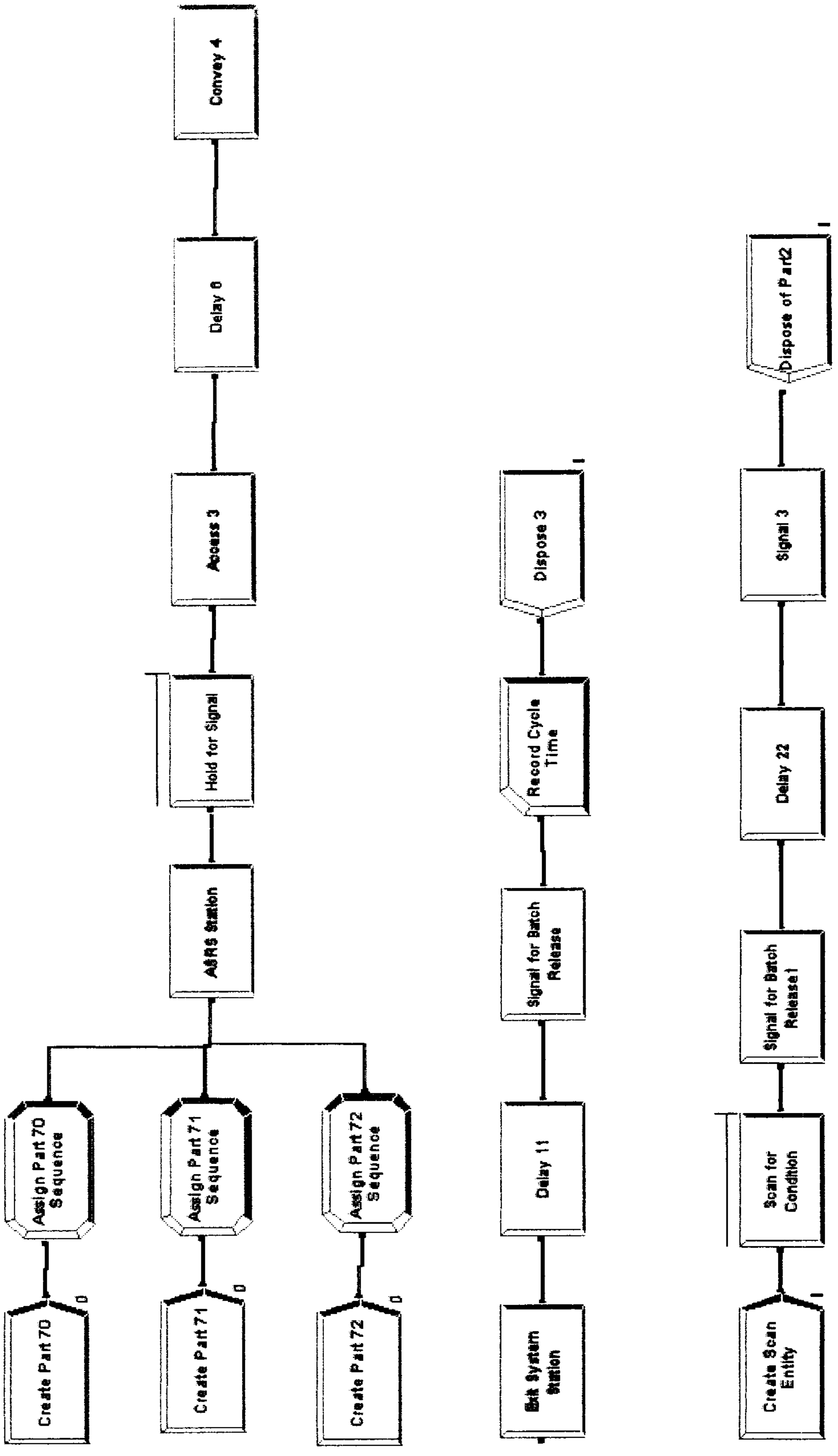


Figure 6.2: AS/RS Station and Scan Entity

Once created, an entity is sent to an Assign module where five assignments are made. The first is to assign the part index to the entity. The part index not only allows to refer to the part type based on the defined part types in the Set data module, but it also allows to refer to the previously defined Part Sequences in the Sequence data module so that the proper sequence will be associated with each part type.

The second assignment is to associate a sequence name with each arriving entity. The assigned sequence names are the same as the ones used in the Sequence data module enabling the part types to get the information of the proper process plan table.

The third assignment is to record the arrival time, the current simulation time, for later data collection.

The fourth assignment is to associate a Process Time period to each arriving entity. This Process time will be used later in the model to decide which part in the queue should be released first in case of SPT dispatching rule.

The fifth assignment is the due date of the entity, which is assumed to be equal for all the entities of the same type.

After the Assign module, entities go to the AS/RS station, which represents just one location in the model. The arriving items are then sent to the Hold module. The Hold module holds entities until a matching signal is received from elsewhere in the model. When a matching signal is received, the Hold module releases up to a maximum number of entities based on the specified limit, unless the signal contains additional limit information. As arriving items do not cause a signal to be sent, some other mechanism must be put into the model to cause the start of the first operation.

The Create Scan Entity Create module is used to initiate the first operation in the simulation model. The Create Scan Entity Create module, releases only a single entity at time 0. This entity is sent directly to the Hold module that follows. The Scan for Condition Hold module allows holding an entity until the defined condition is true; at that time, the entity is allowed to depart the module.

The waiting entities are held in an internal queue during the waiting period. Nothing happens until the Hold for signal queue has items equal to the value of the initial release variable. At that time, the entity is released from the Scan for Condition Hold module and is sent to the signal module. This module broadcasts a signal across the whole model, which causes the entities in the Hold for signal queue, up to a maximum Batch Size, to be released. This entity then enters a delay module where it waits for three minutes and then the entity is sent to the next signal module to allow the first waiting part at the buffer station to be released and finally it is disposed.

The released entities from the Hold for signal queue will enter the Access module to gain access to the conveyor. Once they gain access to the conveyor they endure a loading delay and finally they are conveyed to the next location in the system based on their process plan. The accumulating conveyor method is used in simulating the conveyor since upon arrival of a pallet at a station for loading or unloading, other pallets keep moving until they are block by the pallet at the station. Upon completion of their processes, entities will return to the AS/RS station (named as Exit System Station) by way of the conveyor. Once they enter the station they endure unloading delay, then signal for the release of the next part to the system, record the required time and are finally disposed.

6.3.2. Workstation 1 Conveyor Station and Buffer

Figure 6.3 shows a diagram of the workstation1 conveyor station and buffer. The conveyed entities from the AS/RS station enter the Cell 1 station where they go through a decide module to be identified as raw material or final product. The raw materials then request the assistance of the robot to be moved to the next location. The Robot is modeled as a resource with a capacity of one. Upon seizing the robot, a loading delay is endured, the conveyor space is released and the part is routed to the next location in the system according to its process plan (Buffer Station). The routed parts enter the buffer station where they endure unloading delay and then release the robot resource and enter the buffer queue. When there are a number of entities in a queue waiting for a particular and similar resource, the factor that determines which entity in the queue gets the resource first is the queue ranking rule (or dispatching rule) used to order the entities. Arena provides four ranking options: First In, First Out (FIFO); Last In, First Out (LIFO); Low Value First; and High Value First. The FIFO, ranks the entities in the order that they entered the queue. The last two rules rank the queue based on attributes of the entities in the queue.

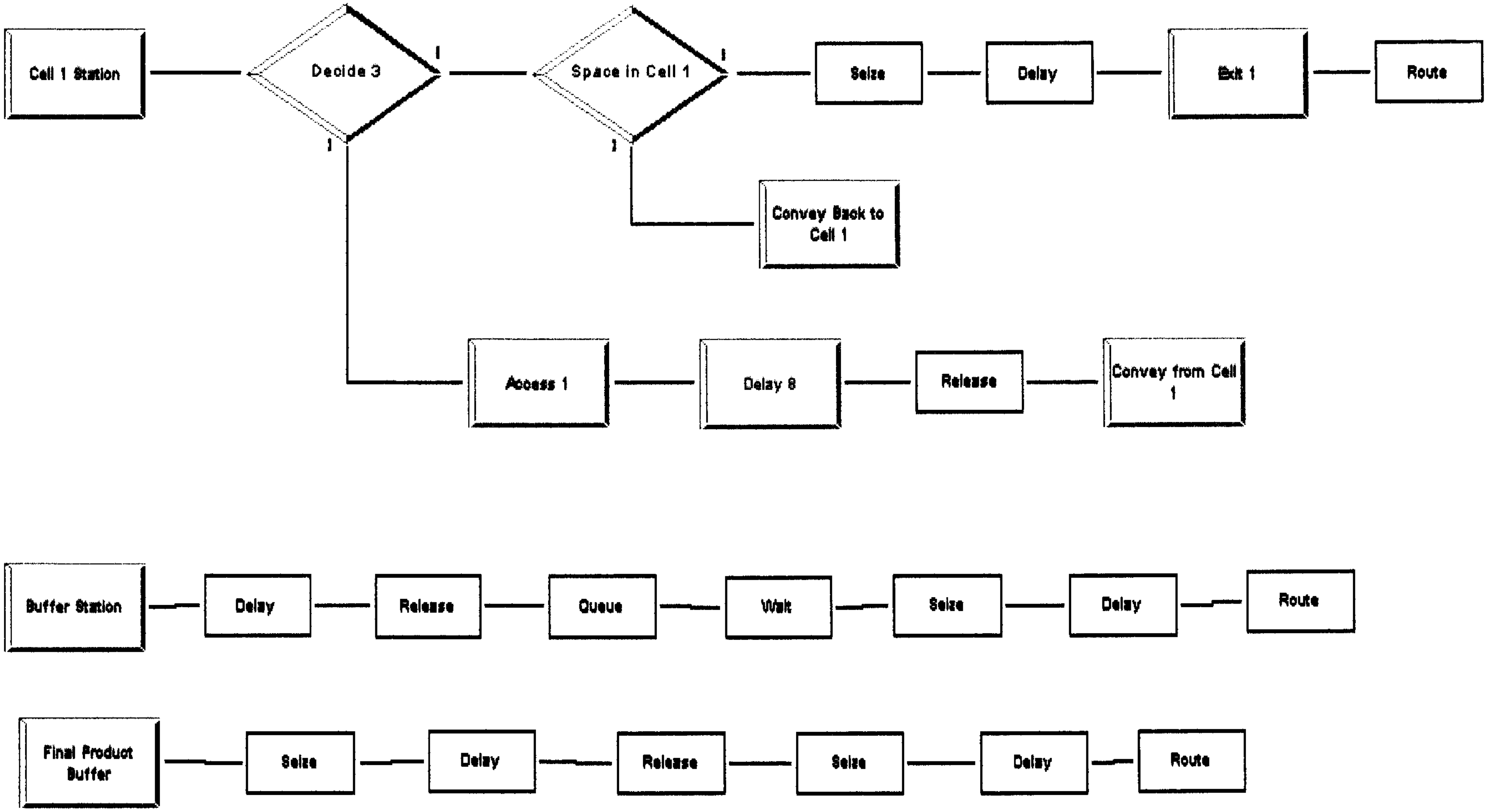


Figure 6.3: Workstation 1 Conveyor Station and Buffer

In this experiment, as each entity arrives in the system, a due date is assigned to an attribute of that entity. By selecting Low Value First based on the due-date attribute, the EDD dispatching rule is defined. As each successive entity arrives in the queue, it is placed in position based on increasing due dates. The same principle is used for the SPT dispatching rule where the Low Value First is used as the queue's ranking option based on the entity's Process Time attribute.

The capacity of buffer queue is defined by the variable *Buffer*. This variable is set at the beginning of each simulation run according to the set-up of the experimental design runs (see Table 5.2). Queued parts wait for the proper signal to be released from the queue according to the defined priority rule in the queue. The initial signal is set by the scanning entity described earlier. Upon receiving the proper signal, the released entity acquires the assistance of the robot, endures the loading delay and is routed to the next destination according to its production plan.

Finished products return to the buffer station and go through the same process as described for the raw material with two major differences. The first difference is the fact that the finished products do not need to wait for a proper signal and they should exit the buffer as soon as possible. The second difference is based on the fact that a separate buffer location is assigned for the final product, yet the buffer is modeled as a resource with the capacity of one and not as a queue. The final product should release this buffer resource before it exit the station. The reason for this difference is twofold. Since there is only once material handling resource available at Cell 1 it is very possible to encounter a deadlock. For this reason the system is modeled based on the Pull strategy, where the final product has the highest priority and entering raw material the lowest priority to receive the robot service. The logic behind this strategy is driven from the fact that since the model is a flow shop there is only one final part that is waiting to exit Cell 1 but there are number of raw materials in the queue waiting to be processed.

After exiting the buffer station, final products return to the cell 1 station and would choose the alternative path in the decide block where they obtain the access to the conveyor, endure the unload delay, release the robot and are conveyed back to the AS/RS station.

6.3.3. CNC Lathe and CNC Mill

The final set of block diagrams describes the CNC Lathe and CNC Mill processes in the model (Figure 6.4). The entities normally follow a "seize-hold-release" pattern once they seek the service of a processing unit. The operation is represented by a resource with certain capacity which should be seized before receiving the required operation. Upon seizing the resource, it will be held for processing based on the specified process time and then it will be released. The time needed for the processing operation is represented by a triangular distribution in the model.

Each machine may have different states, including *busy (processing)*, *idle (starved)* and *blocked*. A processing unit is blocked if, after the completion of the current operation, it is unable to pass the part to the next block which may be due to unavailability of the required resource or of the material transporter unit. The following block could be unavailable because it is currently serving another entity or its capacity is reached. In this case the current block must remain idle while it waits for the downstream resource. On the other hand, a current block is starved if an upstream block is currently serving another entity. In other words, even if operational, a starved station will become idle.

In this research, of particular interest are the blocking and starvation effects, because they are dependent on the buffers and the material handling systems which have a great significance on the performance of the system. Consequently, the capacity of the buffers and material handling systems can be considered as important design factors where a large capacity may increases the in-process inventories and a small capacity may cause the upstream processes to be blocked.

After exiting the buffer station, raw material enters the CNC Lathe station where it is delayed for unloading, releases the robot and seizes the CNC resource. Having seized the resource, it exits the Seize module and enters the following Assign module where it sets the CNC resource state to Processing, and then undergoes the processing delay. After processing, the CNC resource state is assigned to Blocked since at this point, it is not certain that there is room in the buffer at the buffer station. These assignments are necessary to collect the required data about the performance of the CNC machines in the final simulation report.

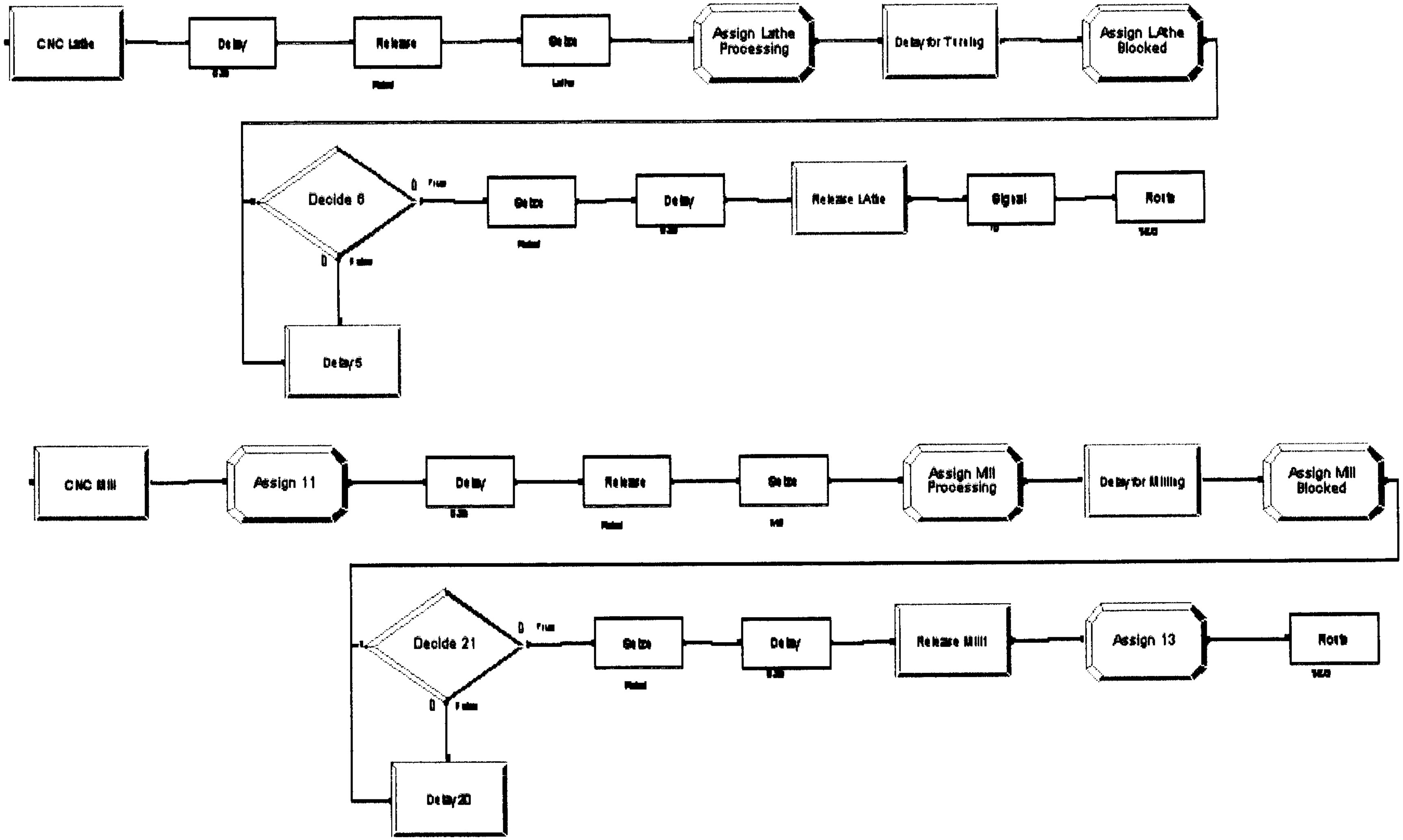


Figure 6.4: CNC Lathe and CNC Mill

After leaving the assign module, the entity enters the decide module to see if the next resource (CNC Mill) is free. If the CNC Mill is not available, the entity goes through a delay loop until the time the CNC Mill becomes free, then the part leaves the decide module.

Next, the entity enters the Seize module and requests robot assistance. Once it has the robot resource, it undergoes a loading delay, releases the CNC Lathe resource, sends the signal to show that the CNC Lathe is available and thus the next part in the buffer queue can be released to gain access of this resource. Finally, the entity departs from the CNC Lathe station to the next destination (CNC Mill) according to its process plan.

The CNC Mill Block diagram is similar to the CNC Lathe with two minor differences. Unlike the CNC Lathe, after arriving at the CNC Mill station, the entity goes into an assign module where it assigns the value of the global variable "Mill Busy" to one. This is the value that is being checked by the part in the CNC Lathe decide module to see if the CNC Mill is busy. Upon leaving the CNC Mill, the entity assigns the value of this variable back to zero indicating the availability of this resource. In the decide module the entity checks the availability of the final product buffer resource. If the resource is not available, the entity goes through a delay loop until the time that resource becomes free, then the part leaves the decide module. The finished product then goes to the next destination (final product buffer).

6.4. Model Verification and Validation

Once a working model is created, it should be verified and then validated. Verification is to ensure that the model behaves as intended. Verification essentially is debugging the model in such a way that it would run to completion without having logical or syntax errors. Validation on the other hand is to ensure that the model behaves the same as the real system which is quite different in nature. The most common sources of problem in this respect are wrong assumptions, wrong input data, over-simplification of the system and limitation of the software.

Initially, the verification of the model was conducted by way of using the "Highlight Active Module" animation option in the Arena software. In this regard the following observations were made to ensure the correct behavior of the created model:

– the number of entities entering and exiting the system,

– the queues and the number of entities in them, especially the buffer queue,

– the machines' status, and

– the simulation run time.

For validation of the model, the real FMS was setup to run with one part type, an initial part release of three, four buffers and SPT as selected dispatching rule with five replications. The full results are presented appendix B. Next, the simulation model was run under the same conditions. The results of these simulations are shown in table 6.1.

Table 6.1 Results from One of the Simulation Model Runs

	Factor 1	Factor 2	Factor 3	Response 1	Response 2	Response 4	Response 5
Run	A: Dispatching Rule	B: Initial Part Release	C: Buffer	Total Run Time	Maximum Queue Length	Machine Efficiency	Mean Flow Time
	name	Number	Number	Min	Number	%	Min
1	SPT	3	4	174.44	2	50.03	101.68
2	SPT	3	4	171.53	2	50.05	99.830
3	SPT	3	4	172.76	2	49.46	100.71
4	SPT	3	4	176.62	2	49.49	102.75
5	SPT	3	4	169.35	2	49.46	99.386

The next table shows the comparison of the total run time and machine efficiency of the real system and simulation runs:

Table 6.2: Comparative Results from Real System and Simulation Runs

Run #	Total Run Time (Min)		Machine Efficiency (%)	
	Real	Simulation	Real	Simulation
1	171	174	50.76	50.03
2	179	172	49.17	50.05
3	171	173	49.89	49.46
4	168	177	50.17	49.49
5	175	169	50.01	49.46
Average	173	173	50.00	49.70

As can be seen the simulation model results agree with the real system runs.

6.5. Model Results

Dispatching rule, number of initial parts released and number of buffers are variables in the main study. As explained in chapter five, a total of 270 runs are made. Table 6.3 shows the first 15 simulation runs. Column one marks the related order number in the standard 270 factor-level setup where these factor-level setup runs are randomized by the D.O.E. software. For example, the fist simulation run made (column 2) is standard 251 (column 1), which has a setup of EDD as the dispatching rule, 12 as the number of initially released parts and 5 buffers. The simulation model calculates the total run time, maximum queue length, production cost, machine efficiency and means flow time. The results of all 270 simulation runs are presented in appendix C. The results of the simulation runs for total run time, machine efficiency and mean flow time are analyzed further in the following chapter.

Table 6.3 Partial Results from the Main Simulation Model Runs

		Factor 1	Factor 2	Factor 3	Response 1	Response 2	Response 3	Response 4	Response 5
Std	Run	A: Dispatching Rule	B: Initial Part Release	C: Buffer	Total Run Time	Maximum Queue Length	Production Cost	Machine Efficiency	Mean Flow Time
		name	Number	Number	Min	Number	$	%	min
251	1	EDD	12	5	161.2	5	80.6	51.05	91.530
249	2	FIFO	12	5	159.88	5	79.94	51.06	94.499
77	3	EDD	12	3	161.22	3	80.61	52.69	92.854
176	4	SPT	12	4	161.38	4	80.69	50.55	93.091
181	5	FIFO	3	5	162.13	2	81.07	50.92	94.813
32	6	FIFO	8	3	158.43	3	79.21	51.68	94.719
209	7	SPT	3	5	162.4	2	81.2	49.71	93.858
240	8	SPT	8	5	160.56	5	80.28	50.91	91.698
22	9	SPT	3	3	161.07	2	80.53	50.26	94.833
179	10	SPT	12	4	161.64	4	80.82	50.35	91.941
21	11	SPT	3	3	164.74	2	82.37	50.28	95.233
35	12	FIFO	8	3	157.24	3	78.62	51.31	92.494
242	13	FIFO	12	5	158.73	5	79.36	50.93	91.906
151	14	FIFO	12	4	159.7	4	79.85	52.46	95.068
264	15	SPT	12	5	163.74	5	81.87	50.63	93.420

7. STATISTICAL ANALYSIS METHOD AND ANALYSIS OF RESULTS

7.1. Statistical Analysis of Terminating System

The simulation study used for the experiments in this study is a terminating system simulation, since the manufacturing system has low volume production capacity for each run cycle due to the limited storage capacity of the AS/RS. After completion of each production batch, the system should be stopped, the final product collected from AS/RS and new raw materials placed for the next production cycle. The significance of the experimental design alternatives is interpreted by way of statistical analysis [43, 47, 49] which is explained in the following.

7.1.1. Basic Definitions

A main purpose of the statistical analysis is to understand the characteristics of collected data (in the case of this study, the performance measures). For this purpose, two measures are usually used; the mean, the variance, the coefficient of variation are described in the following formulas:

Assuming that the number of replication is *n*, the mean of the collected data for each design set is:

$$\bar{y} = \sum_{j=1}^{n} y_j / n \qquad (7.1)$$

Also, the related variance for each design factors set is calculated as follows:

$$S^2 = \sum_{j=1}^{n} (y_j - \bar{y})^2 / (n-1) \qquad (7.2)$$

The coefficient of variation (C.V.), the standard deviation expressed as a percentage of the mean is calculated as follows:

$$C.V. = (S / \bar{y}) \times 100\% \qquad (7.3)$$

The confidence interval *(β)* is determined as follows.

$$\beta\% = \bar{y} \pm c_{(k,\beta)} \times \left(\frac{s^2}{n} \right)^{1/2} \qquad (7.4)$$

where $\bar{y}$ is the mean, S^2 is the variance and $c_{(k,\beta)}$ is a value depending on the degrees of freedom (k=n-1) and on the level of confidence interval *(β)* (*β* is taken as 95% in this research); these values can be found from the *t*-tables.

7.1.2. The Hypothesis Testing

To ensure the statistical validity of the collected data (from the simulation experiments) for the statistical analyses, hypothesis testing is used. Hypothesis testing is based on establishment of a null hypothesis and search for its either acceptance or rejection. Upon its acceptance, it can be concluded that the simulation model is valid. If it is rejected, then the model is invalid. In this study, an *F*-test Hypothesis testing is conducted. The details of these tests are described in the following:

The *F*-Test: Comparing Variances

The *F*-test is conducted for comparing model variance with residual (error) variance. This is done by calculating the ratio of the Model Mean Square divided by Residual Mean Square. If the variances are close to the same, the ratio will be close to one and it is less likely that any of the factors have a significant effect on the response. This ratio is then compared to a critical *F* value at a selected level of statistical significance (5% since selected *β* is 95%) based on the degrees of freedom of the larger sample variance as the numerator and the degrees of freedom of the smaller sample variance as the denominator. These values can be found from the *F*-tables. Small probability values call for rejection of the null hypothesis.

Null hypothesis (H_0):

$S_M^2 = S_m^2$ (variances are equal)

where

S_M^2 the variance of the model.

S_m^2 the variance of the residual.

Alternative hypothesis (H_1):

$S_M^2 \neq S_m^2$ (variances are not equal)

The value of the observed F-test is calculated according to the following formula:

$$F = \frac{S_M^2}{S_m^2} \tag{7.5}$$

The null hypothesis is rejected if the F value of the test statistic (observed) exceeds the critical value:

$$F\,(\text{observed}) > F\,(\text{critical}) \tag{7.6}$$

Under that condition, the assumption that the variability of the collected data is the same in all sets is not satisfied.

Alternatively, it is possible to compare the F value with the p-value. The p-value is the probability value that is associated with the F value, which is the probability of getting an F Value of the calculated size if the factor under consideration did not have an effect on the response. Small probability values call for rejection of the null hypothesis. The probability equals the proportion of the area under the curve of the F-distribution that lies beyond the observed F value. In general, a term that has a probability value less than 0.05 would be considered a significant effect. Normally, a probability value greater than 0.10, is not significant.

7.1.3. Calculation of Effects

Analysis of variance (ANOVA) is based on a ratio of the variance between different alternative data sets divided by the variance within the different alternative data sets. When the ratio is large, it indicates that one or more of the alternatives is influencing the output of the design and thus they are significant factors. ANOVA is also used to identify the interactions effect between factors. That is the combed effects of two or more factors on the output. However, interactions between more than two factors are assumed to be negligible in this research. The formulation of the analysis of variance for a three factor levels factorial experiment is presented in the following table considering *a* levels of factor *A*, *b* levels of factor *B*, c levels of factor C and *n* replicates [43]:

Table 7.1: The Analysis of Variance Table for the Three-Factor Model

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0
A	SS_A	$a-1$	MS_A	$F_0 = \frac{MS_A}{MS_E}$
B	SS_B	$b-1$	MS_B	$F_0 = \frac{MS_B}{MS_E}$
C	SS_C	$c-1$	MS_C	$F_0 = \frac{MS_E}{MS_E}$
AB	SS_{AB}	$(a-1)(b-1)$	MS_{AB}	$F_0 = \frac{MS_{AB}}{MS_E}$
AC	SS_{AC}	$(a-1)(c-1)$	MS_{AC}	$F_0 = \frac{MS_{AC}}{MS_E}$
BC	SS_{BC}	$(b-1)(c-1)$	MS_{BC}	$F_0 = \frac{MS_{BC}}{MS_E}$
Error	SS_E	$abc(n-1)$	MS_E	
Total	SS_T	$abcn-1$		

The analysis of variance computations are done using a statistics *Design of Experiment* software package. However, the formulas for the sums of squares are introduced in the following [43]:

The total sum of squares is calculated by the following formula

$$SS_T = \sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{c}\sum_{l=1}^{n} y_{ijkl}^2 - \frac{y_{....}^2}{abcn} \qquad (7.7)$$

The sums of squares for the main effects are formulated as follows:

$$SS_A = \frac{1}{bcn}\sum_{i=1}^{a} y_{i...}^2 - \frac{y_{....}^2}{abcn} \qquad (7.8)$$

$$SS_B = \frac{1}{acn}\sum_{j=1}^{b} y_{.j..}^2 - \frac{y_{....}^2}{abcn} \qquad (7.9)$$

$$SS_C = \frac{1}{abn}\sum_{k=1}^{c} y_{..k.}^2 - \frac{y_{....}^2}{abcn} \qquad (7.10)$$

Finally, the sums of squares of two-factor interaction are calculated as:

$$SS_{AB} = \frac{1}{cn}\sum_{i=1}^{a}\sum_{j=1}^{b} y_{ij..}^2 - \frac{y_{....}^2}{abcn} - SS_A - SS_B \qquad (7.11)$$

$$SS_{AC} = \frac{1}{bn}\sum_{i=1}^{a}\sum_{k=1}^{c} y_{i.k.}^2 - \frac{y_{....}^2}{abcn} - SS_A - SS_C \qquad (7.12)$$

$$SS_{BC} = \frac{1}{an}\sum_{j=1}^{b}\sum_{k=1}^{c} y_{.jk.}^2 - \frac{y_{....}^2}{abcn} - SS_B - SS_C \qquad (7.13)$$

7.1.4. The Residual Analysis

The use of the ANOVA analysis method requires that certain assumptions be satisfied. The validity of the results can be checked by the examination of residuals. The residual for observation j in treatment i is defined as follows:

$$e_{ijk} = y_{ijk} - \hat{y}_{ijk} \qquad (7.14)$$

$\hat{y}_{ijk}$ is an estimate of the corresponding observation y_{ij} obtained as follows:

$$\hat{y}_{ijk} = \bar{y}_{...} + (\bar{y}_{i..} - \bar{y}_{...}) = \bar{y}_{i..} \qquad (7.15)$$

Plot of Normal Probability of Residuals

The main assumption in conducting an ANOVA analysis is that the errors are normally and independently distributed with mean zero and constant but unknown variance. To check the normality assumption, a normal probability plot of the residuals can be used. If the distribution of errors is normal, the plot will form a straight line.

Plot of Residuals versus Predicted

If the model is correct and if the assumptions are satisfied, the residuals should be structured less and have no patterns. To check this, a plot of the residuals versus the predicted values' ($\hat{y}_{ij}$) plot can be used. This plot should not have any obvious pattern.

The Predicted Residual Error Sum of Squares (PRESS) is calculated as follows:

$$\text{PRESS}=\sum_{i=1}^{n}(e_{ijk})^2 \qquad (7.16)$$

This is a measure of how the model fits each point in the design. The PRESS is computed by first predicting where each point should be from a model that contains all other points except the one in question. The squared residuals (difference between actual and predicted values) are then summed.

7.2. Experimental Results and Analyses

In the following sections, the results of the conducted experiments on the performance of the selected scheduling dispatching rules on the simulation model of the existing CIM System are presented. Three performance measures, Total Run Time, Average Parts Flow Time and Average Machine Efficiency were used in the experiments. The complete Design Layout of the experiment resulted from the simulation runs are shown in the Appendix C.

ANOVA on all the collected performance measures is conducted followed by the residual analysis for model validation. Finally, plots of factors' effects and interactions presented to analyze the significance of each factor and their interactions.

7.2.1. ANOVA on Average Flow Time

Table 7.2 shows the result of ANOVA on Average Flow Time for all part types used in the experiment including the P-value of the ANOVA F-test

Table 7.2: ANOVA for the Average Flow Time

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	474.76	18	26.38	13.13	< 0.0001	significant
A-Dispatching Rule	*99.67*	*2*	*49.84*	*24.81*	*< 0.0001*	significant
B-Initial Part Release	*294.20*	*2*	*147.10*	*73.23*	*< 0.0001*	significant
C-Buffer	*18.55*	*2*	*9.28*	*4.62*	*0.0107*	significant
AB	*47.21*	*4*	*11.80*	*5.88*	*0.0002*	significant
AC	*0.61*	*4*	*0.15*	*0.075*	*0.9896*	
BC	*14.53*	*4*	*3.63*	*1.81*	*0.1278*	
Residual	504.19	251	2.01			
Lack of Fit	*0.98*	*8*	*0.12*	*0.059*	*0.9999*	*not significant*
Pure Error	*503.21*	*243*	*2.07*			
Cor Total	978.96	269				

The Model *F* value of 13.13 and a p-value of less than 0.0001 of F-test shows that the model is significant. The above table also shows the p-value of the ANOVA F-test on Average Flow Time for all experimental factors and interactions. High *F* values identify the significant factors and interactions. In this case A, B, C and AB are significant model terms. The *F* value of 4.62 indicates that there is an interaction between dispatching rule and initial part release.

Summary statistics for the model including the standard deviation associated with the experiment, overall average of all the response data (Mean), Coefficient of Variation (C.V.) and Predicted Residual Error Sum of Squares (PRESS) are presented below.

Table 7.3: Summary Statistics on Average Flow Time

Std. Dev.	1.42
Mean	93.31
C.V. %	1.52
PRESS	583.41

As was indicated previously, the main assumption in conducting an ANOVA analysis is that the errors are normally and independently distributed. To verify the ANOVA analysis and check the normality assumption, the plots of normal probability of residuals and residuals versus predicted are presented below. If the distribution of errors is normal, the normal plot of residuals should form a straight line, indicating no abnormalities.

As can be seen in the following graph, the normal plot looks OK and thus the normality assumption is satisfied.

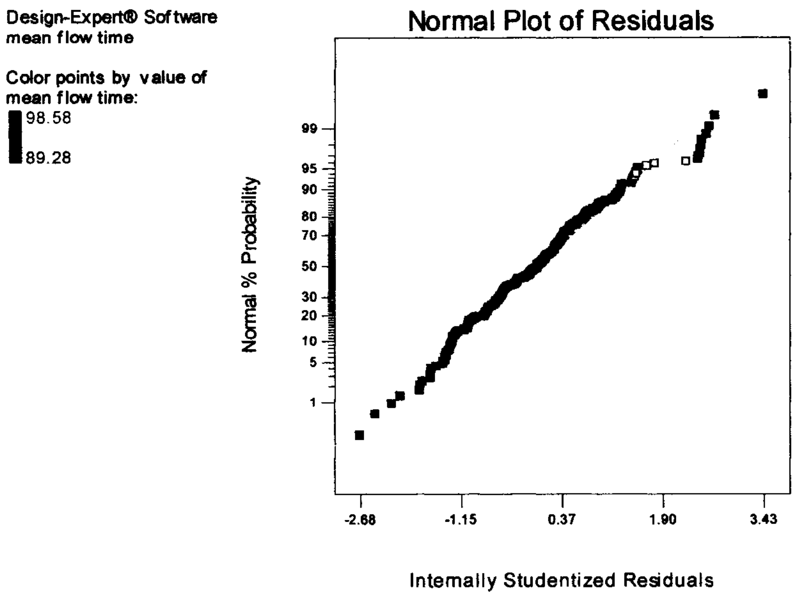


Figure 7.1.1: Average Flow Time – Normal Plot of Residuals

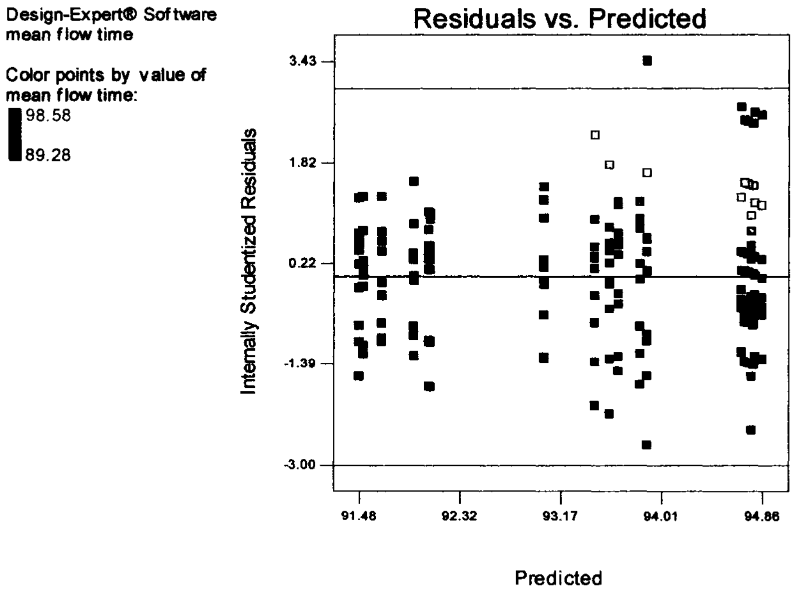


Figure 7.1.2: Average Flow Time – Residuals vs. Predicted

Figure 7.1.2 is a plot of the residuals versus the predicted response values. If the model is correct and if the constant variance assumption is satisfied, the residuals should have no patterns. It can be seen from the graph that there is no obvious pattern and thus the constant variance assumption is satisfied. Having the model validated, concluding that the residual analyses do not reveal any problems, significant factor effects should be looked at. The three graphs below show the average flow time, initial part release and dispatching rule for varying buffer sizes.

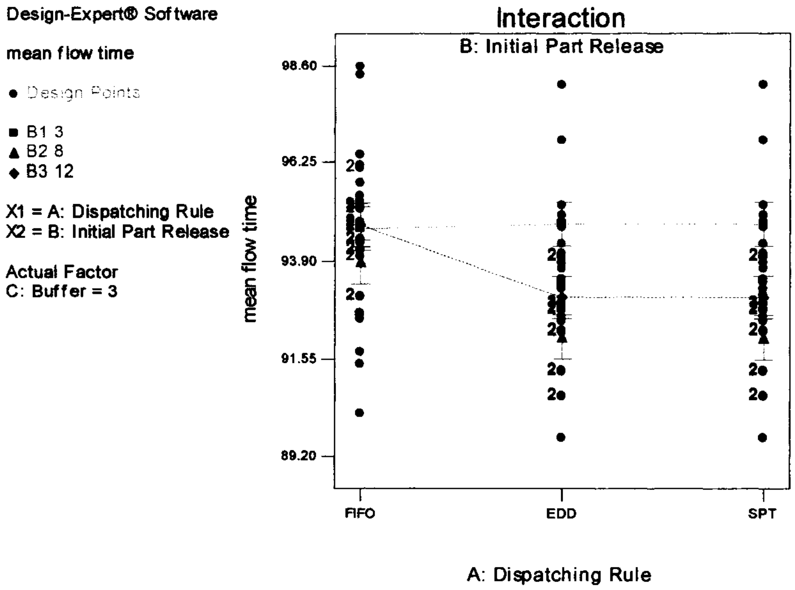


Figure 7.2.1: Average Flow Time, Initial Part Release and Dispatching Rule With Buffer Size 3

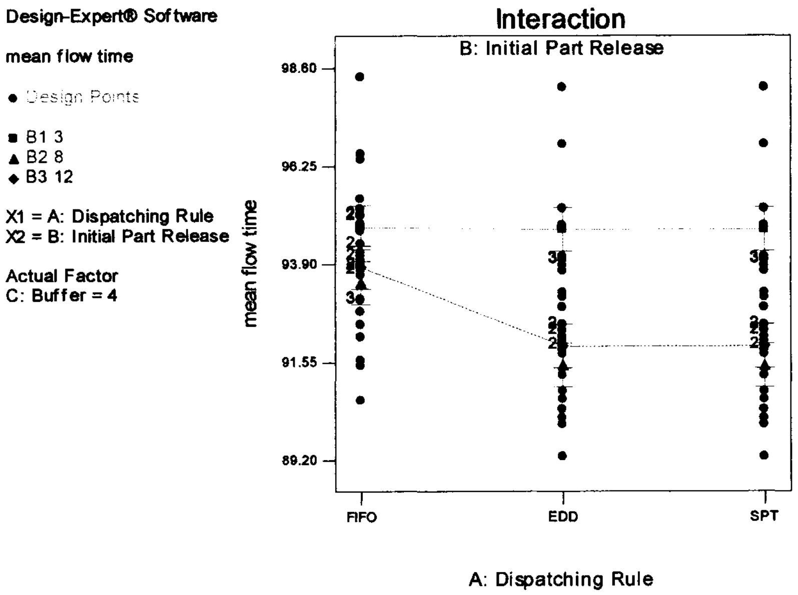


Figure 7.2.2: Average Flow Time, Initial Part Release and Dispatching Rule With Buffer Size 4

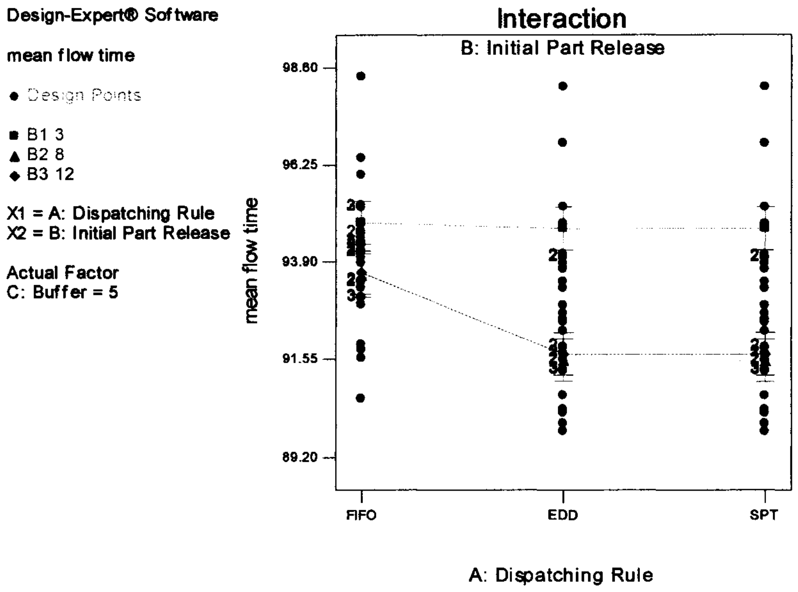


Figure 7.2.3: Average Flow Time, Initial Part Release and Dispatching Rule With Buffer Size 5

The above graphs show the interaction between the initial part release factor and the selected dispatching rule. As can be seen, all the main factors have a sizeable effect on the mean flow time of the parts. When the initial part release is set at three (red line), the selected dispatching rule essentially has no effect on the mean flow time. This result can be justified by the fact that by having only three parts in the system, there will not be enough parts to form a substantial queue in such a way that the effect of different priority rules can be realized. However this is not the case for the other levels of the initial part release factor. In these cases the effect of the selected dispatching rule is identifiable. It can be seen that the EDD and SPT rules reduce the mean flow time of the parts almost the same way compare to FIFO rule. The similarity of the EDD and SPT rules for the model can be explained by the fact that the simulator uses the lowest value of the designated attribute (Due Date and Process Time respectively) to select the next part in the queue; hence these rules seems to behave similarly at the setting levels of this study.

Finally the effect of the number of the buffers in the system can also be seen in the above graphs. Comparing the graphs it becomes evident that as the number of buffers increases in the system the effect of the dispatching rules becomes more pronounced at the higher level of initial part release (blue line). This effect is quite logical; by having a larger queue (bigger buffer size) the effect of the dispatching rule is more pronounced.

Furthermore, from the above graphs it can be noticed that as the number of buffers in the system changes, the part mean flow time also amend.

At a given level of buffer size, there is an optimum number for initial part release which would minimize the part mean flow time. Lower level of initial part release would increase the mean flow time for inefficiency and extra capacity (extra buffers) and also the fact that after the initial part release, each new part enters the system only when a finished part exits the system. At the higher level of initial part release, part mean flow time increases due to the congestion in the system. In Figure 7.2.1, the initial part release of 8 has the lowest mean flow time and thus it is the optimum number. As the number of buffers increases, although the mean flow time reduces but the reduction for the initial part release of 12 is more pronounced that is quite logical. The increase in the number of buffers shifts the optimum number if initial part release toward higher number of initial part release. Consequently the increase in the number of buffers, shifts the initial parts release of 8 (green line) down but not as much as the initial parts release of 12 (blue line).

The following graphs show the interaction between the initial part release factor and the buffer size average flow time, initial part release and buffer size for varying dispatching rule.

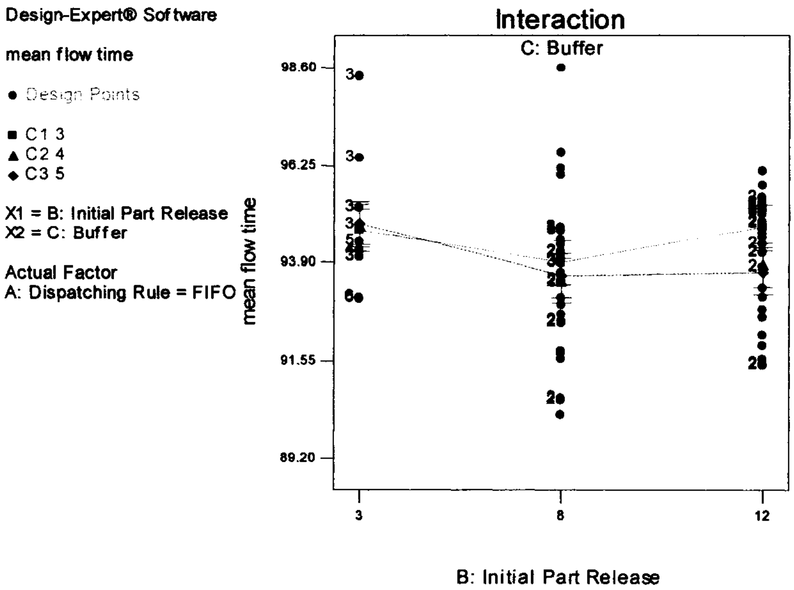


Figure 7.3.1: Average Flow Time, Initial Part Release and Buffer Size With FIFO Dispatching Rule

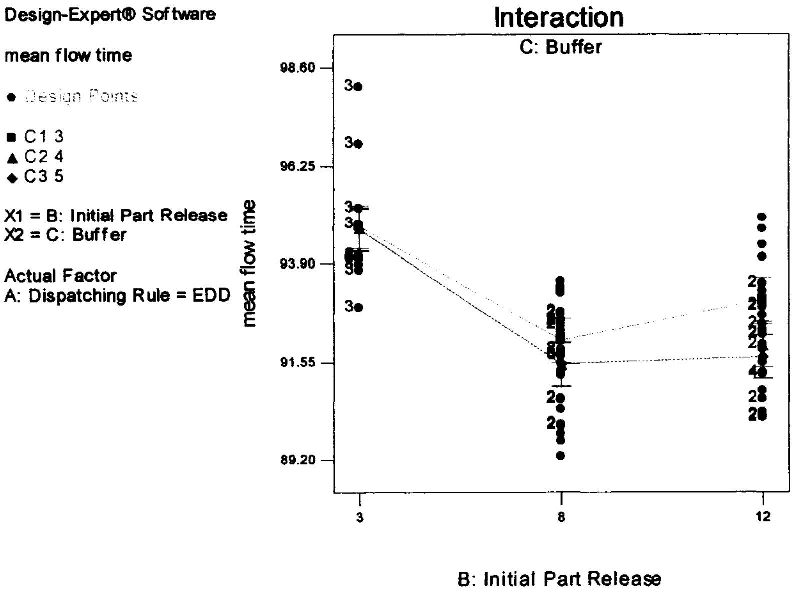


Figure 7.3.2: Average Flow Time, Initial Part Release and Buffer Size With EDD Dispatching Rule

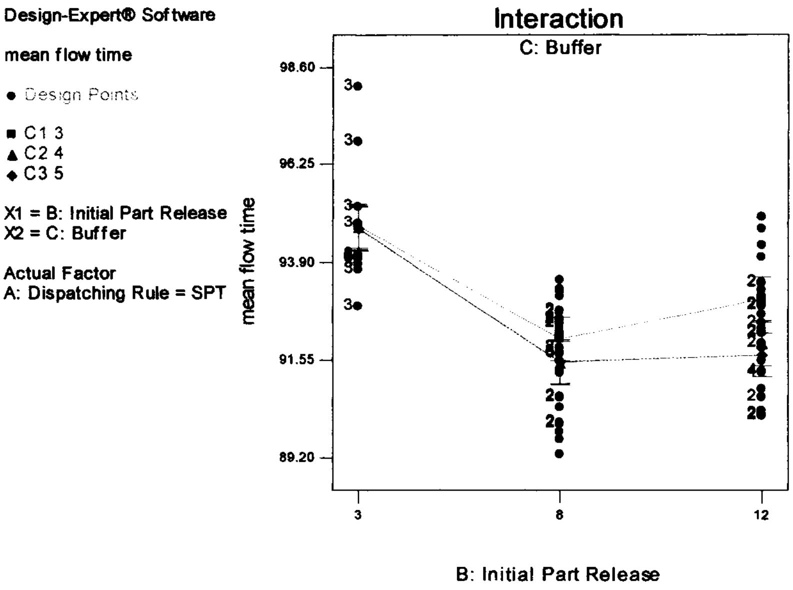


Figure 7.3.3: Average Flow Time, Initial Part Release and Buffer Size With SPT Dispatching Rule

From the above interaction plots, the followings can be noted:

- The performance gap between the buffer size of 3 on the one hand and a buffer size of 4 and 5 on the other hand becomes wider moving from the FIFO dispatching rule to the other two dispatching rules.
- Overall, moving from the FIFO dispatching rule to the other two dispatching rules, reduces the average flow time of parts.
- Initial part release has an interesting effect on the system performance. When going from an initial part release of 3 to 8, the mean flow time of parts reduces markedly. However from that point the mean flow time starts to rise. This effect can be explained by the fact that at the level of 3 of initial part release, there is unused capacity in the CIM system which contributes to the longer mean flow time of the parts in the system. Also in the developed model, after the initial release of the parts, each new part enters the system once a final product leaves the system. However at a level of 8 of initial part release and on, there is no extra capacity in the system. Thus increasing the number of initial part release would create a longer queue and consequently increases the parts waiting time and thus average flow time of parts.

In summary, according to the aforementioned results, the system performs much better considering the Average Flow Time when the selected dispatching rule is either EDD or SPT with buffer size of five and initial part release of eight.

7.2.2. ANOVA on Machine Efficiency

Table 7.3 shows the results of the Analysis of Variance analysis on Machine Efficiency including the p-value of the ANOVA F-test. The Model *F* value of 15.94 and a p-value of less than 0.0001 for the F-test shows that the model is significant. The table also shows the p-value of the ANOVA F-test on Machine Efficiency for all experimental factors and interactions. High *F* values identify the significant factors and interactions. In this case B, C and BC are significant model terms. The *F* value of 9.4 indicates that there is an interaction effect between buffer size and initial part release.

Table 7.4: ANOVA Analysis for Machine Efficiency

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	114.48	18	6.36	15.94	< 0.0001	significant
A-Dispatching Rule	*4.75*	*2*	*2.38*	*5.96*	*0.0030*	
B-Initial Part Release	*74.75*	*2*	*37.38*	*93.66*	*< 0.0001*	significant
C-Buffer	*19.00*	*2*	*9.50*	*23.81*	*< 0.0001*	significant
AB	*0.89*	*4*	*0.22*	*0.56*	*0.6927*	
AC	*0.068*	*4*	*0.017*	*0.042*	*0.9966*	
BC	*15.01*	*4*	*3.75*	*9.40*	*< 0.0001*	significant
Residual	100.17	251	0.40			
Lack of Fit	*0.52*	*8*	*0.065*	*0.16*	*0.9958*	*not significant*
Pure Error	*99.65*	*243*	*0.41*			
Cor Total	214.65	269				

A summary of the statistics for the model is presented below.

Table 7.5: Summary Statistics on Machine Efficiency

Std. Dev.	0.63
Mean	51.24
C.V. %	1.23
PRESS	115.91

To verify the ANOVA analysis, the plots of normal probability of residuals and residuals versus predicted values are presented below. No abnormalities can be seen in the following normal plot, thus the normality assumption is satisfied.

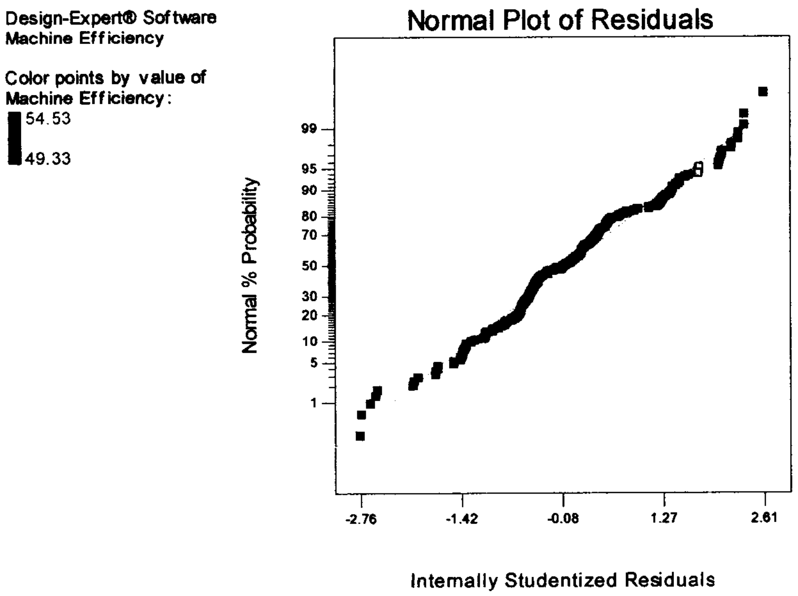


Figure 7.4.1: Machine Efficiency – Normal Plot of Residuals

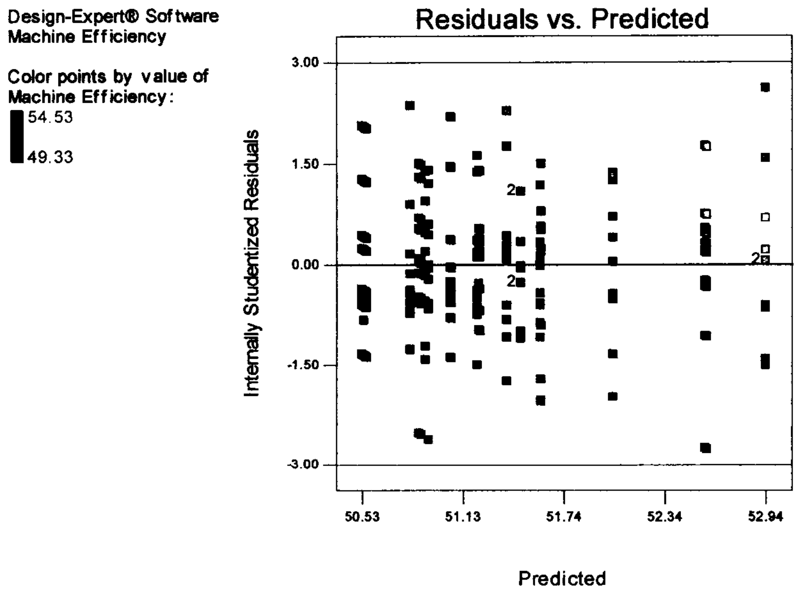


Figure 7.4.2: Machine Efficiency – Residuals vs. Predicted

There is no pattern in the plot of the residuals versus the ascending predicted response values and thus the constant variance assumption is also satisfied.

Having the model validated, the interaction plots of main effects are presented below to identify the significant factors and interactions:

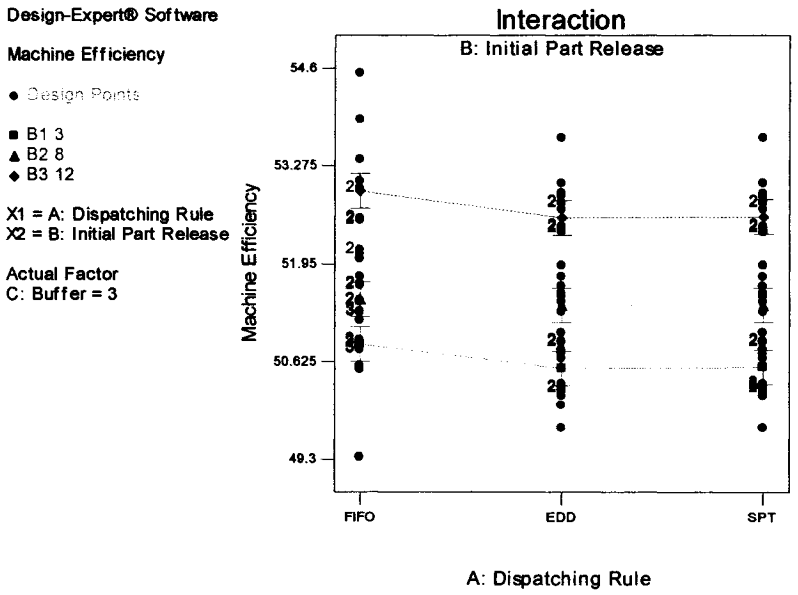


Figure 7.5.1: Machine Efficiency Initial Part Release and Dispatching With Buffer Size 3

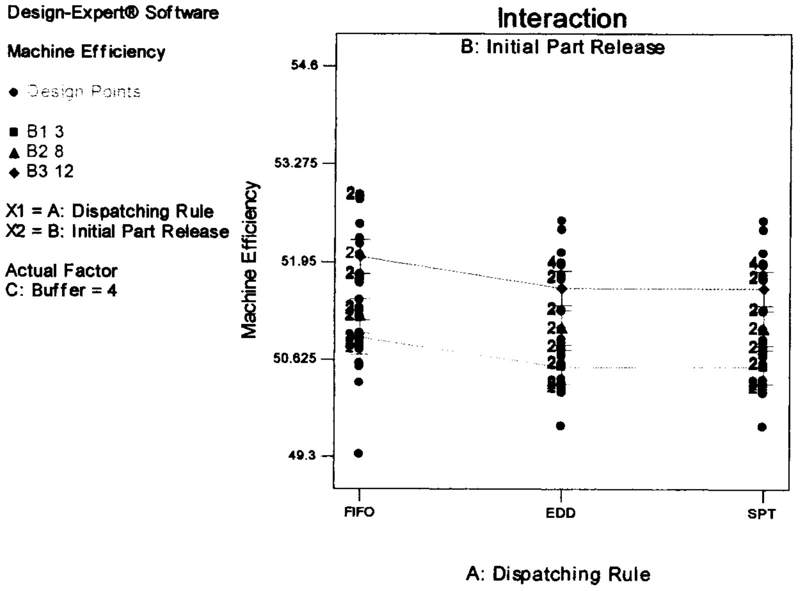


Figure 7.5.2: Machine Efficiency Initial Part Release and Dispatching Rule With Buffer Size 4

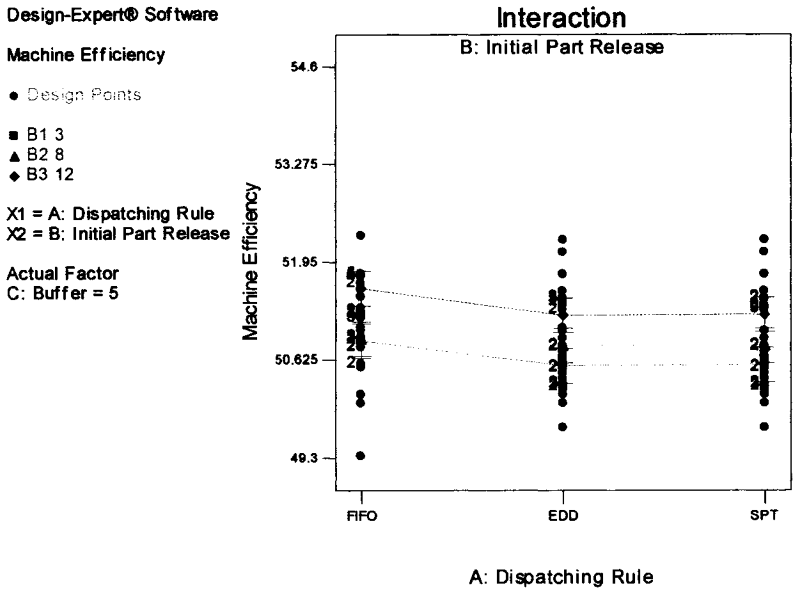


Figure 7.5.3: Machine Efficiency Initial Part Release and Dispatching Rule With Buffer Size 5

The graphs in figure 7.5 show the interaction between the initial part release factor and the selected dispatching rule. It can be seen the selected dispatching rule does not have a sizeable effect on the machine efficiency. However this is not the case for the other two factors. It can be seen that a lower number of initial part release reduces the machine efficiency. This can be justified by the fact that as the number of initial part release increases, the system workload increases which results in more use of the machines and thus a higher machine efficiency.

Finally the effect of the number of the buffers in the system can also be seen in these graphs. Comparing the graphs it become evident that the as the number of buffers increases in the system the effect of the initial release become less (the distance between graphs reduces). This effect is quite logical; by having a smaller buffer size, the machines are used more efficiently to finish the job order. This effect is more pronounced when the initial part release is the highest and the buffer size the lowest (blue line in the last graph).

The following graphs show the interaction between the initial part release factor and the buffer size.

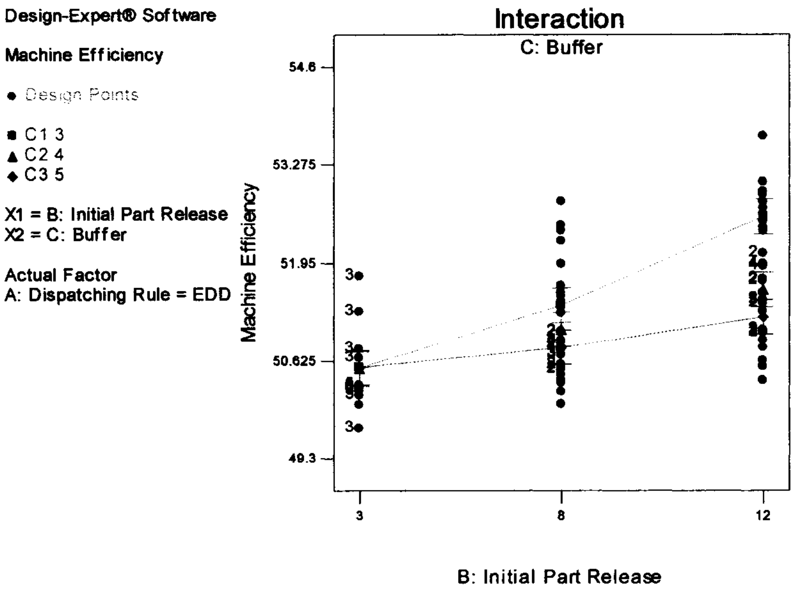


Figure 7.6.1: Machine Efficiency Initial Part Release and Buffer Size With EDD Dispatching Rule

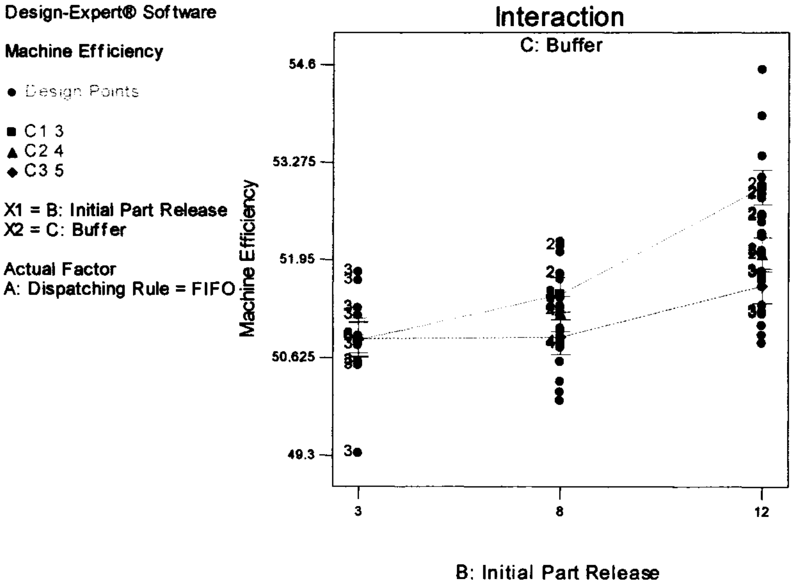


Figure 7.6.2: Machine Efficiency Initial Part Release and Buffer Size With FIFO Dispatching Rule

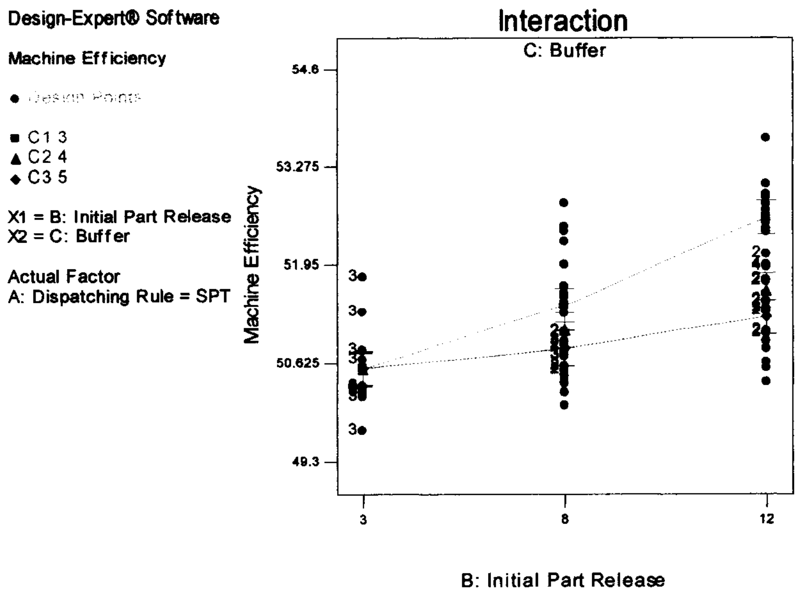


Figure 7.6.3: Machine Efficiency Initial Part Release and Buffer Size With SPT Dispatching Rule

The above interaction plots once again verify the conclusion that is already made. It can be noticed that the selected dispatching rule does not have a marked effect while the effect of the increase in buffer size becomes more pronounced when the number of initial part release increases.

In summary, according to the aforementioned results, the system performs much better considering the Machine Efficiency when the initial part release is maximum and the buffer size is minimum.

7.2.3. ANOVA on Total Run Time

The following table shows the result of Analysis of Variance analysis on the Total Run Time including the p-value of the ANOVA F-test:

Table 7.6: ANOVA Analysis for Total Run Time

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	164.54	18	9.14	2.23	0.0035	significant
A-Dispatching Rule	*22.50*	*2*	*11.25*	*2.74*	*0.0663*	
B-Initial Part Release	*138.33*	*2*	*69.17*	*16.86*	*< 0.0001*	significant
C-Buffer	*0.23*	*2*	*0.11*	*0.028*	*0.9727*	
AB	*0.99*	*4*	*0.25*	*0.060*	*0.9932*	
AC	*2.08*	*4*	*0.52*	*0.13*	*0.9727*	
BC	*0.41*	*4*	*0.10*	*0.025*	*0.9988*	
Residual	1029.52	251	4.10			
Lack of Fit	*6.44*	*8*	*0.81*	*0.19*	*0.9919*	*not significant*
Pure Error	*1023.08*	*243*	*4.21*			
Cor Total	1194.06	269				

The Model *F* value of 2.23 and a p-value of 0.0035 for the F-test shows that the model is significant. The above table also shows the p-value of the ANOVA F-test on Machine Efficiency for all experimental factors and interactions. High *F* values identify the significant factors and interactions. In this case B (Initial Part Release) is the only significant model term. The *F* value of 16.86 indicates its significance. A summary of statistics for the model is presented below:

Table 7.7: Summary Statistics on Total Run Time

Std. Dev.	2.03
Mean	160.60
C.V. %	1.26
PRESS	1191.29

To verify the ANOVA analysis, the plots of normal probability of residuals and residuals versus predicted are presented in Figures 7.9 and 7.10. No abnormalities can be seen in the following normal plot, thus the normality assumption is satisfied.

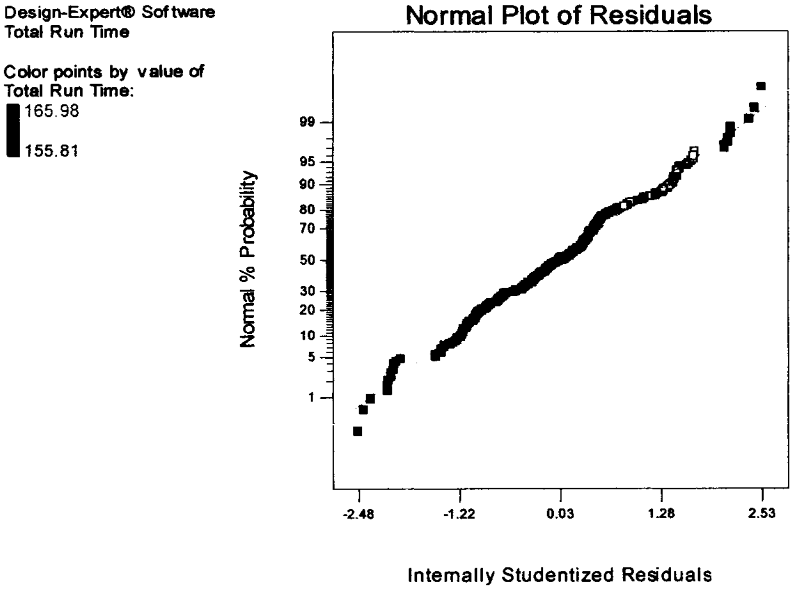


Figure 7.7.1: Total Run Time – Normal Plot of Residuals

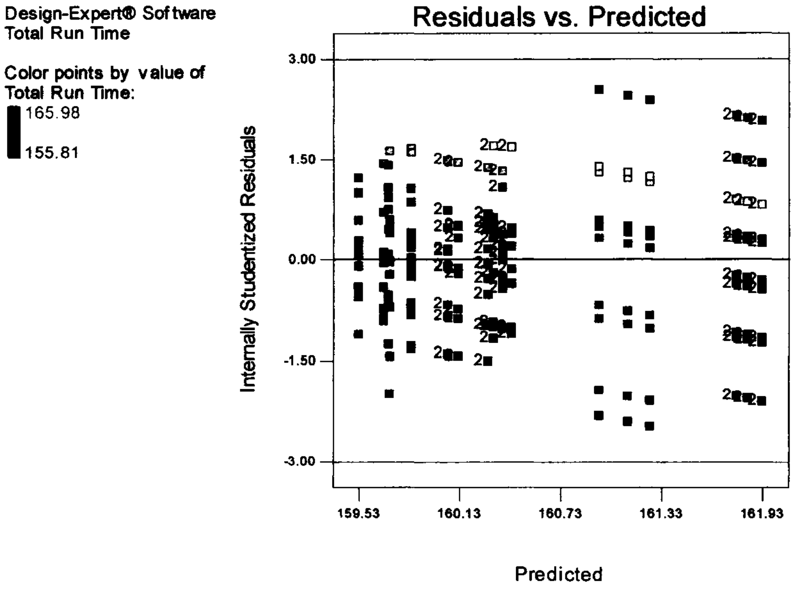


Figure 7.7.2: Total Run Time – Residuals vs. Predicted

There is no pattern in the plot of the residuals versus the ascending predicted response values and thus the constant variance assumption is also satisfied.

Having the model validated, the interaction plots of main effects are presented below to identify the significant factors and interactions:

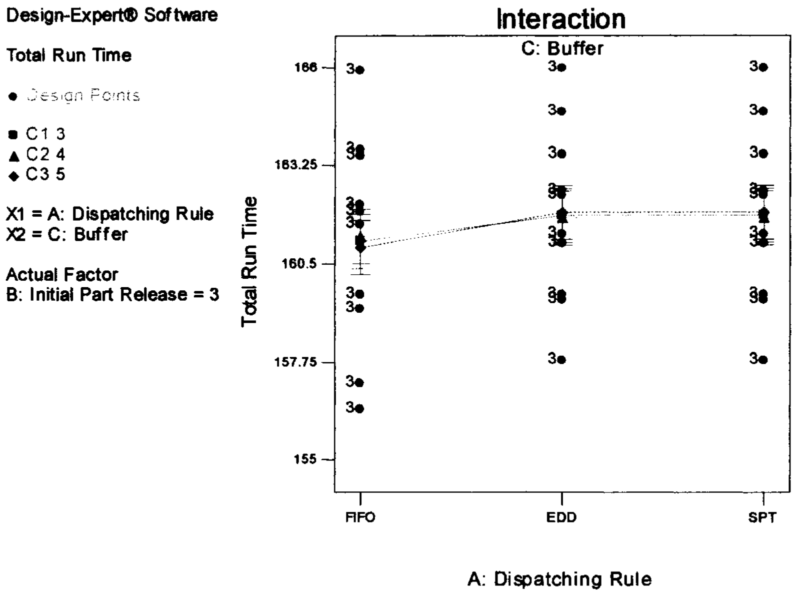


Figure 7.8.1: Total Run Time Dispatching Rule and Buffer Size With Initial Part Release 3

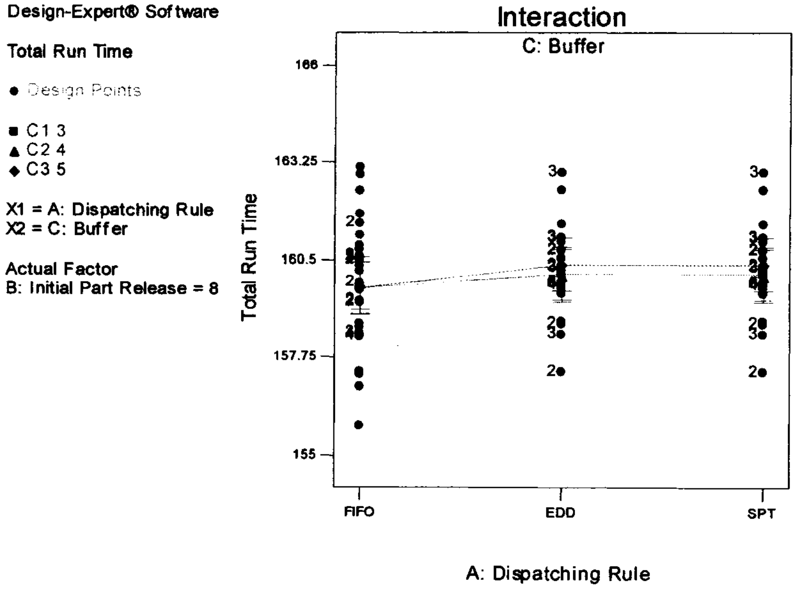


Figure 7.8.2: Total Run Time Dispatching Rule and Buffer Size With Initial Part Release 8

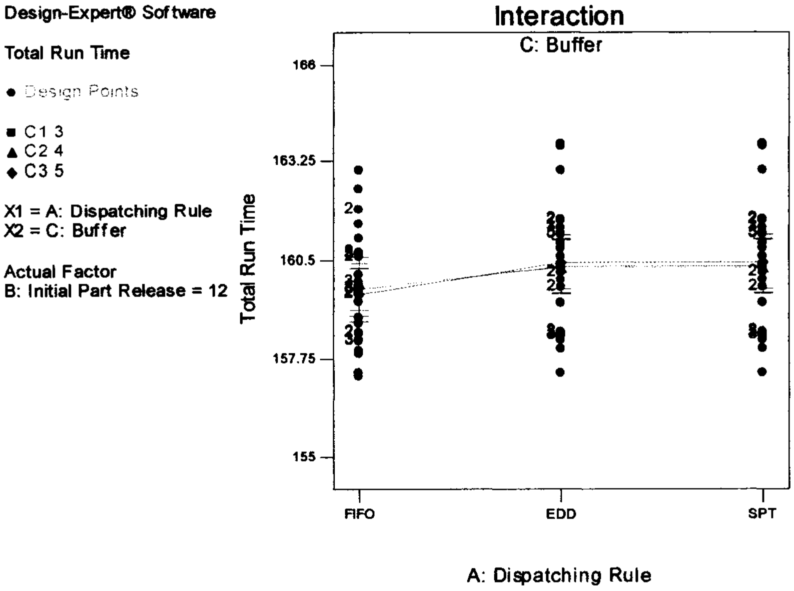


Figure 7.8.3: Total Run Time Dispatching Rule and Buffer Size With Initial Part Release 12

The above graphs show the interaction between the initial part release factor and the selected dispatching rule. From above graphs, it can be seen that the selected dispatching rule and buffer size do not have a sizeable effect on the total run time. However this is not the case for the initial part release factor. It can be seen that the lower number of initial part release (3) increases the total run time. Yet the highest number of initial part release does not have a significant effect. This can be explained by the fact that at the lowest level of initial part release, there is unused capacity in the CIM system which contributes to the total run time of the production order. Also in the developed model, after the initial release of the parts, each new part enters the system once a final product leaves the system. However for a level of 8 of initial part release and on, there is no extra capacity in the system. Thus increasing the number of initial part release would reduce the total run time.

In summary, according to the aforementioned discussion, the system's total run time performs markedly better when the initial part release is set at eight or higher.

8. CONCLUSIONS AND FUTURE RESEARCH

8.1. Conclusions

The objective of this research was to identify the potential effect of a selected number of dispatching rules and two other factors, the number of buffers and initial number of part release, on the performance of the existing Computer Integrated Manufacturing systems with different part types where the machines are the major resource constraints.

A review of the current literature on scheduling optimization in manufacturing systems, particularly in the area of dispatching rules along with a detailed description of the existing CIM system, its programming and control logic, provided the foundation for this research.

This research a simulation model based on a real flexible CIM system and its control logic was developed in order to provide results about the performance of the real system when the factors under study changes. The use of Arena simulation software, made possible to introduce the factors of interest as different variables, which could be changed to examine their impact on the system's performance.

Furthermore, Design of Experiments (D.O.E.) method and Design Expert software is used to set up runs for the experimental study of combinations of number of environment factors in various levels. This followed by the execution of the simulation runs on the created simulation model and collecting the performance measures of interest as the output.

Significant impacts of the factor levels in the performance of the manufacturing system have been identified by evaluating the result by use of ANOVA statistical analyses of variance.

The following summarizes the findings of this research. The study results revealed that:

- Selection of the initial part release factor, number of buffers and the dispatching rule has a sizeable effect on the mean flow time of the parts, except for the lower numbers of initial part release. As the number of buffers increases the effect of the dispatching rules on the part Average Flow Time becomes more pronounced at the higher level of initial part release due to formation of a larger queue.

- At a given level of buffer size, there is an optimum number for initial part release which minimizes the part mean flow time. A lower level of initial part release increases the mean flow time.
- The increase in the number of buffers reduces the part Mean Flow Time with more effect on the higher number of the initial part release.
- Moving from the FIFO dispatching rule to the other two dispatching rules, reduces the average flow time of parts.
- Contrary to the number of initial part release and number of buffers in the system, the selection of the dispatching rule does not have a sizeable effect on the machine efficiency.
- A lower number of initial part release, reduces the machine efficiency since the increase of the number of initial part release would increase the system workload which results in more use of the machines and thus, higher machine efficiency.
- Increases of the number of buffers in the system reduce the effect of the initial number of part release on the machine efficiency, since by having a smaller buffer size, the machines are used more efficiently to finish the job order.
- The selected dispatching rule and buffer size do not have a sizeable effect on the total run time. However this is not the case for the initial part release factor. Lower number of initial part release increases the total run time. Yet the highest number of initial part release does not have a significant effect. At the lowest level of initial part release, there is unused capacity in the CIM system. This fact coupled with the control logic of the CIM system (each new part enters the system once a final product leaves the system) explains this effect.

In summary, according to the aforementioned results, the system performs much better considering the Machine Efficiency when the initial part release is maximize and the buffer size is minimum. Furthermore, considering the Average Flow Time, the system performs much better when the selected dispatching rule is either EDD or SPT with buffer size of five and initial part release of eight.

In Chapter three, according to the reviewed literature, it was concluded that the overall best simple dispatching rules among all other simple rules in order of their performance are SPT, EDD & FIFO. Where this research concludes that the performance of the FIFO is worse than other two rules however a tangible difference between the SPT and EDD was not observed.

8.2. Contribution of the Research

The major contributions of this research are as follows:

- This research is among the few conducted researches to study the effect of the dispatching rules on the performance of the CIM systems with use of terminating simulation analyzing. This is also significant giving the nature of the CIM systems that are mostly use to produce different parts in varying quantities and thus do not produce parts on a continuing basis.
- A simulation model with a factorial design experiment was developed that can be used for more experiments and further advancement of this research. In the conducted research, there were a limited number of factors and levels for the experiment set-up. In addition to this fact, the scheduling rules evaluated were limited to the three most prominent used in manufacturing environments (First In First Out, Earliest Due Date, and Shortest Process Time). However, the applicability of the developed model is not limited to the above mentioned dispatching rules. The flexibility of the model allows adding additional factors with varying levels and other scheduling rules to study there effects.
- This research is amongst the first to study the combined effect of dispatching rule and the buffer size in the CIM systems where the job arrivals are predetermined and depend on the completion of the existing parts in the system. A description of how buffer size and initial part release is related to the performance of the CIM system under study for the studied priority dispatching rule is also provided.

8.3. Recommendations for Future Research

The following are suggested areas for future research:

1. In this research, a limited number of factors and levels were considered for the experiment set-up. However the flexibility of the model allows experimenting with additional factors and levels.
2. In the simulation experiments of this research, three scheduling dispatching rules (FIFO, EDD, SPT) were used. In future research, the effect of other dispatching rules on the system performance can be compared.
3. This research also was limited in that only three different part types with similar routing (flow shop) and constant due date were considered. It is possible to introduce additional flexibility into the design of the experiment, including the different part routings (job shop design) and variable due dates and conduct a experiment to see if the results of this experiment will be hold for the those other situations. The simulation model and method used in this thesis can be adapted easily to study this.
4. A non-terminating simulation model can also be used as another research direction to compare the results and findings with collected results from the terminating simulation model of this study.
5. Certain assumptions were made during this research. These assumptions can be addressed in further research. One important assumption is that there is no failure in the system. It would be a good idea during future research to consider the effect of machine breakdown.
6. In the simulation experiments of this research it was considered that all the jobs are ready to be dispatched to the system. In future research, it would be interesting to investigate how the system performs when, for example, an exponential distribution is used for the job arrival similar to the majority of the studies in this field.
7. Finally, simulation experiments could also be conducted to study the effect of the dispatching rules on the system performance for an assembly shop where two or more part are used to produce one final product.

REFERENCES

1. Cagliano, R.; Spina, G., "Advanced manufacturing technologies and strategically flexible Production", *Journal of Operations Management,* v 18, n 2, Feb., 2000, p 169–190
2. Nagalingam, S.V.; Lin, G.C.I., "Latest developments in CIM", *Robotics and Computer Integrated Manufacturing,* v 15, n 6, Dec., 1999, p 423-430
3. Theodorou, P.; Florou, G., "Manufacturing strategies and financial performance - the effect of advanced information technology: CAD/CAM systems", *Omega, The International Journal of Management Science,* Available online (Science Direct), 15 Feb. 2006,
4. Tseng, M.C., "Strategic choice of flexible manufacturing technologies", *International Journal of Production Economics,* v 91, n 3, Oct 18, 2004, p 223-227
5. Asfahl, C.R., "Robots and manufacturing automation", Second Edition, John Wiley & Sons Inc., 1992
6. Holthaus, O.; Rajendran, C. "New dispatching rules for scheduling in a job shop - an experimental study", *International Journal of Advanced Manufacturing Technology,* v 13, n 2, Feb., 1997, p 148-153
7. Conway, R.W., "Priority dispatching and work-in-process inventory in a job shop", *Journal of Industrial Engineering,* v 16, n 2, 1965, p 123-130
8. Montazeri, M.; Van Wassenhove, L.N., "Analysis of scheduling rules for an FMS", *International Journal of Production Research,* v 28, n 4, 1990, p 785-802
9. Jain, A.S.; Meeran, S., "Job-shop scheduling using neural networks", *International Journal of Production Research,* v 36, n 5, May, 1998, p 1249-1272
10. Jones, Albert; Rabelo, L.C. "Survey of job shop scheduling techniques", Technical Report, National Institute of Standards and Technology, Gaithersburg, MD, 1998
11. Martinis, K.P., "A hybrid method for selecting scheduling schemes in a manufacturing environment", M.Sc. Thesis, The University of Tennessee, Knoxville, Dec., 2003
12. Brucker, P., "Scheduling algorithms", Springer, 1995

13. Basnet, C.; Mize, J. H., "Scheduling and control of flexible manufacturing systems: A Critical Review", *International Journal of Computer Integrated Manufacturing,* v 7, n 6, 1994, p 340-355

14. Gordon, V.; Proth, J.M.; Chu, C., "A survey of the state-of –the-art of common due date assignment and scheduling research", *European Journal of Operational Research, v139, n 1, 2002, p 1-25*

15. Yoo, W.-S.; Martin-Vega, L.A., "Scheduling single-machine problems for on-time delivery", *Computer and Industrial Engineering*, v 39, n 3-4, April, 2001, p 371-392

16. Kogan, K.; Levner, E., "A polynomial algorithm for scheduling small scale manufacturing cells served by multiple robots", *Computers and Operational Research*, v 25, n 1, Jan., 1998, p 53-62

17. Agnetis, A.; Pacciarelli, D., "Part sequencing in three-machine no-wait robotic cells", *Operations Research Letters*, v 27, n 4, Nov, 2000, p 185-192

18. Brauner, N.; Finke, G., "Optimal moves of the material handling system in a robotic cell", *International Journal of Production Economics,* v 74, n 1, Dec., 2001, p 269-277

19. Beasley, J.E. (Editor), "Advances in linear and integer programming", Oxford University Press, 1996

20. Metaxiotis, K.S.; Askounis, D.; Psarras, J., "Expert systems in production planning and scheduling: a state of the art survey", *Journal of Intelligent Manufacturing*, v 13, n 4, Aug., 2002, p 253-260

21. Wang, H.G.; Rooda, J.E.; Haan, J.F., "Solve scheduling problems with a fuzzy approach", *IEEE International Conference on Fuzzy Systems*, v 1, 1996, p 194-198

22. Drake, G.R.; Smith, J.S.; Peters, B.A., "Simulation as a planning and scheduling tool for flexible manufacturing systems", *Winter Simulation Conference, Proceedings of the 27th Conference on Winter Simulation, Arlington, Virginia, U.S.A.,* 1995, p 805-812

23. Mohanansundaram, K.M.; Natarajan, K.; Viswanathkumar, G.; Radhakrishnan, P.; Rajendran, C., "Scheduling rules for dynamic shops that manufacture multi-level jobs", *Computer and Industrial Engineering,* v 44, n 1, Jan., 2003, p 119-131

24. Sabuncuoglu, I.; Lejmi, T., "Scheduling for non regular performance measure under the due window approach", *Omega, The International Journal of Management Science,* v 27, n 5, Oct., 1999, p 555-568

25. Wu, D. "An expert systems approach for the control and scheduling of flexible manufacturing systems", Ph.D. Dissertation, Pennsylvania State University, 1987

26. Conway, R.W., "Priority dispatching and job lateness in a job shop", *Journal of Industrial Engineering,* v 16, n 4, Jul.-Aug., 1965, p 228-236

27. Rajendran, C.; Holthaus, O., "A comparative study of dispatching rules in dynamic flow shops and job shops", *European Journal of Operational Research,* v 116, n 1, Jul., 1999, p 156-170

28. Blackston, J.H.; Phillips, D.T.; Hogg, G.L., "State of the art survey of dispatching rules for manufacturing job shop operations", *International Journal of Production Research",* v 20, n 1, Jan.-Feb., 1982, p 27-45

29. Conway, R.W.; Johnson, B.M.; Maxwell, W.L., "An experimental investigation of priority dispatching", *Journal of Industrial Engineering,* v 11, 1960, p 221-230

30. Baker, C.T.; Dzielinski, B.P., "Simulation of a simplified job shop", *Management Science,* v 6, n 3, Apr.,1960, p 311-323

31. Shanker, K.; Tzen, Y.J.J., "A loading and dispatching problem in a random flexible manufacturing system", *International Journal of Production Research,* v 23, n 3, May-Jun, 1985, p 579-595

32. Persi, P.; Ukovich, W.; Pesenti, R.; Nicolich, M., "A hierarchic approach to production planning and scheduling of a flexible manufacturing system", *Robotics and Computer Integrated Manufacturing,* v 15, n 5, Oct., 1999, p 373-385

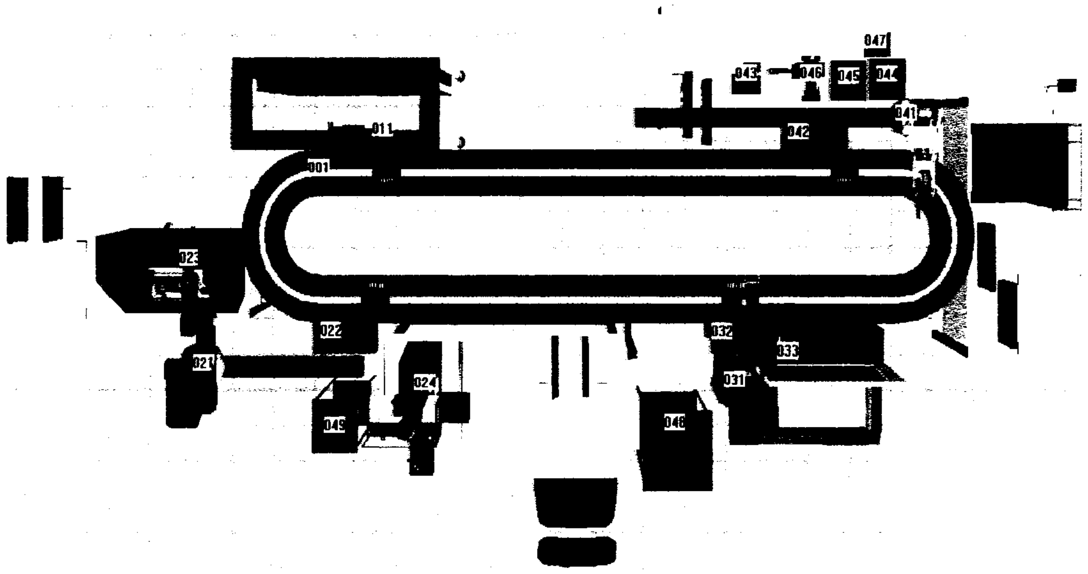
33. Choi, R.H.; Malstrom, E.M., "Evaluation of traditional work scheduling rules in a flexible manufacturing system with a physical simulator", *Journal of Manufacturing Systems,* v 7, n 1, 1988, p 33-45

34. Horng, H.C.; Chou, S.H., "Comparing dispatching rules in an open shop-a simulation study", *Proceedings of the 2002 IIE Annual Research Conference,* (CD-ROM, Paper No. 2082)

35. Co, H.C.; Jaw, T.J.; Chen, S.K., “Sequencing in flexible manufacturing systems and other short queue-length systems”, *Journal of Manufacturing Systems,* v 7, n 1, 1988, p 1-8
36. Chan, F.T.S.; Chan, H.K.; Lau, H.C.W.; Ip, R.W.L., “Analysis of dynamic dispatching rules for a flexible manufacturing system”, *Journal of Materials Processing Technology*, v138, n 1-3, Jul., 2003, p 325-331
37. Veral, E.A., “Computer simulation of due-date setting in multi-machine job shops”, *Computers and Industrial Engineering*, v 41, n 1, Oct., 2001, p 77-94
38. Allahverdi, A.; Gupta, J. N.D.; Aldowaisan, T., “A review of scheduling research involving setup considerations”, *Omega, The International Journal of Management Science*, v 27, n 2, Apr. 1999, p 219-239
39. Candar, O., “Machine scheduling problems with blocking and no-wait in process”, Department of Industrial Engineering, Bilkent University, Apr. 1999
40. Lawley, M.; Reveliotis, S.; Ferreira, P. “Design guidelines for deadlock handling strategies in flexible manufacturing systems”, *International Journal of Flexible Manufacturing Systems,* v 9, n 1, Jan., 1997, p 5-30
41. Sabuncuoglu, I.; Bayiz, M., “Analysis of reactive scheduling problems in a job shop environment”, *European Journal of Operational Research,* v 126, n 3, Nov., 2000, p 567-586
42. “OpenCIM, OpenCIM Offline, OpenCIM Intro and OpenFMS, computer integrated manufacturing for industrial training applications, software version 4.0, user manual”, Catalog No. 100094 Rev. E, Intelitek, (2004)
43. Montgomery, D.C., “Design and analysis of experiment”, Fifth Edition, John Willey & Sons Inc., 2001
44. Kelton, W.D.; Law, A.M., “An analytical evaluation of alternative strategies in steady-state simulation”, *Operational Research*, v 32, n 1, Jan.-Feb., 1984, p 169-184
45. Schmeiser, B., “Batch size effects in the analysis of simulation output”, *Operational Research*, v 30, n 3, May-Jun, 1982, p 556-568
46. Kelton, W.D.; Sadowski, R.P.; Sadowski, D.A. “Simulation with Arena”, Second Edition, McGraw Hill, 2003

47. Chung, C.A., “Simulation modeling handbook: a practical approach”, CRC Press, 2004
48. Bertisimas, D.; Freund, R. M., “Data, models and decisions: the fundamentals of management science”, Thomson Limited, 2005

Appendix A. FMS's Device Specifications



1 CORBOT-ER IX (item #021, # 031)

- Number of Axes: 5 plus gripper
- Maximum Operating Radius 691mm (27.2") without gripper
- End Effector: Electric DC Servo Gripper
- Feedback Incremental optical encoders with index pulse
- Transmission: Harmonic Drive gears and timing belts
- Maximum Payload 2 kg (4.4 lb.), including gripper
- Communicates over an RS232 serial data line
- Operate with ACL language (Advanced Control Language)
- The robot controller: Eshed Robotec Controller B

  Communication: 2 integrated RS232 channels

2 SCORBOT-ER V plus (item #047)

- Number of Axes: 5 plus gripper
- Maximum Operating Radius 610mm (24.4") without gripper

- End Effector: DC servo gripper, with optical encoder, parallel finger motion; Measurement of object's size/gripping force by means of gripper sensor and software.
- Feedback Incremental optical encoders with index pulse
- Transmission: Gears, timing belts, lead screw
- Maximum Payload 1 kg (4.4 lb.), including gripper
- Communicates over an RS232 serial data line
- Operate with ACL language (Advanced Control Language)
- The robot controller: Eshed Robotec Controller B
- Communication: 2 integrated RS232 channels

3 proLIGHT 3000 Turning Center (item #023)

- The robot controller: Eshed Robotec Controller B
- A 2-axis lathe CNC
- Communicates over an RS232 serial data line
- Programs may be executed as they are entered, or when they are completely ordered
- Feed rates up to 25 ipm
- EIA RS-274D standard G&M code programming
- Multiple tool programming
- Computer-controlled spindle speeds from 0 to 3,600 RPM at low range, and 0 to 3,6000 RPM at high range
- A built-in full-screen NC program editor with graphic tool path verification

4 proLIGHT 1000 Machining Center (item #024)

- A 3-axis milling CNC
- Communicates over an RS232 serial data line
- Programs may be executed as they are entered, or when they are completely ordered
- Computer controlled spindle speeds from 200 to 5,000 RPM

- Rapid traverse rates up to 50 rpm on all axes
- EIA RS-274D standard G&M code programming
- Multiple tool programming
- A built-in full-screen NC program editor

5 Closed Loop Conveyor Belt System (item #001)

- Magnetic codes embedded on the underside of the pallets enable tracking
- Conveyor stops alongside each CIM workstation include magnetic sensors for pallet detection and pneumatic pistons for halting and releasing the pallets
- A PLC control unit monitors and manages the flow of pallets on the CIM conveyor
- Communication PCB for fast I/O and RS232 connection, as well as control of station indicator lights
- Conveyor motor and gear assembly 220/380 Vac Motor, 3-phase, 0.75 hp, 1390 rpm

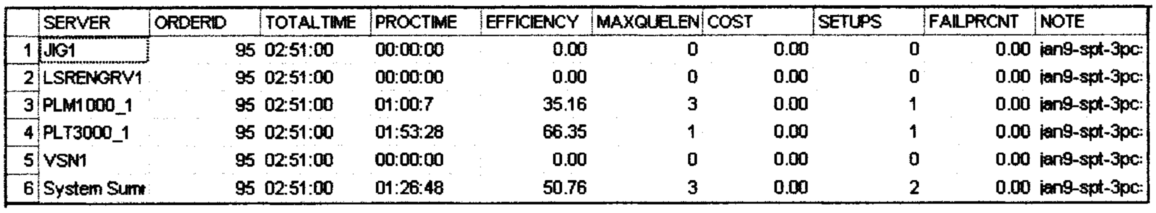
6 Vision System: View Flex image processor for quality control (item #043)

- interactive vision software based on the Inspector image
- processing engine
- A USB digital color camera that provides both still and video images
- software offers an extensive set of optimized functions for image
- processing and enhancement, blob analysis, gauging and measurement, and pattern matching
- The system supports applications such as precision measurement, flaw detection
- Image Sensor: Progressive Scan CCD type
- Effective Pixels: 640x480
- Field of View: 44 degrees
- Focus Distance: 25.4 mm (1 inch) to infinity

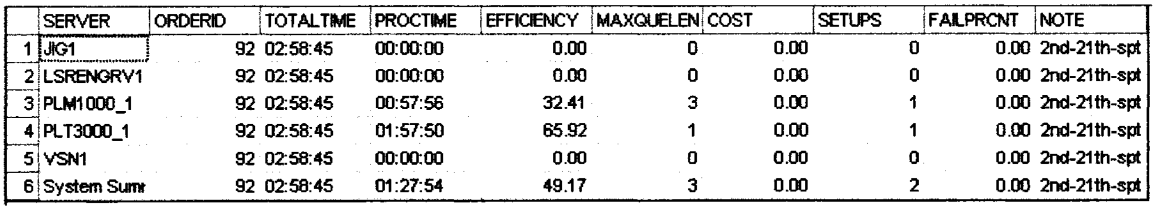
7 AS/RS (item #011)

- 36 cells in 6 x 6 array
- Cartesian robot with rotational axis movement of end effector
- Max. speed: 300 mm/sec
- Load capacity (Max.): 1.5 kg (3.3 lb)
- End effector: Standard: Fork-lift type gripper
- Feedback: Optical encoder on each axis
- Actuators/transmission: 24 VDC and 30 VDCc servo motors; timing-belt drive
- Dimensions: L=1330 mm, W=630 mm, H=1250 mm
- The robot controller: Eshed Robotec Controller B
    - Communication: 2 integrated RS232 channels

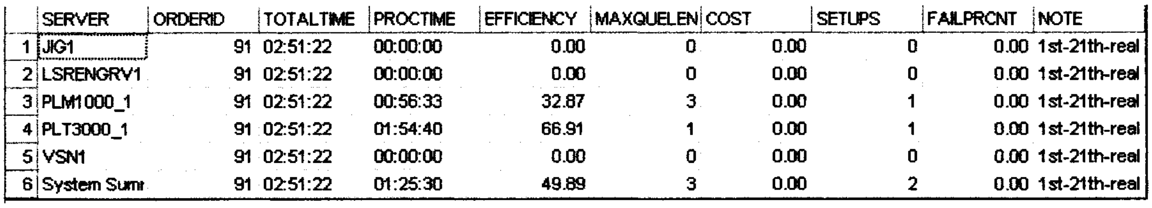
Appendix B. Results from Real System Run with SPT Dispatching Rule, Initial Part Release of 3 and 4 Buffers



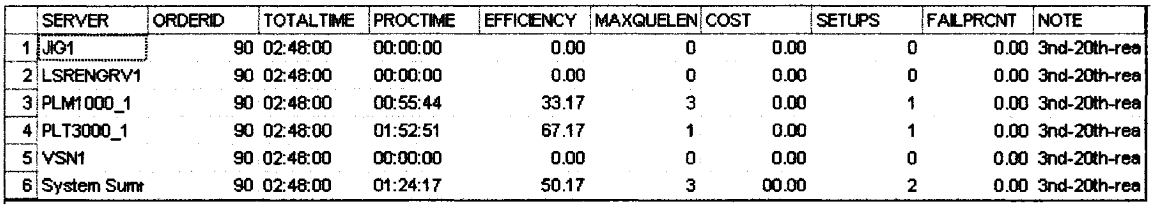
	SERVER	ORDERID	TOTALTIME	PROCTIME	EFFICIENCY	MAXQUELEN	COST	SETUPS	FAILPRCNT	NOTE
1	JIG1	95	02:51:00	00:00:00	0.00	0	0.00	0	0.00	jan9-spt-3pc:
2	LSRENGRV1	95	02:51:00	00:00:00	0.00	0	0.00	0	0.00	jan9-spt-3pc:
3	PLM1000_1	95	02:51:00	01:00:7	35.16	3	0.00	1	0.00	jan9-spt-3pc:
4	PLT3000_1	95	02:51:00	01:53:28	66.35	1	0.00	1	0.00	jan9-spt-3pc:
5	VSN1	95	02:51:00	00:00:00	0.00	0	0.00	0	0.00	jan9-spt-3pc:
6	System Sumr	95	02:51:00	01:26:48	50.76	3	0.00	2	0.00	jan9-spt-3pc:



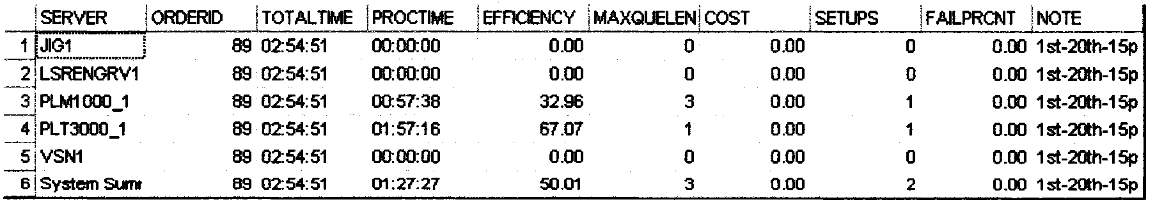
	SERVER	ORDERID	TOTALTIME	PROCTIME	EFFICIENCY	MAXQUELEN	COST	SETUPS	FAILPRCNT	NOTE
1	JIG1	92	02:58:45	00:00:00	0.00	0	0.00	0	0.00	2nd-21th-spt
2	LSRENGRV1	92	02:58:45	00:00:00	0.00	0	0.00	0	0.00	2nd-21th-spt
3	PLM1000_1	92	02:58:45	00:57:56	32.41	3	0.00	1	0.00	2nd-21th-spt
4	PLT3000_1	92	02:58:45	01:57:50	65.92	1	0.00	1	0.00	2nd-21th-spt
5	VSN1	92	02:58:45	00:00:00	0.00	0	0.00	0	0.00	2nd-21th-spt
6	System Sumr	92	02:58:45	01:27:54	49.17	3	0.00	2	0.00	2nd-21th-spt



	SERVER	ORDERID	TOTALTIME	PROCTIME	EFFICIENCY	MAXQUELEN	COST	SETUPS	FAILPRCNT	NOTE
1	JIG1	91	02:51:22	00:00:00	0.00	0	0.00	0	0.00	1st-21th-real
2	LSRENGRV1	91	02:51:22	00:00:00	0.00	0	0.00	0	0.00	1st-21th-real
3	PLM1000_1	91	02:51:22	00:56:33	32.87	3	0.00	1	0.00	1st-21th-real
4	PLT3000_1	91	02:51:22	01:54:40	66.91	1	0.00	1	0.00	1st-21th-real
5	VSN1	91	02:51:22	00:00:00	0.00	0	0.00	0	0.00	1st-21th-real
6	System Sumr	91	02:51:22	01:25:30	49.89	3	0.00	2	0.00	1st-21th-real



	SERVER	ORDERID	TOTALTIME	PROCTIME	EFFICIENCY	MAXQUELEN	COST	SETUPS	FAILPRCNT	NOTE
1	JIG1	90	02:48:00	00:00:00	0.00	0	0.00	0	0.00	3nd-20th-rea
2	LSRENGRV1	90	02:48:00	00:00:00	0.00	0	0.00	0	0.00	3nd-20th-rea
3	PLM1000_1	90	02:48:00	00:55:44	33.17	3	0.00	1	0.00	3nd-20th-rea
4	PLT3000_1	90	02:48:00	01:52:51	67.17	1	0.00	1	0.00	3nd-20th-rea
5	VSN1	90	02:48:00	00:00:00	0.00	0	0.00	0	0.00	3nd-20th-rea
6	System Sumr	90	02:48:00	01:24:17	50.17	3	00.00	2	0.00	3nd-20th-rea



	SERVER	ORDERID	TOTALTIME	PROCTIME	EFFICIENCY	MAXQUELEN	COST	SETUPS	FAILPRCNT	NOTE
1	JIG1	89	02:54:51	00:00:00	0.00	0	0.00	0	0.00	1st-20th-15p
2	LSRENGRV1	89	02:54:51	00:00:00	0.00	0	0.00	0	0.00	1st-20th-15p
3	PLM1000_1	89	02:54:51	00:57:38	32.96	3	0.00	1	0.00	1st-20th-15p
4	PLT3000_1	89	02:54:51	01:57:16	67.07	1	0.00	1	0.00	1st-20th-15p
5	VSN1	89	02:54:51	00:00:00	0.00	0	0.00	0	0.00	1st-20th-15p
6	System Sumr	89	02:54:51	01:27:27	50.01	3	0.00	2	0.00	1st-20th-15p

Appendix C. Output of the Simulation Study

		Factor 1	Factor 2	Factor 3	Response 1	Response 2	Response 3	Response 4	Response 5
Std	Run	A: Dispatching Rule	B: Initial Part Release	C: Buffer	Total Run Time	Maximum Queue Length	Production Cost	Machine Efficiency	Mean Flow Time
		name	Number	Number	Min	Number	$	%	min
251	1	EDD	12	5	161.2	5	80.6	51.05	91.530
249	2	FIFO	12	5	159.88	5	79.94	51.06	94.499
77	3	EDD	12	3	161.22	3	80.61	52.69	92.854
176	4	SPT	12	4	161.38	4	80.69	50.55	93.091
181	5	FIFO	3	5	162.13	2	81.07	50.92	94.813
32	6	FIFO	8	3	158.43	3	79.21	51.68	94.719
209	7	SPT	3	5	162.4	2	81.2	49.71	93.858
240	8	SPT	8	5	160.56	5	80.28	50.91	91.698
22	9	SPT	3	3	161.07	2	80.53	50.26	94.833
179	10	SPT	12	4	161.64	4	80.82	50.35	91.941
21	11	SPT	3	3	164.74	2	82.37	50.28	95.233
35	12	FIFO	8	3	157.24	3	78.62	51.31	92.494
242	13	FIFO	12	5	158.73	5	79.36	50.93	91.906
151	14	FIFO	12	4	159.7	4	79.85	52.46	95.068
264	15	SPT	12	5	163.74	5	81.87	50.63	93.420
142	16	SPT	8	4	159.83	4	79.92	50.57	91.736
204	17	SPT	3	5	165.98	2	82.99	50.22	98.130
31	18	FIFO	8	3	161.53	3	80.76	50.81	98.583
49	19	EDD	8	3	161.11	3	80.55	50.89	93.480
222	20	EDD	8	5	159.83	5	79.92	50.44	91.518
230	21	EDD	8	5	160.56	5	80.28	50.91	91.698
68	22	FIFO	12	3	158.23	3	79.11	52.97	95.333
116	23	SPT	3	4	162.53	2	81.27	50.79	96.767
54	24	SPT	8	3	162.96	3	81.48	50.33	93.090
122	25	FIFO	8	4	159.33	4	79.67	50.83	94.113
259	26	EDD	12	5	160.81	5	80.4	51.3	92.222
143	27	SPT	8	4	158.4	4	79.2	51.94	90.049
132	28	EDD	8	4	159.83	4	79.92	50.57	91.736
107	29	EDD	3	4	163.54	2	81.77	50.3	93.731
60	30	SPT	8	3	160.76	3	80.38	51.56	92.699
44	31	EDD	8	3	162.96	3	81.48	50.33	93.332
102	32	EDD	3	4	161.07	2	80.53	50.26	94.833
195	33	EDD	3	5	159.5	2	79.75	50.16	92.848
148	34	SPT	8	4	160.28	4	80.14	51.28	92.158
193	35	EDD	3	5	159.64	2	79.82	51.78	94.024
80	36	EDD	12	3	161.58	3	80.79	53.04	94.993
232	37	SPT	8	5	159.83	5	79.92	50.44	91.518
136	38	EDD	8	4	159.85	4	79.93	51.03	91.226
185	39	FIFO	3	5	157.16	2	78.58	51.19	93.031
27	40	SPT	3	3	163.54	2	81.77	50.3	93.731
83	41	SPT	12	3	158.5	3	79.25	53.65	91.239
227	42	EDD	8	5	159.78	5	79.89	52.25	90.010

170	43	EDD	12	4	160.59	4	80.29	51.93	92.302
153	44	FIFO	12	4	157.24	4	78.62	52.79	91.467
15	45	EDD	3	3	159.5	2	79.75	50.16	92.850
253	46	EDD	12	5	158.46	5	79.23	52.08	90.330
236	47	SPT	8	5	161.12	5	80.56	50.58	91.843
58	48	SPT	8	3	159.69	3	79.85	51.65	92.553
82	49	SPT	12	3	158.38	3	79.19	52.9	91.279
96	50	FIFO	3	4	161.94	2	80.97	50.89	96.421
47	51	EDD	8	3	158.69	3	79.35	52.78	89.645
208	52	SPT	3	5	161.32	2	80.66	50.67	94.084
39	53	FIFO	8	3	161.8	3	80.9	50.87	94.747
19	54	EDD	3	3	162.4	2	81.2	49.71	93.858
10	55	FIFO	3	3	156.43	2	78.22	51.66	93.060
239	56	SPT	8	5	160.35	5	80.18	50.04	91.289
12	57	EDD	3	3	161.07	2	80.53	50.26	94.830
115	58	SPT	3	4	159.5	2	79.75	50.16	92.848
205	59	SPT	3	5	159.5	2	79.75	50.16	92.848
182	60	FIFO	3	5	159.24	2	79.62	51.29	94.396
37	61	FIFO	8	3	158.69	3	79.35	52.14	90.232
187	62	FIFO	3	5	163.51	2	81.75	50.52	94.012
130	63	FIFO	8	4	160.56	4	80.28	51.32	93.859
218	64	FIFO	8	5	160.78	5	80.39	50.8	94.318
211	65	FIFO	8	5	159.64	5	79.82	51.19	94.661
17	66	EDD	3	3	163.54	2	81.77	50.03	93.730
129	67	FIFO	8	4	160.35	4	80.18	50.3	93.894
172	68	SPT	12	4	158.38	4	79.19	52.08	90.203
166	69	EDD	12	4	161.38	4	80.69	50.55	93.091
91	70	FIFO	3	4	162.13	2	81.07	50.92	94.813
131	71	EDD	8	4	161.51	4	80.76	50.78	92.427
108	72	EDD	3	4	161.32	2	80.66	50.67	94.084
169	73	EDD	12	4	161.64	4	80.82	50.36	91.941
167	74	EDD	12	4	160.15	4	80.08	51.91	90.849
186	75	FIFO	3	5	161.94	2	80.97	50.89	96.421
168	76	EDD	12	4	159.73	4	79.86	51.71	91.947
212	77	FIFO	8	5	158.33	5	79.17	51.02	94.145
67	78	FIFO	12	3	159.57	3	79.79	54.53	95.765
7	79	FIFO	3	3	163.51	2	81.75	50.52	94.010
24	80	SPT	3	3	165.98	2	82.99	50.22	98.130
93	81	FIFO	3	4	159.64	2	79.82	51.78	94.191
252	82	EDD	12	5	158.4	5	79.2	51.55	90.252
117	83	SPT	3	4	163.54	2	81.77	50.3	93.731
155	84	FIFO	12	4	159.52	4	79.76	51.71	93.764
145	85	SPT	8	4	157.31	4	78.65	50.86	90.411
56	86	SPT	8	3	159.85	3	79.93	51.44	92.224
38	87	FIFO	8	3	161.19	3	80.59	50.8	94.009
29	88	SPT	3	3	162.4	2	81.2	49.71	93.858
70	89	FIFO	12	3	161.08	3	80.54	52.97	95.452
225	90	EDD	8	5	159.54	5	79.77	50.73	91.829
258	91	EDD	12	5	159.73	5	79.86	51.46	91.266
158	92	FIFO	12	4	158.23	4	79.11	52.83	95.113

270	93	SPT	12	5	161.19	5	80.59	51.44	92.652
228	94	EDD	8	5	160.78	5	80.39	50.52	91.692
266	95	SPT	12	5	161.38	5	80.69	50.81	92.445
120	96	SPT	3	4	157.81	2	78.91	51.3	93.988
123	97	FIFO	8	4	158.4	4	79.2	52.05	91.592
100	98	FIFO	3	4	156.43	2	78.22	51.66	93.057
90	99	SPT	12	3	161.58	3	80.79	53.04	94.993
260	100	EDD	12	5	161.19	5	80.59	51.44	92.652
114	101	SPT	3	4	165.98	2	82.99	50.22	98.130
248	102	FIFO	12	5	159.32	5	79.66	51.33	94.127
223	103	EDD	8	5	158.4	5	79.2	51.36	89.821
99	104	FIFO	3	4	163.67	2	81.84	49.33	95.230
45	105	EDD	8	3	157.31	3	78.65	51.02	90.642
157	106	FIFO	12	4	160.64	4	80.32	52.27	92.759
256	107	EDD	12	5	161.38	5	80.69	50.81	92.445
134	108	EDD	8	4	162.96	4	81.48	50.21	93.201
175	109	SPT	12	4	157.34	4	78.67	52.51	91.842
268	110	SPT	12	5	159.73	5	79.86	51.46	91.266
156	111	FIFO	12	4	161.91	4	80.95	51.21	94.891
103	112	EDD	3	4	159.64	2	79.82	51.78	94.024
150	113	SPT	8	4	161.01	4	80.5	50.9	92.048
42	114	EDD	8	3	159.83	3	79.92	51.51	92.445
196	115	EDD	3	5	162.53	2	81.27	50.79	96.767
139	116	EDD	8	4	160.35	4	80.18	50.71	92.306
203	117	SPT	3	5	159.64	2	79.82	51.78	94.024
163	118	EDD	12	4	159.29	4	79.64	51.94	90.655
263	119	SPT	12	5	158.46	5	79.23	52.08	90.330
14	120	EDD	3	3	165.98	2	82.99	50.22	98.130
106	121	EDD	3	4	162.53	2	81.27	50.79	96.767
97	122	FIFO	3	4	163.51	2	81.75	50.52	94.012
267	123	SPT	12	5	160.15	5	80.08	51.35	90.651
2	124	FIFO	3	3	159.24	2	79.62	51.29	94.400
52	125	SPT	8	3	159.83	3	79.92	51.51	92.445
18	126	EDD	3	3	161.32	2	80.66	50.67	94.084
3	127	FIFO	3	3	159.64	2	79.82	51.78	94.190
1	128	FIFO	3	3	162.13	2	81.07	50.92	94.810
62	129	FIFO	12	3	157.88	3	78.94	52.57	92.577
59	130	SPT	8	3	161.11	3	80.55	50.89	93.480
61	131	FIFO	12	3	159.7	3	79.85	52.54	95.185
207	132	SPT	3	5	163.54	2	81.77	50.3	93.731
23	133	SPT	3	3	159.64	2	79.82	51.78	94.020
192	134	EDD	3	5	161.07	2	80.53	50.26	94.833
119	135	SPT	3	4	162.4	2	81.2	49.71	93.858
234	136	SPT	8	5	162.96	5	81.48	50.37	93.263
269	137	SPT	12	5	160.81	5	80.4	51.3	92.222
255	138	EDD	12	5	158.26	5	79.13	51.01	91.244
197	139	EDD	3	5	163.54	2	81.77	50.3	93.731
237	140	SPT	8	5	159.78	5	79.89	52.25	90.010
94	141	FIFO	3	4	165.91	2	82.95	50.57	98.382
161	142	EDD	12	4	161.2	4	80.6	51.04	92.442

66	143	FIFO	12	3	159.88	3	79.94	53.36	96.108
118	144	SPT	3	4	161.32	2	80.66	50.67	94.084
216	145	FIFO	8	5	158.35	5	79.18	51.26	93.458
241	146	FIFO	12	5	160.7	5	80.35	51.78	94.348
74	147	EDD	12	3	163.66	3	81.83	52.38	94.709
174	148	SPT	12	4	162.98	4	81.49	51.74	94.019
9	149	FIFO	3	3	163.67	2	81.84	49.33	95.230
165	150	EDD	12	4	157.34	4	78.67	52.51	91.842
262	151	SPT	12	5	158.4	5	79.2	51.55	90.252
34	152	FIFO	8	3	162.46	3	81.23	51.31	96.167
190	153	FIFO	3	5	156.43	2	78.22	51.66	93.057
113	154	SPT	3	4	159.64	2	79.82	51.78	94.024
84	155	SPT	12	3	163.66	3	81.83	52.38	94.709
76	156	EDD	12	3	161.38	3	80.69	51.93	94.316
261	157	SPT	12	5	161.2	5	80.6	51.33	91.530
135	158	EDD	8	4	157.31	4	78.65	50.86	90.411
245	159	FIFO	12	5	157.34	5	78.67	51.58	93.056
41	160	EDD	8	3	161.14	3	80.57	50.73	92.747
6	161	FIFO	3	3	161.94	2	80.97	50.89	96.420
217	162	FIFO	8	5	159.28	5	79.64	51.76	90.582
25	163	SPT	3	3	159.5	2	79.75	50.16	92.848
265	164	SPT	12	5	158.26	5	79.13	51.01	91.244
4	165	FIFO	3	3	165.91	2	82.95	50.57	98.380
124	166	FIFO	8	4	163.1	4	81.55	50.91	96.550
71	167	EDD	12	3	161.2	3	80.6	50.91	92.891
43	168	EDD	8	3	158.4	3	79.2	52.46	90.671
127	169	FIFO	8	4	158.6	4	79.3	52.2	90.633
191	170	EDD	3	5	164.74	2	82.37	50.28	95.233
194	171	EDD	3	5	165.98	2	82.99	50.22	98.130
101	172	EDD	3	4	164.74	2	82.37	50.28	95.233
231	173	SPT	8	5	162.49	5	81.24	50.51	92.518
183	174	FIFO	3	5	159.64	2	79.82	51.78	94.191
85	175	SPT	12	3	158.02	3	79.01	52.77	92.191
121	176	FIFO	8	4	161.53	4	80.76	51.43	94.710
200	177	EDD	3	5	157.81	2	78.91	51.3	93.988
246	178	FIFO	12	5	161.91	5	80.95	51.22	95.228
201	179	SPT	3	5	164.74	2	82.37	50.28	95.233
73	180	EDD	12	3	158.5	3	79.25	53.65	91.239
215	181	FIFO	8	5	155.81	5	77.9	51.48	92.877
63	182	FIFO	12	3	157.96	3	78.98	52.08	91.430
65	183	FIFO	12	3	158.26	3	79.13	53.9	94.335
226	184	EDD	8	5	161.12	5	80.56	50.58	91.843
224	185	EDD	8	5	162.96	5	81.48	50.37	93.263
247	186	FIFO	12	5	159.65	5	79.83	52.31	93.278
36	187	FIFO	8	3	159.85	3	79.93	51.44	92.642
20	188	EDD	3	3	157.81	2	78.91	51.3	93.988
141	189	SPT	8	4	161.51	4	80.76	50.78	92.427
133	190	EDD	8	4	158.4	4	79.2	51.94	90.049
189	191	FIFO	3	5	163.67	2	81.84	49.33	95.230
221	192	EDD	8	5	162.49	5	81.24	50.51	92.518

13	193	EDD	3	3	159.64	2	79.82	51.78	94.020
171	194	SPT	12	4	161.2	4	80.6	51.04	92.442
147	195	SPT	8	4	158.76	4	79.38	52.39	89.281
202	196	SPT	3	5	161.07	2	80.53	50.26	94.833
98	197	FIFO	3	4	161.59	2	80.79	50.79	94.399
213	198	FIFO	8	5	156.9	5	78.45	51.75	91.778
55	199	SPT	8	3	157.31	3	78.65	51.02	90.642
26	200	SPT	3	3	162.53	2	81.27	50.79	96.770
233	201	SPT	8	5	158.4	5	79.2	51.36	89.821
109	202	EDD	3	4	162.4	2	81.2	49.71	93.858
235	203	SPT	8	5	159.54	5	79.77	50.73	91.829
250	204	FIFO	12	5	160.09	5	80.04	51.79	94.602
210	205	SPT	3	5	157.81	2	78.91	51.3	93.988
87	206	SPT	12	3	161.22	3	80.61	52.69	92.854
244	207	FIFO	12	5	161.48	5	80.74	51.24	95.287
92	208	FIFO	3	4	159.24	2	79.62	51.29	94.396
238	209	SPT	8	5	160.78	5	80.39	50.52	91.692
5	210	FIFO	3	3	157.16	2	78.58	51.19	93.030
177	211	SPT	12	4	160.15	4	80.08	51.91	90.849
11	212	EDD	3	3	164.74	2	82.37	50.28	95.230
16	213	EDD	3	3	162.53	2	81.27	50.79	96.770
112	214	SPT	3	4	161.07	2	80.53	50.26	94.833
137	215	EDD	8	4	158.76	4	79.38	52.39	89.281
50	216	EDD	8	3	160.76	3	80.38	51.56	92.699
126	217	FIFO	8	4	159.85	4	79.93	50.98	93.040
149	218	SPT	8	4	160.35	4	80.18	50.71	92.306
30	219	SPT	3	3	157.81	2	78.91	51.3	93.988
180	220	SPT	12	4	160.59	4	80.29	51.93	92.302
199	221	EDD	3	5	162.4	2	81.2	49.71	93.858
257	222	EDD	12	5	160.15	5	80.08	51.41	90.651
128	223	FIFO	8	4	160.19	4	80.09	51.28	93.633
111	224	SPT	3	4	164.74	2	82.37	50.28	95.233
229	225	EDD	8	5	160.35	5	80.18	50.04	91.289
159	226	FIFO	12	4	159.88	4	79.94	51.76	94.112
78	227	EDD	12	3	159.94	3	79.97	52.87	93.236
40	228	FIFO	8	3	160.6	3	80.03	51.46	94.437
138	229	EDD	8	4	160.28	4	80.14	51.28	92.158
64	230	FIFO	12	3	162.48	3	81.24	52.02	95.149
254	231	EDD	12	5	163.74	5	81.87	50.63	93.420
51	232	SPT	8	3	161.14	3	80.57	50.73	92.747
206	233	SPT	3	5	162.53	2	81.27	50.79	96.767
88	234	SPT	12	3	159.94	3	79.97	52.86	93.236
152	235	FIFO	12	4	158.48	4	79.24	52.86	92.157
146	236	SPT	8	4	159.85	4	79.93	51.03	91.226
173	237	SPT	12	4	159.29	4	79.64	51.94	90.655
86	238	SPT	12	3	161.38	3	80.69	51.93	94.316
144	239	SPT	8	4	162.96	4	81.48	50.21	93.201
46	240	EDD	8	3	159.85	3	79.93	51.44	92.224
75	241	EDD	12	3	158.02	3	79.01	52.77	92.191
33	242	FIFO	8	3	158.4	3	79.2	52.14	91.714

105	243	EDD	3	4	159.5	2	79.75	50.16	92.848
214	244	FIFO	8	5	162.9	5	81.48	50.16	96.014
57	245	SPT	8	3	158.69	3	79.35	52.78	89.645
184	246	FIFO	3	5	165.91	2	82.95	50.57	98.382
110	247	EDD	3	4	157.81	2	78.91	51.3	93.988
140	248	EDD	8	4	161.01	4	80.5	50.9	92.048
164	249	EDD	12	4	162.98	4	81.49	51.74	94.019
81	250	SPT	12	3	161.2	3	80.6	50.91	92.891
125	251	FIFO	8	4	157.31	4	78.65	50.76	92.451
95	252	FIFO	3	4	157.16	2	78.58	51.19	93.031
72	253	EDD	12	3	158.38	3	79.19	52.91	91.279
53	254	SPT	8	3	158.4	3	79.2	52.46	90.671
188	255	FIFO	3	5	161.59	2	80.79	50.79	94.399
8	256	FIFO	3	3	161.59	2	80.79	50.79	94.150
198	257	EDD	3	5	161.32	2	80.66	50.67	94.084
154	258	FIFO	12	4	162.98	4	81.49	50.82	95.474
104	259	EDD	3	4	165.98	2	82.99	50.22	98.130
220	260	FIFO	8	5	160.9	5	80.45	50.57	93.411
48	261	EDD	8	3	159.69	3	79.85	51.65	92.553
243	262	FIFO	12	5	158.46	5	79.23	51.66	91.576
219	263	FIFO	8	5	160.5	5	80.25	50.04	93.875
178	264	SPT	12	4	159.73	4	79.86	51.71	91.947
89	265	SPT	12	3	160.94	3	80.47	52.43	93.398
79	266	EDD	12	3	160.94	3	80.47	52.43	93.398
162	267	EDD	12	4	158.38	4	79.19	52.08	90.203
160	268	FIFO	12	4	160.59	4	80.29	52.05	93.768
28	269	SPT	3	3	161.32	2	80.66	50.67	94.084
69	270	FIFO	12	3	158.88	3	79.44	53.07	94.839