JOB SHOP SCHEDULING: A QUANTIFIED SEQUENCING RULE FOR IMPROVING SYSTEM PERFORMANCE UNDER DIVERSIFIED OPERATIONAL PARAMETERS

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I The Problem and its Setting

Introduction

Organizing shop floor activities is an important task that affects the overall performance of a manufacturing enterprise. One of these activities is scheduling the jobs that are to be processed on the machines on the shop floor.

In this research, we consider the scheduling problem in a job shop environment. A make-to-order system is studied. Each job has its own due date, and if a job is finished before its due date, it waits until its due date before being shipped to the customer. This characteristic is commonly referred to as forbidden early shipment. Job shops are one of the most popular shop floor structures in industry. Therefore, exploring the potential of improving the cost performance of job shop manufacturing is of high importance for both researchers and practitioners.

Considering that the industrial community is giving considerable attention to speed and agility in the decade of the 90's, it is justifiable that scheduling deserves significant study and research from the industrial engineering research community. In the decade of the 70's, technology was the key for a successful manufacturing business. The factors that affect the investment in technology (such as automated manufacturing systems or robots) were easily quantified in terms of financial measures. Therefore, the process of justifying such investments was relatively easy. On the other hand, quality was the key word of a successful manufacturing business in the decade of the 80's. It was more difficult to measure the performance of a manufacturing system in terms of financial measures if quality was the aspect of concern. However, the existence of functions such as the Taguchi loss function helped to bridge the gap between technical and financial performance measures. For example, a technical performance measure such as variation from target can be related to financial performance measures such as cost.

However, in terms of the decade of the 90's, where the primary concern is time to market, the gap between technical and financial performance measures is not fully bridged. Considering that lead-time is a technical measure of speed or agility, the effect of reducing the lead-time is not easily quantified in terms of cost or profit. Hence, an investment that leads to reducing the lead-time may not be financially justified. Also, there are other performance measures that are considered in a scheduling problem in addition to the lead-time such as inventory level, lateness and tardiness. Improving one of these performance measures may, and in many cases does, affect other performance measures. However, the trade off between these measures is not clearly understood.

Dispatching Rules

Dispatching rules are a popular technique in scheduling. Dispatching rules are simple heuristics that enable the decision-maker to choose which job to load on a machine (if more than one is available) once it becomes idle. Dispatching rules are also known as sequencing rules. In this research, the terms dispatching rules and sequencing rules are used as synonyms. Dispatching rules provide good results and they are widely used because of their simplicity. Previous research findings in this area show that the dispatching rule that provides the best performance depends on system variables such as due date tightness, tardiness cost and inventory cost.

Performance Measures

Different performance measures are being used in this research area. These performance measures can be divided into two basic categories. The first category is time based performance measures, such as tardiness, earliness, absolute deviation from due date, throughput, time in system, average number of jobs in queue, and several other measures. The second category of measures is monetary based measures such as total cost per period and net present value.

In this research, the primary performance measure of concern is a monetary based performance measure, which is relative cost per job (this term is briefly defined later in this chapter and thoroughly discussed in Chapter IV). However, the cost performance of a system is highly sensitive to the cost structure. Therefore, time based performance measures are monitored as supplementary performance measures to avoid any bias in results caused by the cost structure.

Problem Statement

The sequencing problem in previous research efforts is modeled as a problem that has a continuous action range (the setting of system parameters), and a discrete reaction domain (available sequencing rules). This inconsistency represents a potential problem and an area of research opportunity. This research attempts to model this problem as a problem that has both continuous range and continuous domain. Therefore, the objective of this research can be stated as to "investigate the potential of improving the performance of manufacturing systems through introducing a sequencing rule that has a continuous decision domain".

Definition of Terminology

We define here some of the key terminology used in this research.

Lead-time: Lead time for a job j is defined as the difference between the due date of job j and the order arrival date of job j.

Relative cost: relative cost for a job j is defined as the total incurred cost by a job (due to inventory holding cost and tardiness penalty cost) divided by its selling price.

Forbidden early shipment: If a job is completed before its due date, the job is stored in a storage area until its due date. In this research, the cost associated with completing a job before its due date is the cost of holding this job as inventory. No other penalties are realized as a consequence of completing the job early. However, the holding cost of finished goods is higher than the holding cost of work-in-process.

II Literature Review

Introduction

In this chapter, a review of related literature is presented. This review focuses on the research that studies job shop scheduling in a forbidden early shipment environment considering economic performance measures, since this is the area of concern in this research. The scheduling problem has several aspects including order review and release rules, due date setting and sequencing. The sequencing aspect of the scheduling problem is reviewed in this chapter. Other aspects of the scheduling problem are not reviewed since they are not relevant to this research. The literature review is divided into three sections. First, different methodologies for modeling the financial aspects of the scheduling problem are reviewed. Next, the sequencing problem is considered. Finally, different experimental designs are reviewed in order to help designing the experiment of this resesrch.

Literature Review on Constructing Cost Models

Most studies in this field consider tardiness cost and inventory carrying cost as the two basic cost segments that are affected by scheduling policies. However, the implications of these two factors have been modeled differently.

Ragatz and Mabert (1988), Ahmed (1990), Ahmed and Fisher (1992), and Philipoom et al. (1993) use the same cost structure. The performance measure used in these studies is total cost per period. Holding cost is calculated as a proportion of the work completed on a job (constant per week per hour processing time completed). This assumption means that no cost is associated with holding raw materials, which might not be a realistic assumption. Tardiness penalty cost is considered as a proportion of the holding cost (constant per week per hour processing time completed). The ratio between holding cost and tardiness penalty cost in these studies is 1:20. Other ratios are used for sensitivity analysis. In addition, tardiness penalty in this cost structure is proportional to the work content. Considering that due date allowance is proportional to the work content, the cost structure that is used in the above mentioned studies results in a proportional relationship between due date allowance and tardiness penalty. In the current study, we explore a more realistic tardiness penalty; one that is proportional to some measure of relative tardiness, such as tardiness divided by lead-time.

Rohleder and Scudder (1992) use net present value as the performance measure. They evaluated the inventory holding cost as a proportion of the job cost. Also in their study, there is no inventory cost associated with holding raw materials in stock. The job cost is calculated as the cost of operating the machines (including set-up cost) that a job has visited. They use a holding cost ratio of 20% of the inventory value per year (i.e., 20% of the job value will be incurred as inventory cost if a job waits for one year). The tardiness cost in their study is calculated as 10% of the selling price per year. Scudder et al. (1993) use the same cost structure but modify the holding cost ratio to be 30% and the tardiness penalty ratio to be 20%.

Scudder et al. (1990) also use net present value as the performance measure. In their study, the inventory holding cost is proportional to the job value. They also define the job value as the cost of machine set-up and the cost of machine operation. The researchers assume a just-in-time environment where raw materials arrive at the time of the first operation. Hence, there is no holding cost for raw materials. Two levels of tardiness penalty cost are explored. The first level is zero, i.e., there is no penalty associated with late delivery. The second level is at 25% of job cost per day. This ratio may represent a highly perishable product considering that the average work content is 36 working hours. The same cost structure is used by Yang and Sum (1994).

In a study by Amar and Xio (1997), the authors present an analytical model to minimize total cost in a static job shop (no order arrivals). The authors in this study consider inventory cost only. The authors show that a linear approximation of the time value of money effect is reasonable. The resulting cost structure, after neglecting the compounding effect of interest, is a linear relationship between holding cost and the inventory value multiplied by the waiting time.

Kawtummachai et al. (1997) study static scheduling in an automated flow shop. In their study, tardiness is handled by working overtime. Therefore, the actual tardiness penalty is the extra cost of overtime. Inventory holding cost is divided into two segments. First, work-in-process (WIP) inventory cost and second, final product inventory cost. WIP cost is proportional to the number of jobs in system multiplied by average holding time. The final product inventory cost is proportional to the number of finished goods multiplied by the time finished goods wait for their due date. The difference between the two types of inventory cost is the holding cost factor. The average ratio of holding cost factor for finished goods to holding cost factor for WIP is approximately 15, which is high relative to other research efforts.

Different cost structures have been introduced in the literature, several of which have been reviewed above. Most of these cost structures are based on quantifying inventory holding cost and tardiness penalty cost. Some researchers introduce time value of money into the cost structure. However, the effect of compounding discounting rates has not been shown significant (Amar and Xio, 1997). The inventory and penalty cost that have been used in literature can be expressed in the following generic form:

$$I_j = f(V_j, t_j)$$

where;

I_j: the inventory cost for job j

V_j: the value of job j

t_j: the time job j spent in the system

and

$$P_j = f(V_j, d_j - DD_j)\,;\; d_j > DD_j$$

where;

P_j: is the tardiness penalty of job j

d_j: The time job j departed the system

DD_j: Due date of job j

The following points describe the basic differences between different cost structures:

1. differences in the methodology used to estimate the job value through the cycle time,
2. differences in the relationship between tardiness penalty cost and inventory holding cost, and
3. differences in the cost difference between holding finished goods and WIP.

In the reviewed literature, tardiness penalty depends only on the job value and absolute tardiness. This research explores a more realistic cost structure by expressing the tardiness penalty as a function of job value and relative tardiness. The details of this approach are discussed in Chapter IV.

Literature Review on Sequencing Rules

Sequencing jobs on available machines has received considerable attention in the literature. Many sequencing rules have been proposed. However, few studies are found in the area of this research, which is job shop scheduling in a forbidden early shipment environment considering economic performance measures. In this section, sequencing rules that have been used in forbidden early shipment environments considering financial performance measures are reviewed. Sequencing rules in this area can be divided into two major types. The first type is time based sequencing rules, and the second is monetary based sequencing rules. In general, time based rules perform better than monetary based rules (Hoffmann and Scudder 1983, Scudder and Smith-Daniels 1989, Scudder et al. 1990).

Time based sequencing rules are the rules that use the time attributes of jobs to decide job priorities. Table I illustrates the sequencing rules that have been used in this research area. A survey of sequencing rules can be found in Panwalkar and Iskander (1977).

The rules listed in Table I are job-dependent rules. In some research, the authors use the operation-dependent versions of these rules. For example, the operation-based version of SPT is to give the priority for the job that has the shortest operation processing time rather than shortest remaining processing time.

In general, critical ratio (CR) has been found to be the dominant rule that performs best in forbidden early shipment in most shop structures (Ragatz and Mabert 1988, Scudder et. al 1990, Rohleder and Scudder 1992, Ahmed, 1990 and Ahmed and Fisher, 1992).

Sequencing Rule	Description
FCFS (First Come First Served)	Process the job that arrived first to the queue
SPT (Shortest Processing Time)	Process the job that has the least total remaining processing time
CR (Critical Ratio)	Process the job that has the least critical ratio CR= (Time remaining until due date)/ (Total remaining processing time.)
EDD (Earliest Due Date)	Process the job with earliest due date
MDD (Modified Due Date)	Process first the job that has the earliest modified due date. Modified due date is defined as the maximum of job due date and its early finish time. Early finish time is defined as current time plus total remaining processing time.

Table I - Summary of Relevant Time Based Sequencing Rules

In the study by Ragatz and Mabert (1988), CR performs the best regardless of due date tightness and utilization level. In some cases, EDD and CR perform the same statistically (the authors did not specify these cases). In the case of 1:1 cost ratio between inventory cost and lateness cost, EDD dominates other sequencing rules in providing the lowest cost.

In the study of Ahmed and Fisher (1992), EDD and CR are found to be the best rules in most cases depending on the release mechanism and due date setting rule. Their study concentrates on the interaction between sequencing rules, due date assignment rules and release mechanism.

Philipoom et al. (1993) reach interesting results that are not consistent with other literature. They compare the performance of SPT to CR under different conditions of due date tightness, machine utilization and release rules. Their results show that SPT out performs CR in most cases. CR is better only in the case of loose due date setting. The authors conclude that this inconsistency with the literature might be attributed to the high tightness level used. In addition, as the ratio between penalty cost and inventory cost is reduced (1:1), CR outperforms SPT in both loose and medium due date tightness.

Scudder et al. (1990) also find CR to be the best rule, yielding the highest net present value in most of the cases they studied. CR ratio is compared with monetary based rules.

Scudder et al. (1993) find that operation based rules performs better under tight due date conditions, but as due dates are relaxed, job based rules perform better. They find that CR based rules and modified due date (MDD) perform the best considering NPV criterion. The results of this research are consistent with a previous work of Rohleder and Scudder (1992).

Monetary based rules are the rules that use the financial information of jobs. Several researchers have examined monetary based rules. The general findings in this area show that time based rules perform better than monetary based rules (Scudder et al. 1990).

Yang and Sum (1994) introduce two new rules that performed better than CR. The rules they introduce combine CR and tardiness penalty of the job. Their rules consist of a threshold based on the critical ratio. The jobs that have critical ratio above the specified threshold are scheduled based on weighted critical ratio (WCR) defined as follows:

WCR= CR/Hourly tardiness cost

In their study, job value and processing time for a job are sampled from independent distributions, which might give an advantage to the rule they introduced since it considers both processing time and job value (by considering tardiness cost).

However, if job value is considered to be proportional to the processing time, then the hourly tardiness cost will be proportional to the processing time and their rule becomes:

WCR= CR/Total processing time

= Time remaining until due date/ (remaining processing time*total processing time)

The above rule is a modification of the critical ratio rule by modifying the weight of the processing time in the critical ratio rule. However, the improvement achieved by Yang and Sum (1994) is not definitely attributed to modifying the critical ratio rule. The problem scenario in their research, which samples the job value and work content from independent distributions, may have affected the results.

In general, many researchers categorize dispatching rules according to their information content. For example, Chang et al. (1996), divide dispatching rules into, shortest processing time based rules, longest processing time based rules, due date based rules, slack based rules and queue status based rules. The results of choosing the best sequencing rule are usually attributed to the information content of the sequencing rules. Chang et al. conclude that if tardiness is the performance measure of concern, a due date based rule work the best. They also conclude that a shortest processing time based rule is the best rule to choose if completion time or flow time is the major performance measure of concern. Using the same concept, Montazeri and Wassenhove (1990) conclude that shortest processing time based rules minimize waiting times.

The review of research in this area shows critical ratio (CR) performs the best in most configurations. Other rules that performed well in the literature are EDD and to a lesser extent SPT. The literature suggests that the most important factors that affect the performance of sequencing rules are due date tightness level, system utilization, and cost structure of the system.

The best sequencing rule can be changed as the operating conditions change. Pierreval and Mebarki (1997) introduce a strategy that selects the sequencing rule based on the system conditions and/or based on the performance measure considered. Also, Wu and Wysk (1989) introduce an algorithm that allows selecting the sequencing rule for each short period. In both of these research efforts, the selection of the best sequencing rule is limited to the available sequencing rules. Also, at each change oppurtunity, the decision is either to change the current rule or stay with the current rule. Therefore the decision has discrete a domain in these cases.

Literature Review on Experimental Design

The objective of this section is to help in designing the job shop structure that will be studied in this research. A Job Shop is defined by APICS (1970) as follows:

> "A functional organization whose departments or work centers are organized around particular types of equipment or operations, such as drilling, forging, spinning, or assembly. Products flow through departments in batches corresponding to individual orders, which may be either stock orders or individual customer orders."

The factors that affect the job shop structure are the following:

1. the number of machines in the job shop,
2. the number of operations and the routing of each job,
3. the utilization level, order arrival process and processing time, and
4. the due date setting procedure.

Number of machines: Most researchers use environments with the number of machines between five and nine. Ragatz and Mabert (1988), Vig and Dooley (1991) and Ahmed and Fisher (1991) study a five-machine job shop. Christy and Kanet (1990), Kanet and Christy (1989) study an eight-machine job shop environment. A model that is introduced by Hoffmann and Scudder (1983) consists of nine machines. This model has been used in several research efforts thereafter, e.g., Rohleder and Scudder (1992) and Yang and Sum (1994). Philipoom et al. (1993) use a 15-machine job shop as an experimental environment for their research.

Routing and number of operations: In most of the related literature, the average number of operations per job is either four or five operations in most cases. For example, in the study by Philipoom et al. (1993), the number of operations is sampled from a uniform distribution ranging from three to seven operations. Also, in the often used model introduced by Hoffmann and Scudder (1983) the number of operations varies from two to seven with an average of four (no more information about the probability distribution is given). In the above studies, researchers use random routing. Each machine has the same probability of being visited next once a job completes one of its operations. Revisiting is allowed but not consecutively. This purely random routing represents a more difficult control problem and any bias introduced by this purely random flow should be considered in the conservative direction (Ragatz and Mabert, 1988).

Order arrival, processing time and utilization: Consistently, the arrival process follows a Poisson process in the reviewed literature. However, different distributions were used to model the processing time. Philipoom et al. (1993), Ahmed and Fisher

(1991), and Ragatz and Mabert (1984) use an exponential distribution to model the processing time. Vig and Dooley (1991) use a 2-Erlang distribution. Hoffmann and Scudder (1983) use a truncated normal distribution with a standard deviation equal to one ninth of the mean. The variance is increased by other researchers who studied the same system, e.g., Rohleder and Scudder (1992) who use a standard deviation equal to one third of the mean. The mean interarrival time and the mean process time are set to achieve a desired level of utilization. The above researchers use utilization levels between 85% and 93%.

In most of the above research, preemption, breakdown, and splitting of jobs are not considered. Also, setup time is usually included in processing time. Only Hoffman and Scudder (1983) explicitly consider setup time in their model.

Due Date Setting: Many procedures are used in literature to set due dates. Excellent reviews of due date setting mechanisms can be found in Ahmed (1990), Cheng and Gupta (1989), and Ragatz and Mabert (1984). The rule that shows the best performance in different settings is total work content (Kanet and Christy 1989, Baker 1984). Therefore, most of the research in this area use a TWK rule (e.g., Ragatz and Mabert, 1988, and Philipoom et al. 1993). TWK is defined as follows:

$$DD_j = a_j + k\sum_{i=1}^{n} p_{ij}$$

where;

DD_j: is the due date of job j

a_j: Arrival time of job j

p_{ij}: is the processing time of operation i for job j

k: allowance factor

n: number of operations

Different procedures are adopted in the literature to select the value of k. In general, researchers study three values of k that result in three due date tightness levels, loose, medium and tight. Ragatz and Mabert (1988) choose the values of k such that the resulting number of tardy jobs is 5%, 10%, and 20% for loose, medium and tight due dates respectively when FCFS is used. Yang and Sum (1994) use the same procedure but they use CR instead of FCFS. Philipoom et al. (1993) use a k value ranging from 4.3 to 10.9. Baker and Kanet (1983) use allowance factor values between 2.5 and 20.

Conclusion

The literature review shows that the selection of best sequencing rule depends on the systems parameters. Although the change in system parameters has continuous range, the response (selecting the best sequencing rule) has a discrete domain. The research gap that this research attempts to fill is providing a mechanism that quantifies the response domain (selecting the best sequencing rule) over a continuous range.

III Research Goals and Objectives

The main goal of this research is to introduce a sequencing rule that has more flexibility than existing sequencing rules. One important characteristic that is needed in such a rule is that it should have a continuous decision domain.

In this research, we propose a modified critical ratio rule CR_z. We define the modified critical ratio rule as follow

$$CR_z = \frac{DD_j - t}{(rp_j)^z};$$

where;

CR_z: is the modified critical ratio

DD_j: is the due date for job j

rp_j: is the remaining processing time for job j

t: is the current time

z: a power factor

The value of the power factor z is to be determined as a function of system parameters. Consider the following two values of the power factor (z); zero and one. These values of z will result in the following.

1. If z is set to zero, CR_z yields

$$CR_z = \frac{DD_j - t}{(rp_j)^0} = DD_j - t;$$

Which is the EDD rule

2. If z is set to one, CR_z yields

$$CR_z = \frac{DD_j - t}{(rp_j)^1} = \frac{DD_j - t}{(rp_j)};$$

Which is the CR rule.

The above cases show that using an appropriate value of z, the modified critical ratio rule yields decisions consistent with EDD or CR. Using other values of the power factor z, over its continuous range, yields other (hopefully superior) sequencing decisions.

Research Objective

The primary objective of this research is to investigate the potential of improving the cost performance for a given job shop using the modified critical ratio rule. The effect of three factors on z value will be studied in this research. These three factors are due date tightness, cost structure and machine utilization.

Tasks

The tasks required to accomplish the research goal are the following.

1. develop the job shop model and the cost structure,
2. develop the simulation model,
3. perform pilot runs to finalize experimental factors,
4. execute the simulation experimental design,
5. analyze the simulation results,
6. develop the empirical formula of the power factor z,
7. develop conclusions and recommendations,
8. document the research, and
9. identify areas of future research.

IV Research Methodology

Simulation is the evaluation tool in this research. Simulation is widely used in this research area since developing analytical solutions for job shops with dynamic arrivals is difficult and requires many assumptions. In order to use simulation as an analysis tool, we developed a job shop model to be used in this research. The SLAM II simulation language (Pritsker, 1995) is used to simulate the job shop. The job shop was developed to be consistent with other literature based model. In addition, the literature has been considered in developing the cost structure. However, we propose a major modification in modeling the tardiness penalty. Traditionally, tardiness penalty has been calculated as a function of job value and absolute tardiness. In this research, we consider the tardiness penalty as a function of job value and relative tardiness. Relative tardiness will be modeled with respect to lead-time. As discussed in the literature review, tardiness penalty cost and inventory holding cost have been modeled in the following generic forms:

$P_j = f(V_j, d_j - DD_j)$, and

$I_j = f(V_j, t_j)$.

In this research, the inventory carrying cost will follow the same generic form. However, the tardiness penalty cost will be modeled as

$$P_j = f\left(V_j, \left\{\frac{d_j - DD_j}{DD_j - a_j}\right\}\right)$$

where;

I_j: the inventory cost for job j;

V_j: the value of job j.;

P_j: is the tardiness penalty of job j;

d_j: The time job j departed the system;

DD_j: Due date of job j; and

a_j: the order arrival time of job j.

Figure 1 illustrates how the tardiness penalty cost is modeled. A job will accumulate tardiness penalty cost equal to its selling price if it is late for a period proportional to its lead time. The constant pt shown in Figure 1 is defined as the penalty tightness factor. Two levels of penalty tightness factor (pt) are studied in this research; 1 and 2. If the penalty tightness factor is set to 1, it means that a job will incur tardiness penalty cost equal to its selling price if it is late for the period of its lead time. Similarly, a job will incur tardiness penalty cost equal to its selling price if its lateness is twice its lead time, when pt is set to 2.

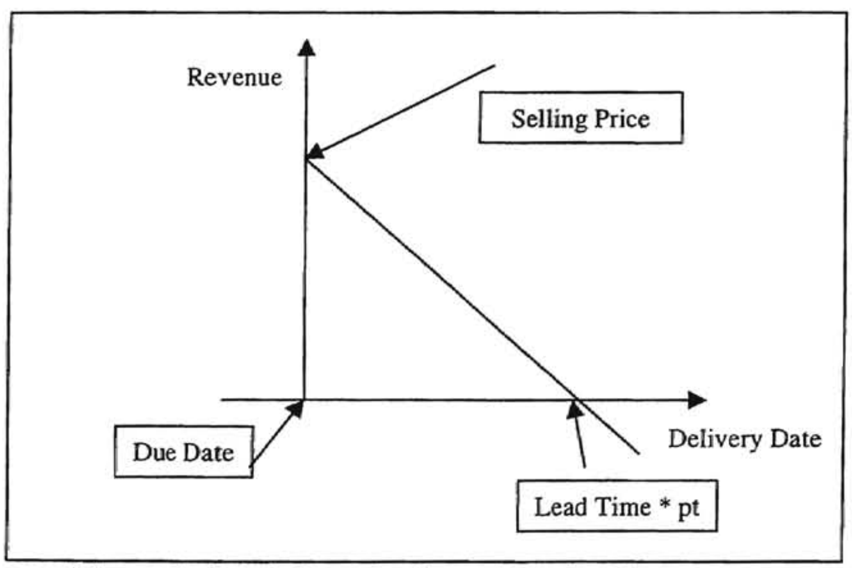

Figure 1 - Modeling Tardiness Penalty Cost

Assumptions

The following assumptions are made in this research.

- Machine breakdown is not considered.

- No scrap or rework is taken into account.
- Queue capacities are infinite.
- Preemption is not allowed.
- Set-up time is included in the work content of each job.
- Time value of money is included in the holding cost and penalty cost factors.
- Jobs are released to the shop floor immediately after receiving the order.
- The cost structure is valid in environments where relative tardiness is valid as a performance measure.

Job Shop Description

In this research, we study a job shop that consists of seven machines. Orders arrive for one unit of each product. Each product is unique therefore, setup time is included in processing time. The number of operations required to complete a job is sampled from a discrete uniform distribution from three to seven operations. The duration of each operation for a job is sampled independently from a uniform distribution of [3.5, 6.5] time units. Routing of jobs is set randomly such that a job has the same chance of visiting any machine except the machine that is visited at the current operation. Therefore, revisiting is allowed but not consecutively. Interarrival time of orders is exponentially distributed. The mean of the exponential distribution is set so that the desired utilization level (an experimental factor) is achieved. The mean of the interarrival time is set according to the following equation

$$\lambda_0 = \frac{1.4\rho}{\mu}$$

where;

λ_0: is the order interarrival time

μ:: is the average processing time

ρ: is the desired machine utilization.

A complete derivation of the above equation can be found in Appendix 1.

After all operations are completed for a job, the job will wait if it is completed before its due date. Otherwise, the job will leave the system.

Due dates are set on one of three levels; loose, medium and tight. The Total Work Content method (TWK) is used to set the dates. The value of the constant k is chosen to be 3, 6 and 9 to generate loose, medium and tight due dates. Some researchers set the due dates tightness based on the number of tardy jobs. For example, Ragatz and Mabert (1988) set the levels of the allowance factor k so as 5%, 10%, and 20% tardy jobs are achieved when FCFS sequencing rule is applied. In this research, we refrained from following this procedure since the percentage of tardy jobs does reflect the actual performance of the manufacturing system of concern in this research. The percentage of tardy jobs depends on the sequencing rule applied at the queues. Also, average tardiness is not correlated with the number of tardy jobs. A given sequencing rule might produce low percentage of tardy of jobs which indicates that the due dates are loose, however, the average tardiness produced by this rule may be high which contradicts the conclusion that the due date are loose.

The selling price (S_j) of each job is linearly proportional to its processing time. The raw material cost of a job j (R_j) is 30% of its selling price (S_j) and the value added to each job is 20% of its selling price. The value added at each operation is proportional to the proportion of work content completed at this operation. This cost structure assumes that 50% of the selling price is allocated for profit and overhead expenses. Also, it is assumed that 25% of the selling price is allocated for overhead expenses and 25% is allocated for profit. After a job is completed, its value is 75% of its selling price (S_j), which includes raw material cost, value added, and overhead expenses. The job value is increased instantaneously after an operation is completed. The job value is used to calculate the inventory value. The various percentages in this approach were set arbitrarily but are believed to be representative of realistic scenarios.

Cost Structure

The performance measure in this research is average relative cost per job as defined below.

$RC_j = TC_j / S_j$

where:

RC_j: average relative cost per job

TC_j: total incurred cost for a job j. The total incurred cost is the sum of inventory holding cost and penalty cost.

S_j: the selling price for job j

Two types of costs are considered in this research. First, the inventory holding cost and second the penalty cost. As discussed in the literature review, these two segments are the two major segments that have been introduced in the literature.

The inventory holding cost per job is defined as follows:

$$I_j = \int_{rj}^{dj} HV_j dt$$

where;

I_j: is the inventory holding cost for job j

H: is the holding cost factor

V_j: is the value of job j

r_j: is the release time for job j (the time at which job j is released to the shop floor)

d_j: is the time job j departed the system.

Since the system of concern is a discrete system, the above integration can be expressed as follows:

$$I_j = \sum_{i=1}^{n+1} HV_{i,j}(t_{i,j} - t_{i-1,j})$$

where;

I_j: is the inventory holding cost for job j;

H: is the holding cost factor;

$V_{i,j}$: is the value of job j before being processed on machine I; and

$t_{i,j}$: is the time at which job j leaves machine i, $t_{0,j} = r_j$.

Note that $V_{1,j}$ is the cost of raw material for job j (R_j). The storage area where jobs wait until their due date is modeled as the machine number (n+1). The value of a job in the storage area will considered 75% of the selling price for the purpose of estimating the holding cost in the storage area. The value of H will be set so the raw material of an average job (5 operations, 5 days each) will incur 5% of its selling price, if the raw material is stored for the period of the job's lead time. The holding cost ratio will vary between 2.7% (for a job that needs 3 operations, 3.5 days each) and 9.1% (for a job that needs 7 operations, 6.5 days each) according to this configuration.

The second segment of cost that is considered is the penalty cost caused by missing a due date. The penalty cost is defined as follows:

$$P_j = p_j[d_j - DD_j]^+ = p_j(\max[0, d_j - DD_j])$$

Where;

P_j: is the penalty cost for job j;

p_j: is the penalty cost factor for job j;

DD_j: is the due date for job j; and

d_j: is the time job j departed the system.

The value of the factor p_j is set so that the tardiness penalty cost is proportional to the job's lead-time. The factor p_j is calculated as follows:

$$p_j = \frac{S_j}{pt(DD_j - a_j)}$$

where;

S_j: is the selling price of job j

pt: is the level of penalty, when pt =1, the penalty cost is equal to the selling price if a job tardiness is equal to its lead time.

p_j: is the penalty cost factor for job j

DD_j: is the due date for job j

a_j: is the arrival time for job j

Example

Consider a simplified system that consists of two machines. The initial conditions are idle and empty. The value of H is 0.01. Two jobs are considered and their attributes are shown in Table II.

	Job 1	Job 2
Arriving time	0	2
Routing	1-2	2-1
Processing Time on machine 1	10	1
Processing Time on machine 2	5	1
Due Date	45	8
Selling price ($)	75	10

Table II - Example Description

Table III describes the events each job goes through:

Time	Event
0	Job 1 starts its first operation on machine 1
2	Job 2 starts its first operation on machine 2
3	Job 2 finishes its first operation and waits for machine 1
10	Job 1 finishes its first operation and starts its second operation on machine 2
10	Job 2 starts its second operation on machine 1
11	Job 2 finishes its second operation and leaves the system
15	Job 1 finishes its second operation and waits until its due date
45	Job 1 leaves the system

Table III – Description of Events

Note that Job 1 finishes 30 time units early and Job 2 finishes 3 time units late. Table IV shows the cost variables that will be used to calculate the cost of each job. The variables shown in Table IV are calculated using the approach described in the previous section. After identifying all the cost variables, the relative cost ratio for each job is calculated as follows.

For Job1:

$$I_1 = \sum_{i=1}^{n+1} HV_{i,1}(t_{i,1} - t_{i-1,1})$$

$$= 0.01(22.5)(10) + 0.01(30)(5) + 0.01(56.25)(30) = \$20.63$$

$$P_1 = p_1[d_1 - DD_1]^+ = 0.08333(0) = \$0.00$$

$TC_1 =$ \$20.63

$RC_1 = 26.63/75 = 27.5\%$

The interpretation of this number is that the sum of inventory cost ($20.63) and tardiness penalty cost ($.00) is 27.5% of the selling price ($75.00)

For job 2:

$$I_2 = \sum_{i=1}^{n+1} HV_{i,2}(t_{i,2} - t_{i-1,2})$$

$$= 0.01(3)(1) + 0.01(4)(10) + 0.01(7.5)(0) = \$0.70$$

$$P_2 = p_2[d_2 - DD_2]^+ = 0.8333(3) = \$2.50$$

$$TC_2 = 0.70 + 2.50 = \$3.20$$

$$RC_2 = 3.2/10 = 32\%$$

Variable	Description	Value
R_1	Raw Material Cost of Job 1	$22.50
R_2	Raw Material Cost of Job 2	$3.00
p_1	Penalty cost factor for job 1	$0.8333/ time unit
p_2	Penalty cost factor for job 1	$0.8333/ time unit
$V_{1,1}$	Value of Job 1 before being processed on machine 1	$22.50
$V_{2,1}$	Value of Job 1 before being processed on machine 2	$30.00
$V_{3,1}$	Value of Job 1 after completing all operations	$56.25
$V_{2,1}$	Value of Job 2 before being processed on machine 1	$3.00
$V_{2,2}$	Value of Job 2 before being processed on machine 2	$4.00
$V_{3,2}$	Value of Job 2 after completing all operations	$7.50

Table IV - Values of Cost Variables

Research Factors

The effect of the following factors on cost performance will be considered:

1. due date allowance factor (k),
2. penalty tightness (pt),
3. power factor z, and
4. system utilization.

Due date allowance factor levels are 3, 6, and 9. Two levels of penalty tightness are considered, pt = 1 and pt = 2. The effect of utilization is studied on two levels of 85% and 92%. At each of these combinations, the value of z that yields the best performance measure of concern is determined experimentally.

Simulation Model

The SLAM II simulation language is used to simulate the job shop described above. All the job's attributes are assigned at the time the job arrives to the system. This ensures that jobs in different simulation scenarios have the same attributes. Therefore, the simulation runs are dependent due to common random numbers and a paired t-test can be used to establish desired conclusions. A paired t-test is stronger since it eliminates the variation between simulation runs due to using different random number streams in different runs. A complete description of the simulation model can be found in Appendix 2.

Simulation Characteristics

Three characteristics are important to ensure good simulation results. These are run length, warm up period and number of replications.

Warm up period is specified by observing variation of the performance measure (average relative cost) with run time. The procedure described in Law and Kelton (1991) was followed to determine the length of the warm up period. The number of replications we used to apply this procedure is seven replications. Also, we used a window length w of 800. The time after which the relative cost values are stable (plus a safety factor) is set to be the warp up time. Figure 2 shows the moving average of the performance measure. As shown in Figure 2, the average relative cost is observed to stabilize after 3,000 to

4,000 jobs leave the system. However, since execution time was not a major limitation in this study, a conservative warm up period of approximately double this number of jobs is used. The warm up time is set at 30,000 time units which corresponds to approximately 7,500 jobs.

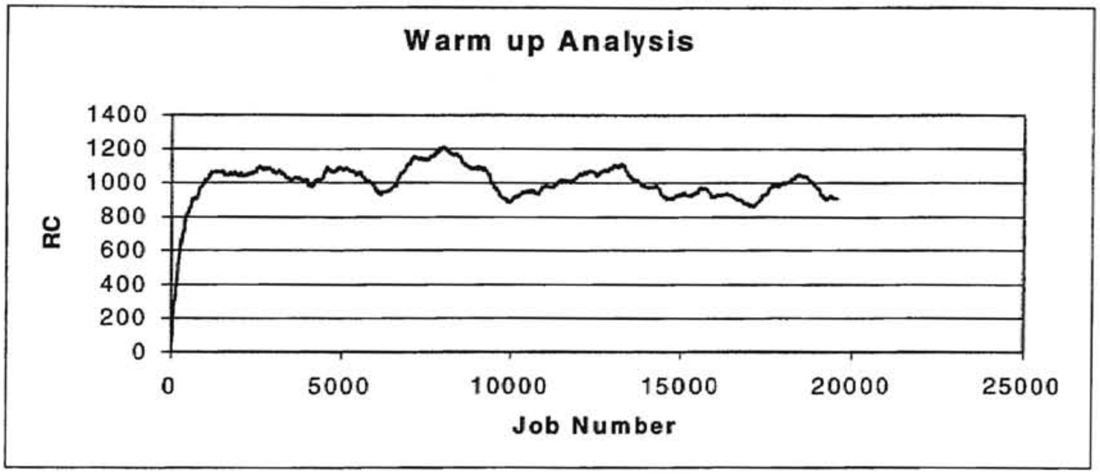

Figure 2 – Warm up Analysis

The run length is determined to be 400,000 time units. This run length is longer than the recommended rule of thumb that suggests a run length equal to ten times the warm up period. The number of replication used in each run is 10 replications.

The above values were acceptable after analyzing the simulation results. The results based on the above characteristics were found accurate enough to establish conclusions based on a paired t-test. The above parameters (run length and number of replications) were chosen so that the performance of different sequencing rules will be statistically different using a paired t test.

Simulation Verification and Validation

Verification is the process of ensuring that the simulation program is executed properly. Tracing is a very effective tool to perform the verification process. Extensive tracing reports were generated. Entities (jobs) were traced to ensure that the entities went through the proper sequence of events and the proper assignment of attribute values. Also, tracing reports showed that priority was given to a job in the queue according to the intended dispatching discipline.

Validation is the process of ensuring that the model is representing the real system. Since there is no existing real system that can be used to compare the simulation results, the validation process can not be conducted in this manner. Validation has been conducted by comparing the simulation results with similar published research results. Consistence with the literature, the critical ratio rule was found to perform the best in most cases, also the shortest processing time was found to be the best rule under very tight due date conditions. Also, the simulation output indicated that the utilization level of the machines, average processing time, and average number of operations corresponded with the expected values.

V Results

As discussed previously, 12 different system configurations were studied. Table V describes the value of each experimental factor for each of these configurations.

Experiment	K (due date allowance factor)	U (Utilization)	pt (penalty tightness factor)
1	3	85%	1
2	3	85%	2
3	3	92%	1
4	3	92%	2
5	6	85%	1
6	6	85%	2
7	6	92%	1
8	6	92%	2
9	9	85%	1
10	9	85%	2
11	9	92%	1
12	9	92%	2

Table V Description of Experimental Configurations

For each experiment, multiple values of the power factor z were evaluated. These values included zero and one, to generate results equivalent to the EDD and CR rules. In addition, the SPT rule was evaluated (not using the CR_z formulation). A search for the best value of z based on relative cost performance was conducted. A statistical comparison of the performance of modified critical ratio rule at the best identified z value and the SPT, EDD, and CR was conducted using a paired t-test.

The primary performance measure of this research is relative cost. Other time based performance measures are monitored to assure that the superior performance of the modified critical ratio is not influenced by the cost structure introduced in this research. The time based performance measure monitored are tardiness, earliness, and absolute deviation from due date.

The following results were collected from the simulation model:

1. average tardiness of tardy jobs,
2. average earliness of early jobs,
3. average relative cost per job,
4. number of early jobs, and
5. number of tardy jobs,

In addition to the above measures, average inventory holding cost per job and average tardiness penalty cost of tardy jobs is collected. However, these statistics were not considered as performance measures; but they are used to help explain and draw conclusions about certain behaviors of the system.

The rest of this chapter is organized as follows. First, the performance of the modified critical ratio rule is compared with other benchmarking rules considering relative cost as the performance measure. Second, the results showing performance of different sequencing rules considering supplementary time based performance measures are presented. The performance of modified critical ratio rule using different values of the power factor z is discussed next. Finally, the setting of the best value of z as a function of the system parameters is discussed.

Results Considering RC Performance Measure

This section compares the performance of the modified critical ratio rule with EDD, CR, and SPT rules. The results presented in this section regarding the performance of the modified critical ratio rule are the results achieved by using a z value that yields the best relative cost value at each configuration. Table VI shows the average relative cost achieved by using the SPT, EDD, CR, and CR_z rules respectively, in each of the experiment configurations listed in Table V. The improvement achieved by using the modified critical ratio rule over the best sequencing rule in each experiment configuration is also presented in Table VI. The best performance among SPT, EDD and CR is marked by an asterisk.

Experiment	Average RC when using SPT	Average RC when using EDD	Average RC when using CR	Average RC when using CR_z	% Improvement compared with best rule
1	38.0%	36.17%	*32.24%	31.95%	0.89%
2	21.4%	20.29%	*18.12%	17.97%	0.79%
3	*101.8%	130.46%	119.33%	103.70%	-1.85%
4	*54.4%	68.42%	62.73%	54.84%	-0.79%
5	16.3%	9.36%	*8.78%	8.76%	0.26%
6	12.7%	8.74%	*8.51%	8.50%	0.19%
7	42.1%	30.66%	*24.81%	23.59%	4.91%
8	16.7%	13.66%	*13.80%	13.64%	0.17%
9	26.2%	19.24%	*16.20%	15.56%	3.95%
10	15.5%	13.65%	*13.79%	13.61%	0.25%
11	15.6%	30.31%	*13.74%	13.40%	2.47%
12	14.0%	22.56%	*12.77%	12.59%	1.46%

Table VI - Results Considering RC Measure

A paired t-test was used to test whether the results are significantly different at 95% confidence level. For each experiment, the performance of each rule was found significantly different from the performance of other rules. Table VII shows the results obtained by applying the modified critical ratio rule and the critical ratio rule for experiment 6 (K=6, U=85%, pt=2).

The procedure followed to test the significance of the difference is demonstrated using the values shown in Table VII.

H_0: The difference between CR and $CR_{1.2}$ is zero

H_1: The difference between CR and $CR_{1.2}$ is not zero

Rejection criterion: Construct a 95% confidence interval for the difference. If the confidence interval contains zero, do not reject the null hypothesis, else reject the null hypothesis.

The width of the confidence interval (CIW) is obtained using the following equation:

$$CIW = t_{\alpha/2} \frac{s}{\sqrt{n}}$$

The value of $t_{\alpha/2}$ for α= 95% is 2.228, and the standard deviation for the difference column in Table VII is 0.145. Hence, the width of confidence interval CIW will be 0.102. The average of the Difference column in Table VII is - 0.153. Therefore, the upper bound of the confidence interval is - 0.509. Hence, the null hypothesis is rejected and we conclude that the performance of $CR_{1.2}$ is statistically better than the performance of CR.

Replication	CR Results	$CR_{1.2}$ Results	Difference
1	84.85	85.03	-0.18
2	84.69	85.04	-0.35
3	84.31	84.23	0.08
4	85.58	85.86	-0.28
5	85.25	85.45	-0.2
6	84.36	84.61	-0.25
7	85.19	85.11	0.08
8	85.14	85.36	-0.22
9	86.04	86.19	-0.15
10	84.09	84.15	-0.06

Table VII – Results of sample experiment (6)

The modified critical ratio rule provides better performance than other tested sequencing rules in all cases except for experiments 3 and 4 at which the utilization level is 92% (high) and the due date allowance factor is 3 (tight). In these cases, the maximum value of z that was tested is 22 due to computer execution limitations[1]. Figure 3 shows the performance of each sequencing rule at the high utilization level and Figure 4 shows their performance at the low utilization level. It is noteworthy that the penalty tightness factor does not appear to affect the conclusion of this research. The performance of different sequencing rules is consistent at the two levels of the penalty tightness factor pt. Also, the next sections will show that the value of best z does not change when the penalty tightness factor pt is changed from 1 to 2.

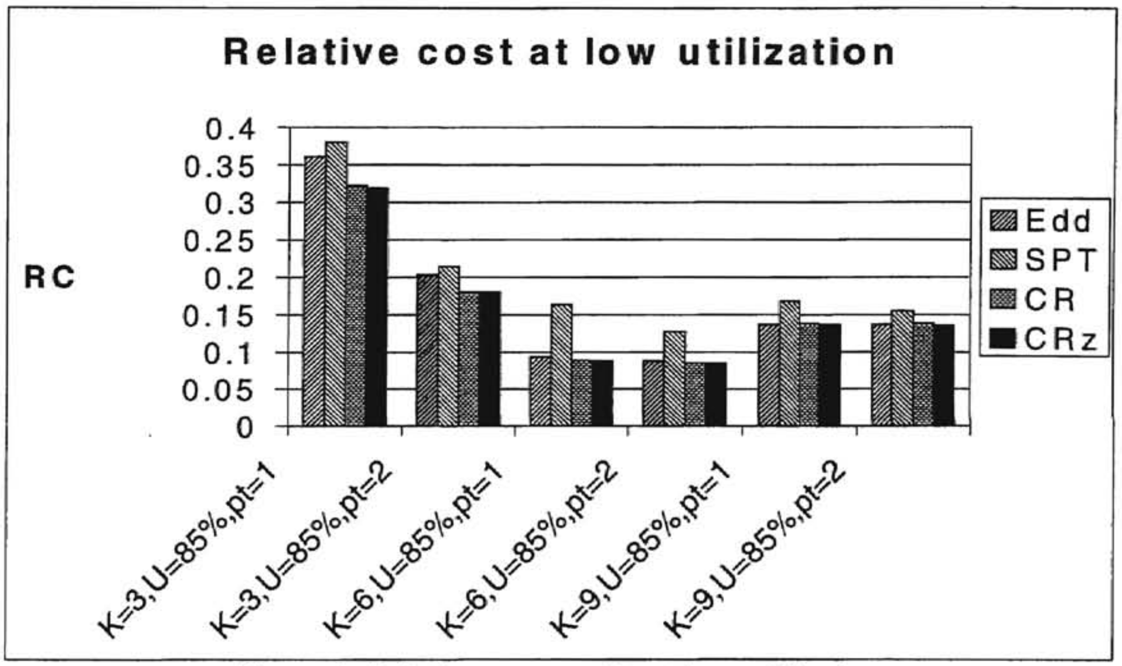

Figure 3- Relative cost results at low utilization

[1] FORTRAN Language gives an execution error if a number is larger than $9.9X10^{38}$. At z value greater that 22, some of the numbers become greater than $9.9X10^{38}$

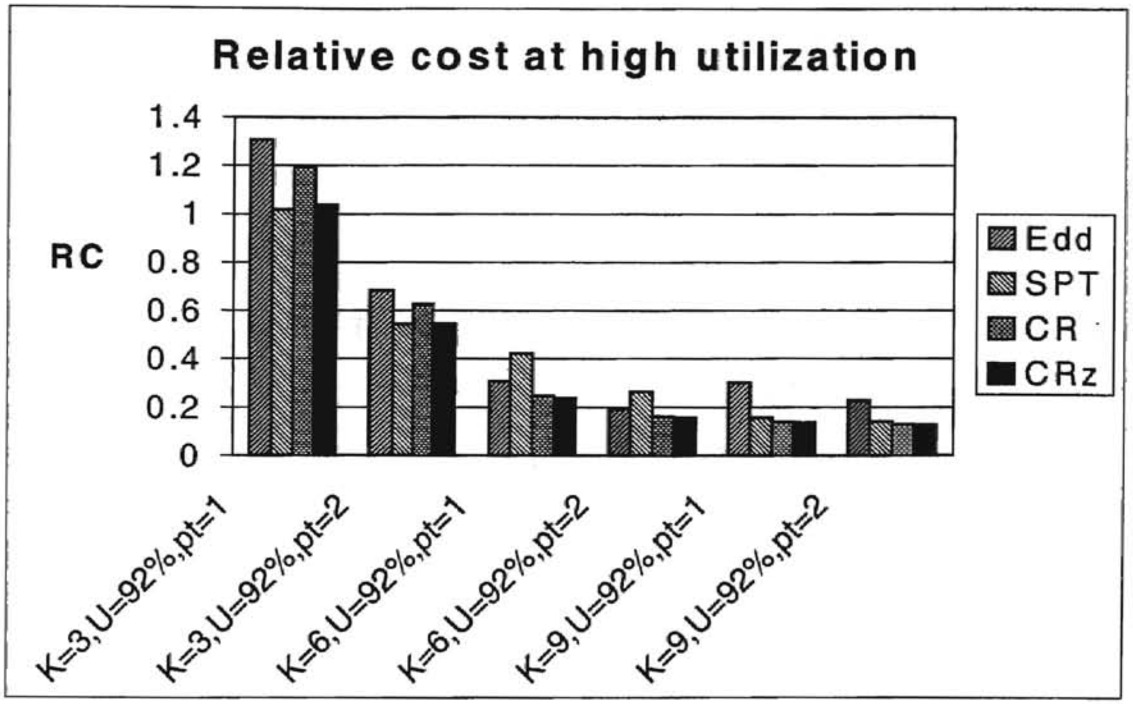

Figure 4 - Relative Cost Results at high utilization

Results Considering Time Based Supplementary Performance Measures

Tables VIII through X present the performance of the modified critical ratio rule compared with other sequencing rules considering tardiness, earliness and absolute deviation from due date measures, respectively. The same set of main experiments shown in table V was used. However, more values of the power factor z were evaluated in some cases to find the z value that yields the best performance for each particular performance measure. Since the cost structure is not a factor when time based performance measures are considered, there are six, rather than 12, experimental configurations when time-based performance measures are considered. The same statistical test discussed showed that the performance of each rule is significantly different than the performance of other rules at each experiment. The SPT rule is known to perform the best when average flow time performance measure is considered. However, since we are concerned with a forbidden early shipment environment, a comparison between the SPT rule and the modified critical ratio rule is not conducted. The comparison between the modified critical ratio rule and the SPT rule is conducted to test whether SPT will still outperform the modified critical ratio rule when due date related measures are considered.

Experiment	Average Tardiness When Using SPT	EDD	CR	CR_z	% Improvement
1, 2	32.22	24.23	21.48	21.28	1.09%
3,4	94.33	89.14	86.09	82.83	3.79%
5,6	14.59	1.96	1.17	0.82	31.73%
7,8	65.07	33.52	26.43	24.88	5.88%
9,10	7.74	0.09	0.03	0.02	39.64%
11,12	48.41	8.96	4.45	3.75	15.58%

Table VIII – Average Tardiness results

Experiment	SPT	EDD	CR	CR_z	% Improvement
1, 2	14.91	6.69	4.67	3.83	17.96%
3,4	10.88	1.24	0.59	0.48	17.67%
5,6	62.85	60.13	52.88	50.55	4.42%
7,8	56.63	21.67	16.77	13.69	18.39%
9,10	141.07	133.87	122.31	119.45	2.34%
11,12	114.95	73.28	63.77	55.39	13.14%

Table IX – Average Earliness Results

Experiment	SPT	EDD	CR	CR_z	% Improvement
1, 2	47.13	30.92	26.15	25.50	2.47%
3,4	105.21	90.39	86.68	83.49	3.68%
5,6	77.44	62.10	54.08	52.35	3.20%
7,8	121.70	55.19	43.20	38.77	10.26%
9,10	148.81	133.96	122.34	119.47	2.35%
11,12	163.37	82.23	68.22	60.11	11.88%

Table X – Average Absolute Deviation from Due Date Results

Figures 5, 6 and 7 show the performance of the modified critical ratio rule compared with other experimented rules. In Figure 5, average tardiness results for experiments 5 and 9, are not included. The average tardiness in these experiments is very small, and it can not be compared with other experimental results on the same scale.

Also, in Figure 7, average earliness results for experiment 4 are not shown for the same reason.

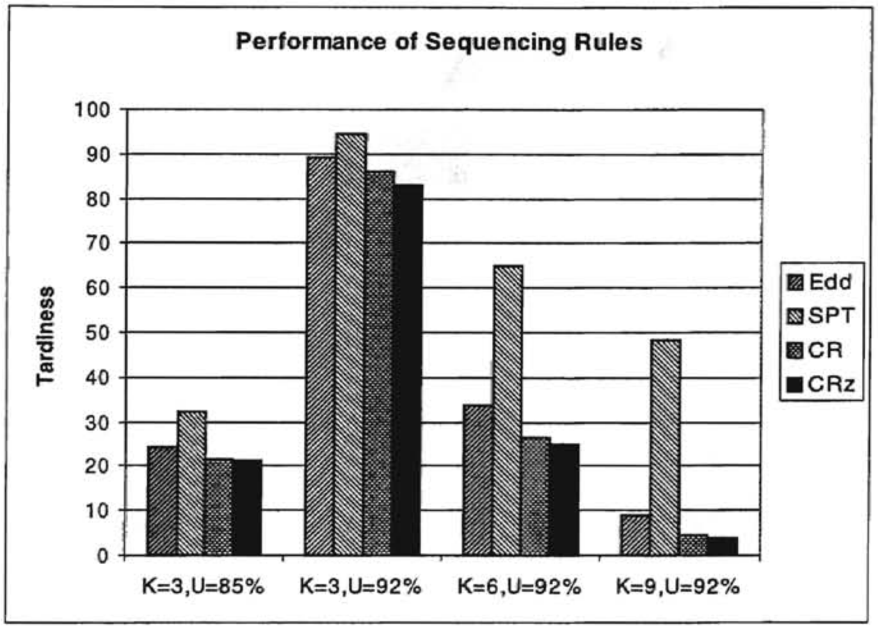

Figure 5- Average Tardiness Results

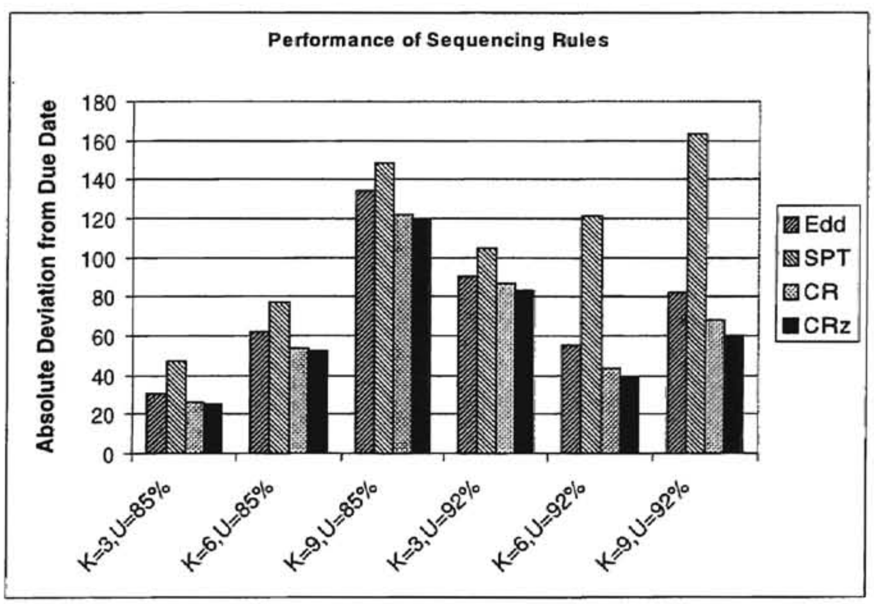

Figure 6 – Average Absolute Deviation from Due Date Results

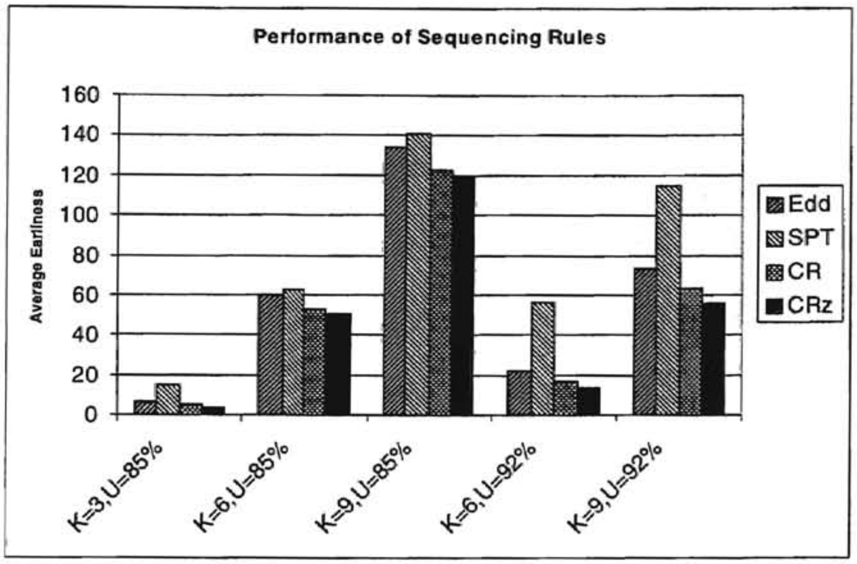

Figure 7- Average Earliness Results

These results show that the modified critical ratio rule outperforms other tested rules in all configuration settings in each time based performance criteria considered. This assures that the superiority of critical ratio rule is not influenced by the cost structure introduced in this research. On the contrary, the cost structure has a negative impact on the performance of the modified critical ratio rule. SPT was the only rule to beat the modified critical ratio in the case of tight due dates and high utilization (experiments 3 and 4). This can be explained by understanding that the SPT rule results in very high variation in the flow time of its jobs. The SPT rule tends to make the jobs of small work content finish early and the jobs of large work content finish late. The jobs that are late have a high work content and consequently high due date allowance (since TWK is used to set due dates). Therefore, although SPT generates higher tardiness than the modified critical ratio, the relative tardiness of the late jobs are not high. Since the cost structure is concerned with relative tardiness rather than absolute tardiness, the SPT rule performs better than the modified critical ratio even though the modified critical ratio produce lower tardiness, and preferred time based performance.

It is also noteworthy that the improvement achieved by the modified critical ratio rule is higher when time based performance measures are considered. When time based performance measures are considered, the performance of the sequencing rules is compared to an ideal value of zero (the ideal tardiness, earliness, and absolute deviation from due date is zero). On the other hand, the ideal performance when relative cost performance measure is not zero. If a job is completed on its due date, it will still incur some inventory holding cost. Therefore, the difference between the performance of sequencing rules will be influenced by the minimum cost incurred by a job, and the percentage of improvement will be less than the improvement realized when time based performance measures are considered.

Another issue to be considered is the practical significance of the improvement realized by the modified critical ratio rule. Previously, we have shown that this improvement is statistically significant. When relative cost performance measure is concerned, we can see that the improvement realized by the critical ratio rule varies between 0.26% to 4.91%. This improvement corresponds to an increase in the profitability of the product, which might be practically significant. The simplicity of applying the modified critical ratio rule does indeed add to its practical significance.

The Effect Of The Power Factor (Z) On Performance Measures

The simulation results presented in previous sections demonstrate the superiority of the modified critical ratio rule. In this section, the values of the power factor (z) that yield this superiority are discussed. Figures 8 through 37 show the values of different performance measures as a function of the power factor z.

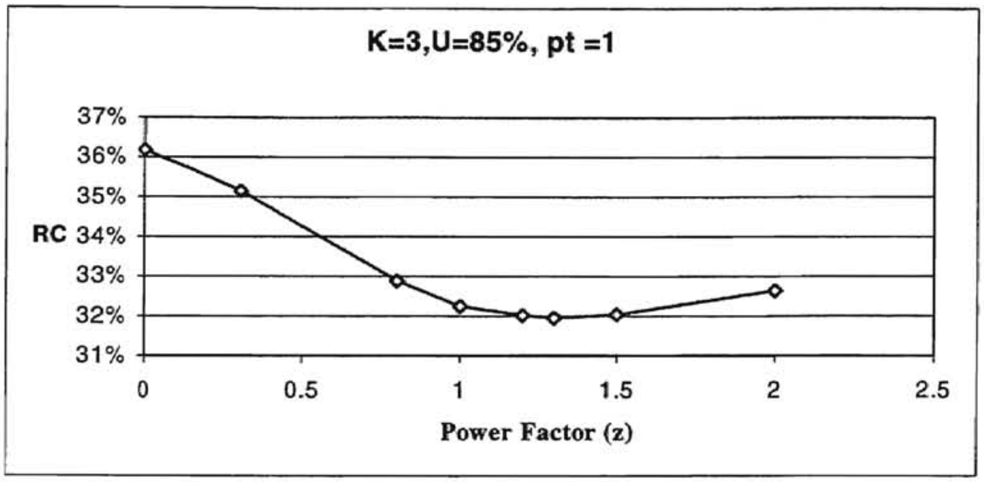

Figure 8 - Relative Cost versus z for Experiment 1

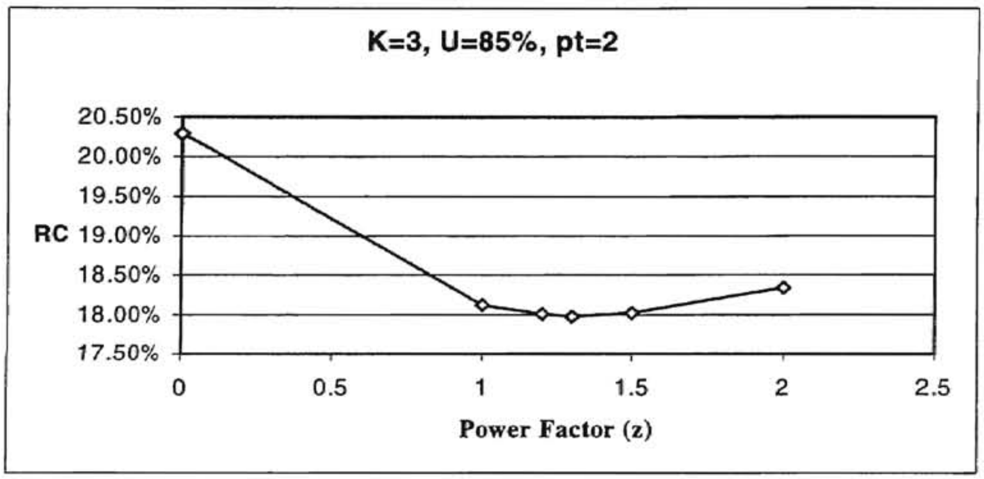

Figure 9 -Relative Cost versus z for Experiment 2

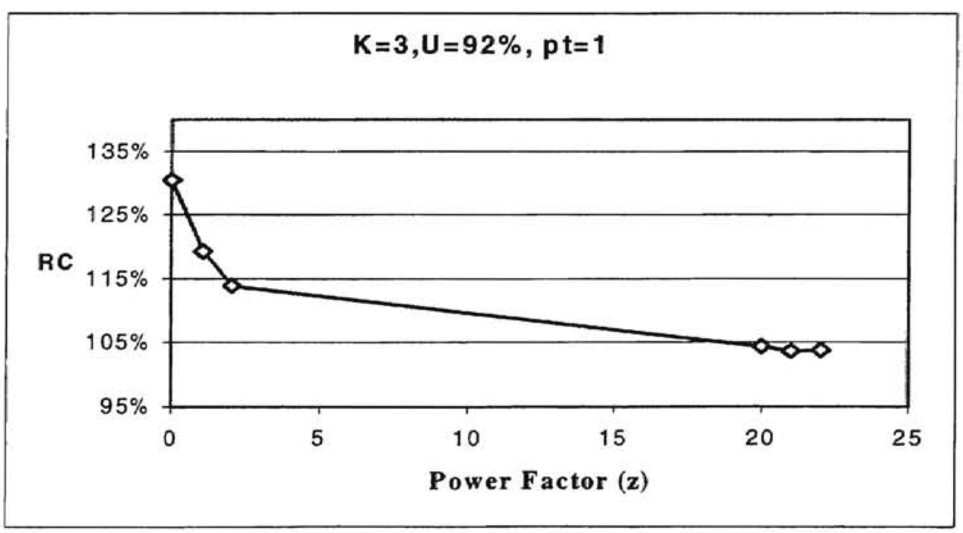

Figure 10- Relative Cost versus z for Experiment 3

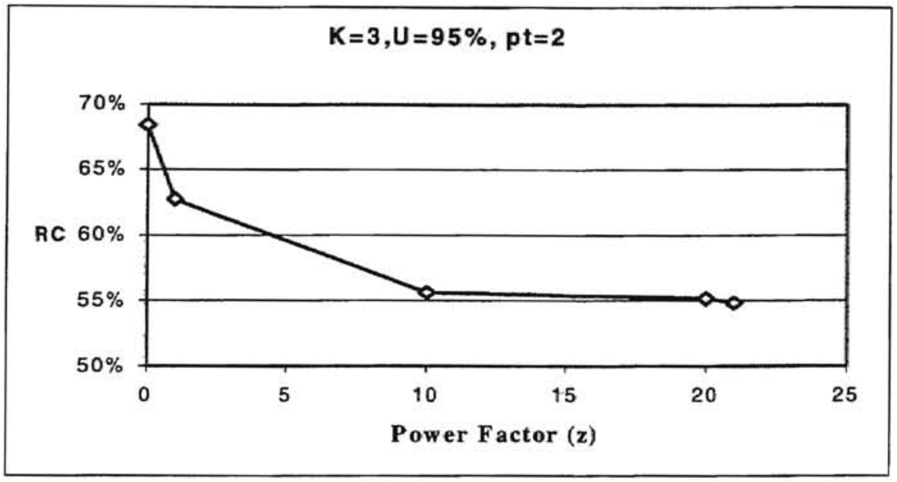

Figure 11- Relative Cost versus z for Experiment 4

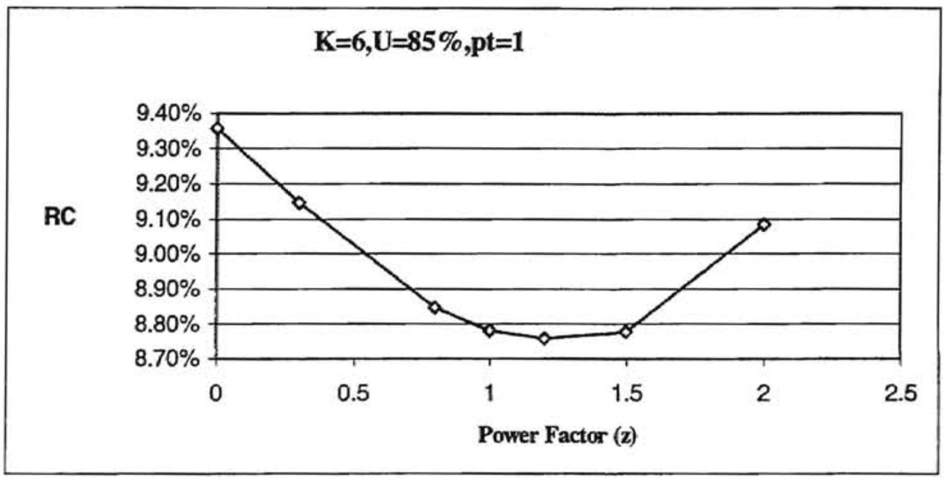

Figure 12- Relative Cost versus z for Experiment 5

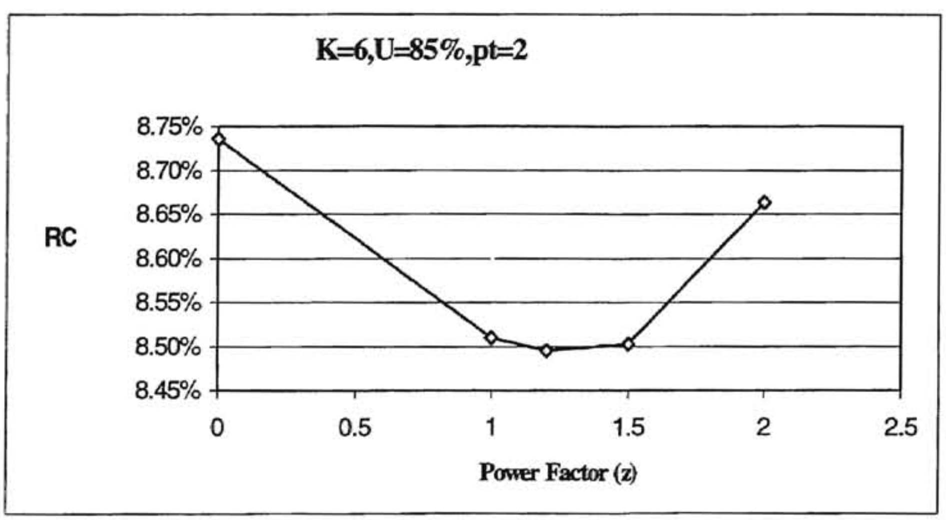

Figure 13 - Relative Cost versus z for Experiment 6

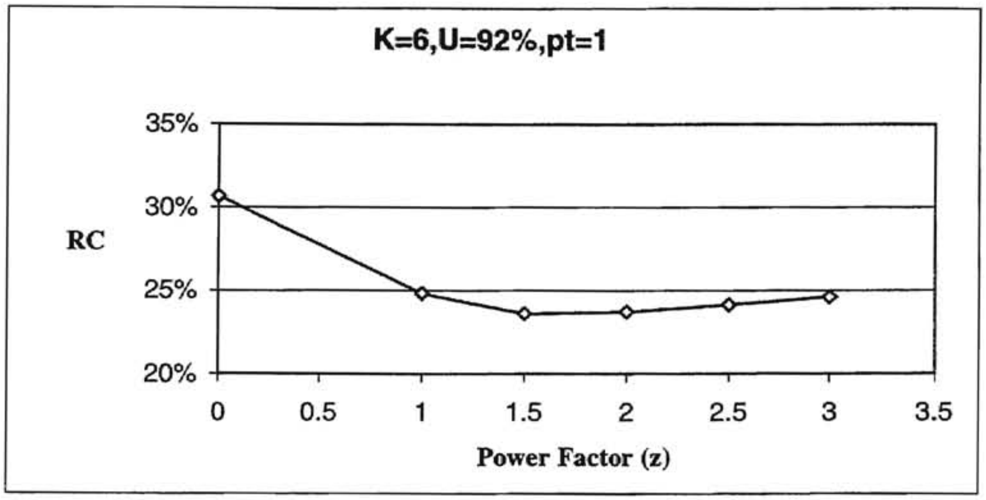

Figure 14 - Relative Cost versus z for Experiment 7

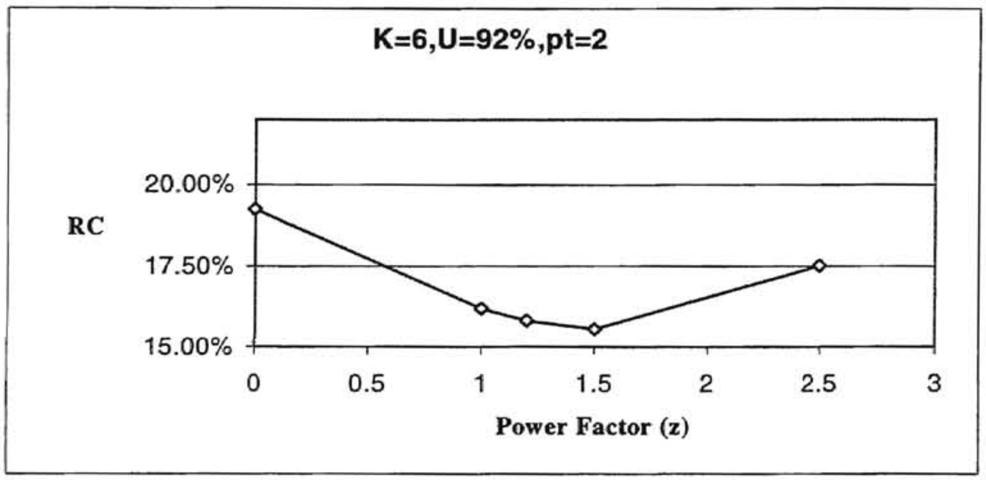

Figure 15 - Relative Cost versus z for Experiment 8

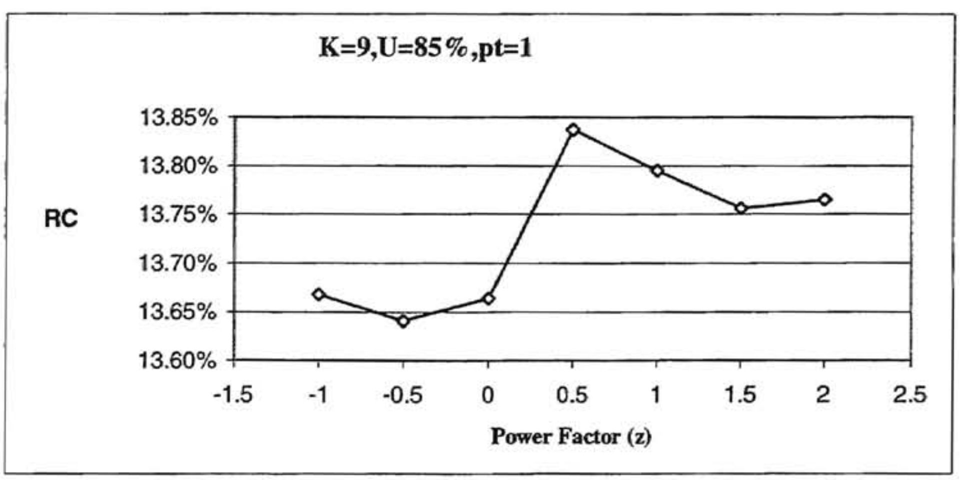

Figure 16 - Relative Cost versus z for Experiment 9

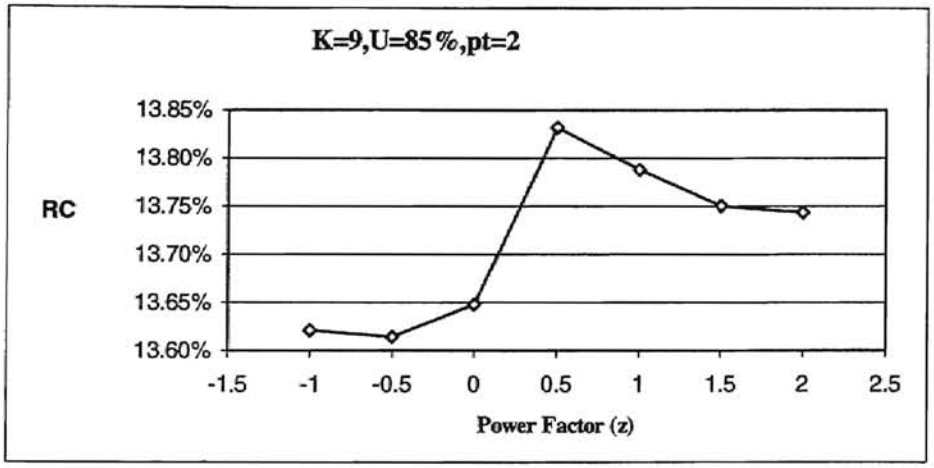

Figure 17 - Relative Cost versus z for Experiment 10

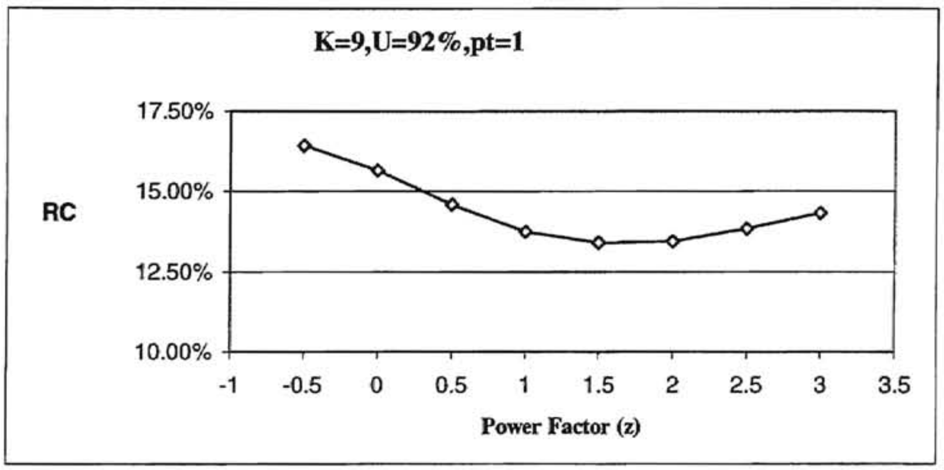

Figure 18 - Relative Cost versus z for Experiment 11

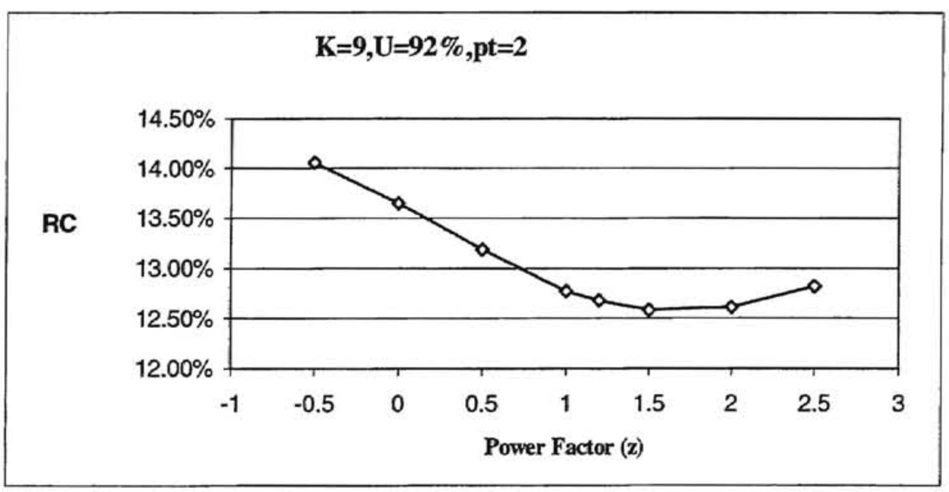

Figure 19 - Relative Cost versus z for Experiment 12

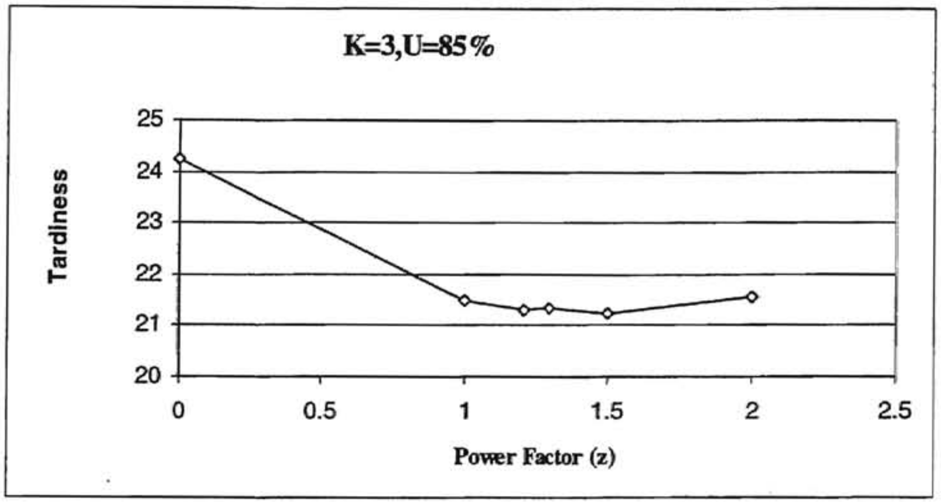

Figure 20 - Tardiness versus z for Experiments 1 and 2

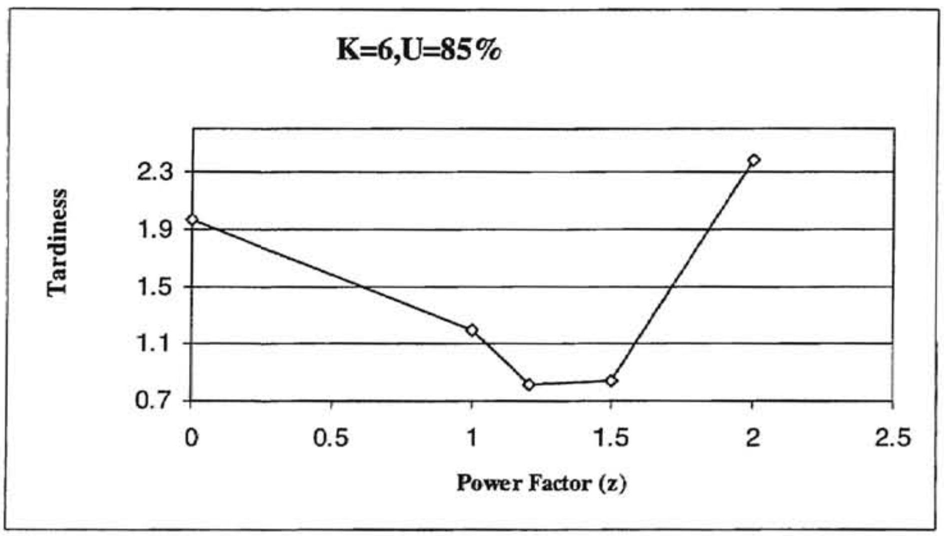

Figure 21 – Tardiness versus z for Experiments 3 and 4

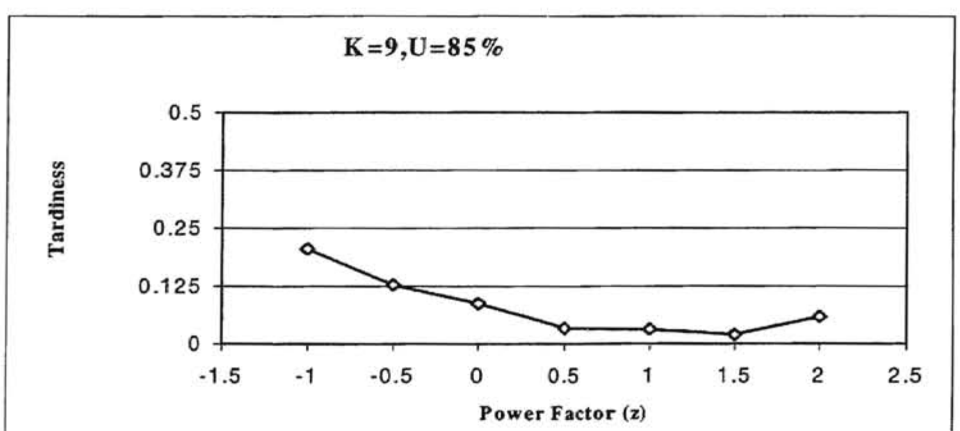

Figure 22 - Tardiness versus z for Experiments 5 and 6

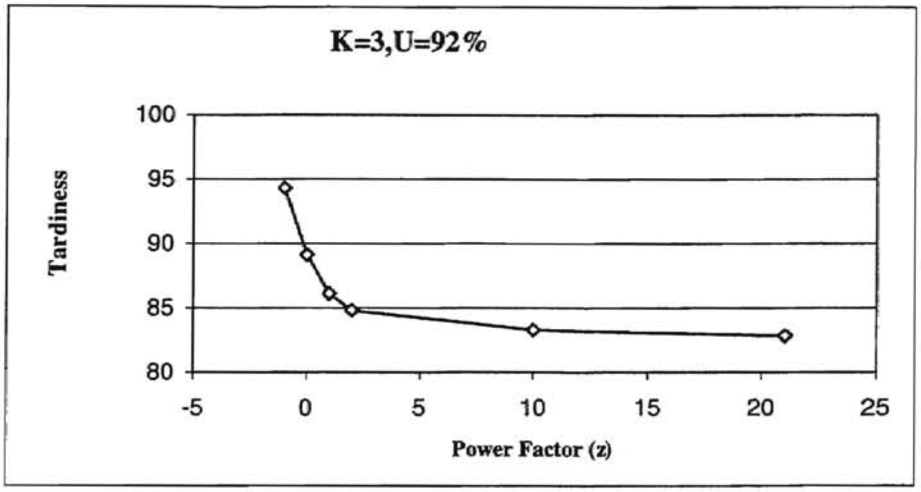

Figure 23 - Tardiness versus z for Experiments 7 and 8

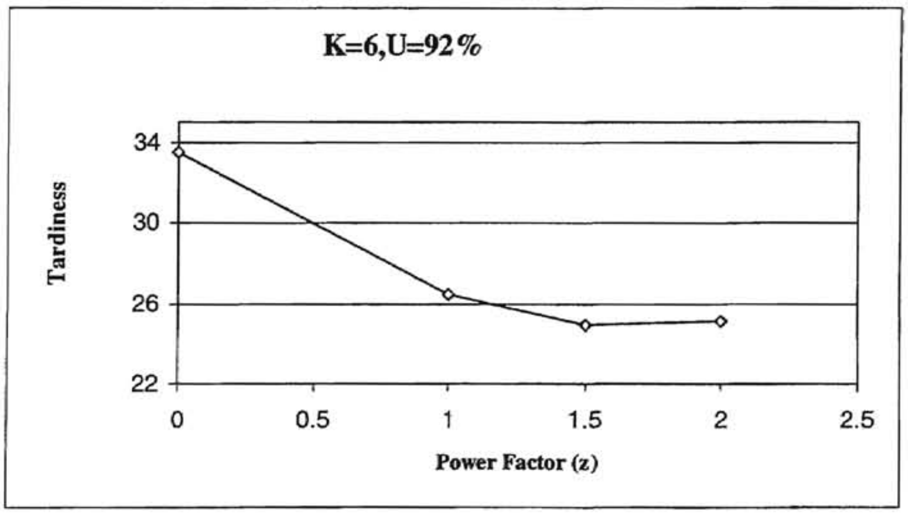

Figure 24 - Tardiness versus z for Experiments 9 and 10

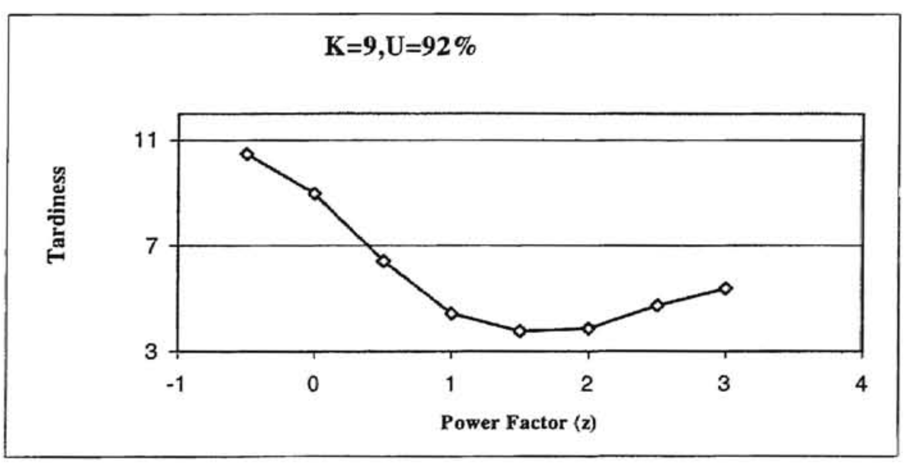

Figure 25 - Tardiness versus z for Experiments 11 and 12

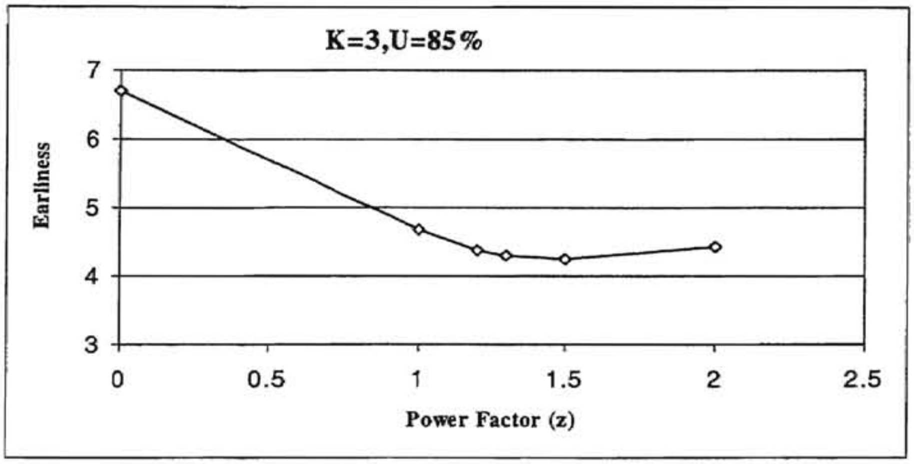

Figure 26 – Earliness versus z for Experiments 1 and 2

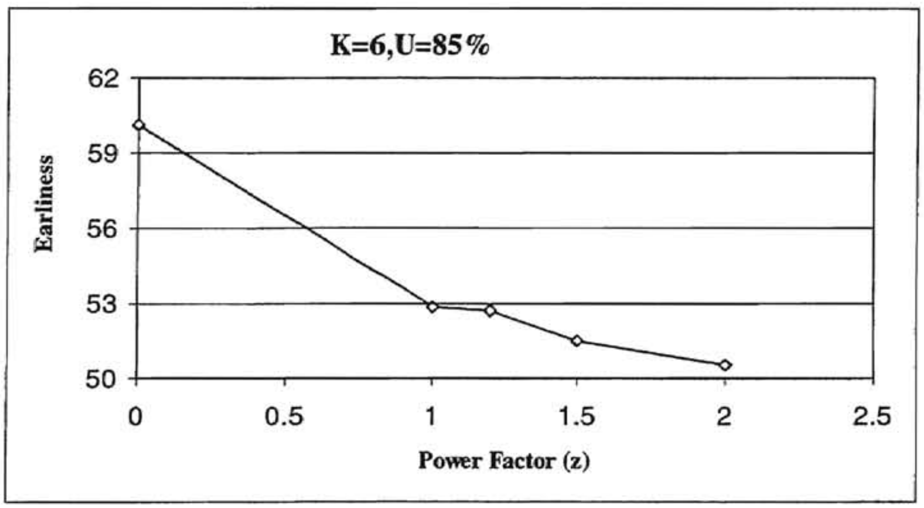

Figure 27 – Earliness versus z for Experiments 3 and 4

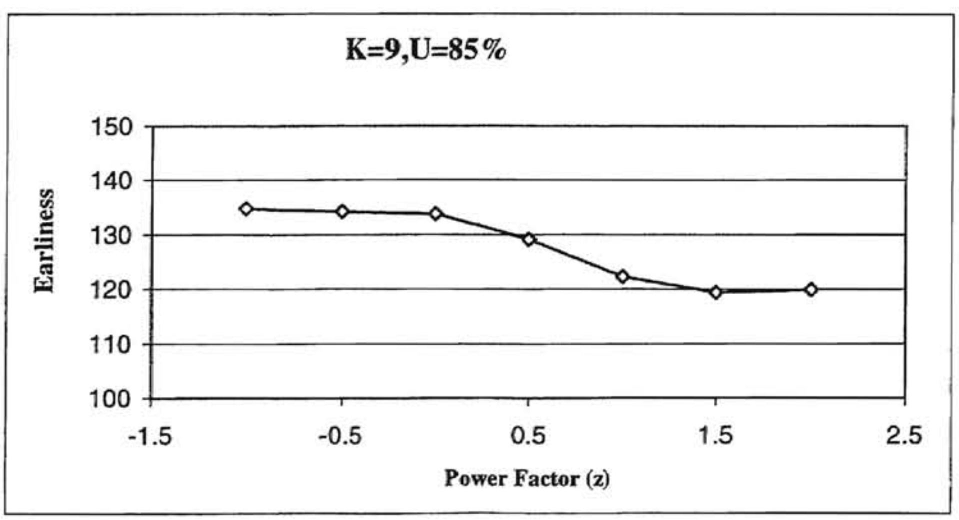

Figure 28 – Earliness versus z for Experiments 5 and 6

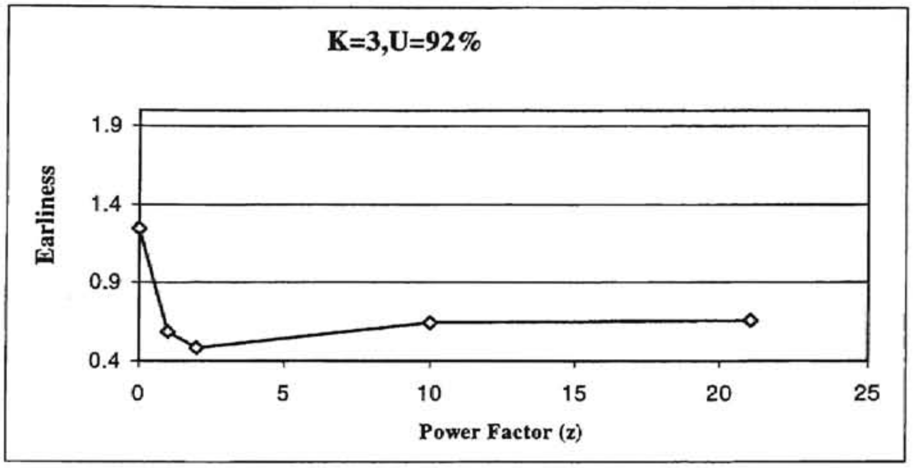

Figure 29 – Earliness versus z for Experiments 7 and 8

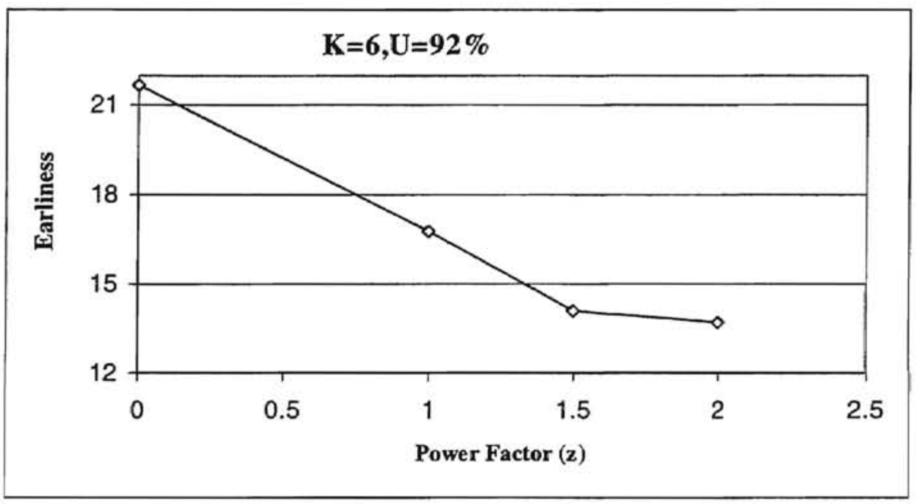

Figure 30 - Earliness versus z for Experiments 9 and 10

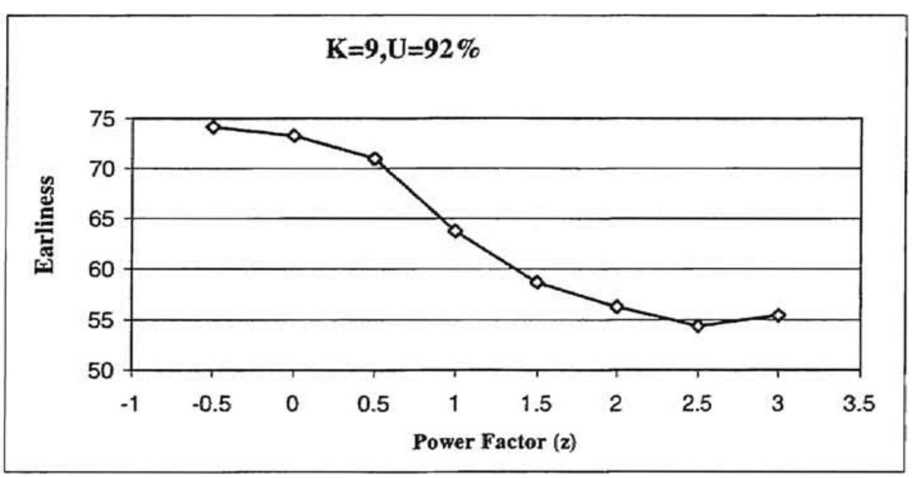

Figure 31 - Earliness versus z for Experiments 11 and 12

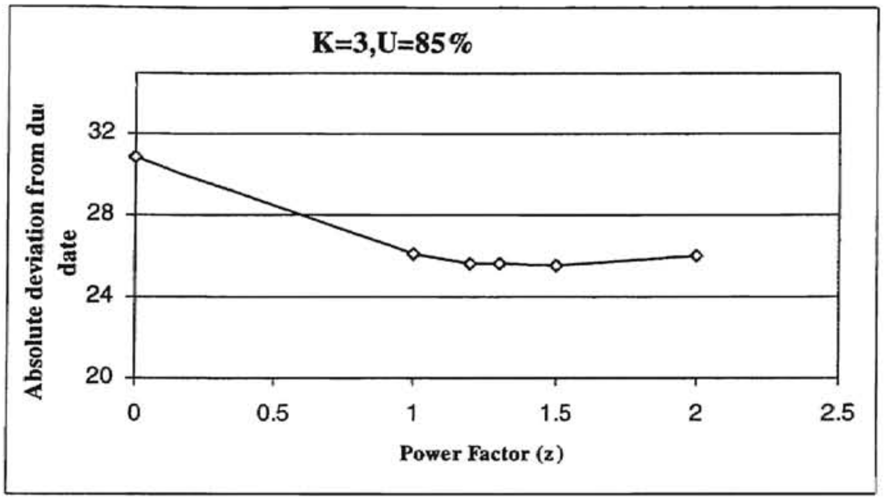

Figure 32 – Absolute Deviation From Due Date versus z for Exp. 1 and 2

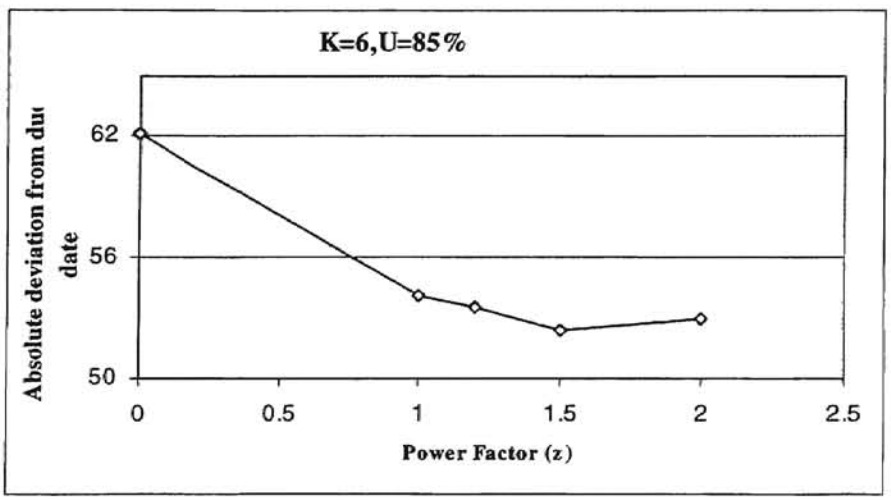

Figure 33 - Absolute Deviation From Due Date versus z for Exp. 3 and 4

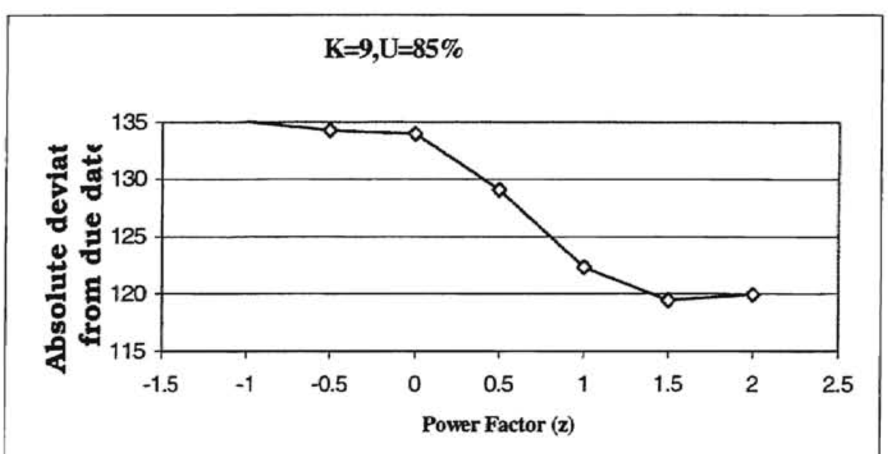

Figure 34 - Absolute Deviation From Due Date versus z for Exp. 5 and 6

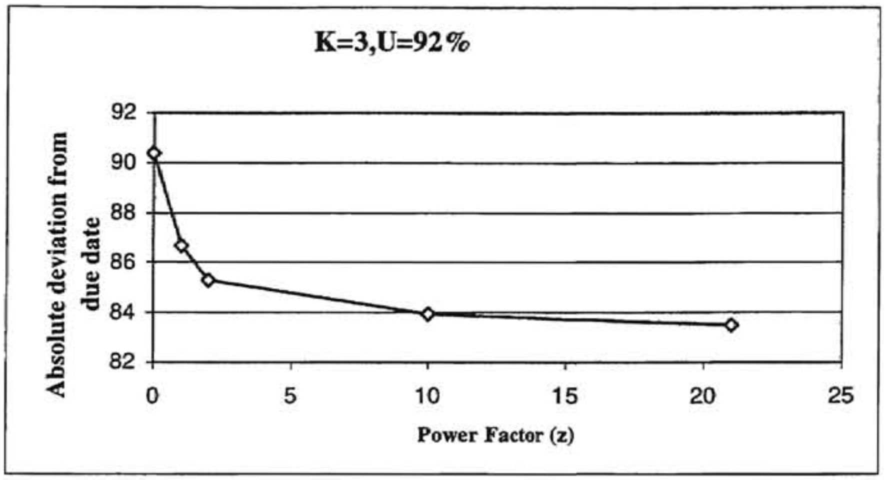

Figure 35 - Absolute Deviation From Due Date versus z for Exp. 7 and 8

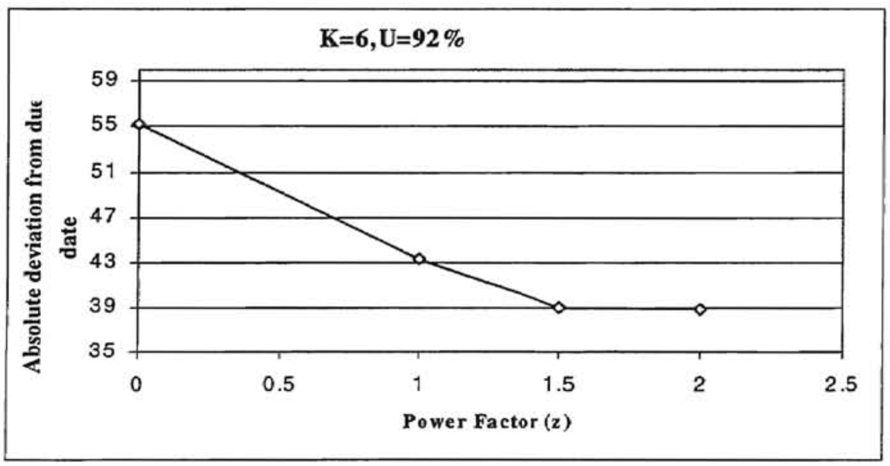

Figure 36 - Absolute Deviation From Due Date versus z for Exp. 9 and 10

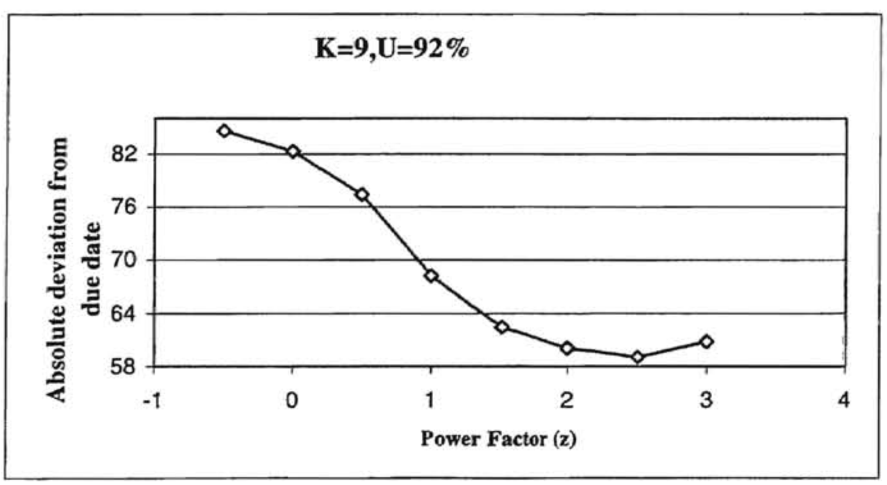

Figure 37 - Absolute Deviation From Due Date versus z for Exp. 11 and 12

Figures 8 through 37 show that a unique optimum exists over the range considered for each of the system configuration when time based performance measures are considered. This is very important because it makes the search for the best value of the power factor z easier. A search for the best value of z will be easier if it is known that there is a unique optimum for the objective performance measure. This property of the modified critical ratio rule is very important, since it makes the search for the best z more structured and facilitates the implementation of the modified critical ratio rule.

In the case of loose due dates and low utilization level, Figures 16 and 17 show that two local optima exist when relative cost performance measure is concerned.

Results show also that the performance measure is sensitive to the value of the power factor z. This can be observed most markedly at z values near zero where the slopes of the performance curves are steep.

Determining the Value of z Based on the System Parameters

The above results show that using the appropriate value of z, the modified critical ratio rule yields better performance than other traditional sequencing rules. The question that arises next is how to choose the best value of z. However, this should not be a limitation for implementing the modified critical ratio rule. If any of the traditional sequencing rules were to be implemented, a search for the best rule is needed to determine the best rule. Therefore, implementing the modified critical ratio rule should not be eliminated because of the search involved in this implementation. The improvement achieved by using the modified critical ratio should justify the extra experiments needed (if any). Nevertheless, we attempted to find a non-search based methodology to specify the best value of z without conducting an extensive search.

The methodology considered in this research to determine the best z value is regression modeling. We attempted to model the best value of the power factor (z) as a function of the system parameters. The power factor (z) was modeled as a function of due date tightness, system utilization and penalty tightness factor. However, the adjusted r square parameter that represents the appropriateness of the regression model was 0.448 (maximum value indicating perfect fit is 1.00). One of the reasons that perhaps lead to this low value of Adjusted R^2 is the lack of data points. This research generated only twelve data points to be used in a regression model. This might explain why the regression approach did not generate a higher adjusted R^2.

Future research efforts might provide a more suitable regression model for determining the best value z by investigating more data points and/or other parameters. This research does not provide a non-search methodology for determining the best value of the power factor z. A search is still needed to determine the best value of z as a finding of this research effort.

VI Conclusion

This chapter presents the conclusions, insights, and future directions of this research. The conclusions and insights regarding the use of the modified critical ratio rule are presented first. Then, we attempt to generalize the findings of this research and their impact on the sequencing research area. Finally, we conclude this chapter by presenting potential research directions to follow this research.

Sequencing Using the Modified Critical Ratio

In the previous chapter, we justified that the modified critical ratio does improve the performance of a manufacturing system. The modified critical ratio is an extension of the critical ratio rule that has shown good performance in the literature. The advantage of the critical ratio rule is that it considers both the remaining slack of the job and its processing time. The critical ratio rule gives priority to the job that has the least ratio of slack time to the processing time. However, there is an underlying assumption when the critical ratio rule is used. The sequence of the jobs generated by the critical ratio rule assumes that the required time needed for a job to flow through the manufacturing system is proportional to its processing time processing time only. Therefore, the job that has the least slack to processing time ratio is given the highest priority. Consider two jobs, the first, job A, has a remaining slack of d days and a remaining processing time of p days, while the second, job B, has a remaining slack of 2d days and a remaining processing time of 2p days. Both jobs will have the same priority if the critical ratio rule is used, since their slack to processing time ratio is d/p. However, depending on the system configuration, a d/p slack to processing time ratio may be sufficient for one job and small for another job. For example, if the operation time for each job is the same, job B will have more remaining operations and consequently it will visit more queues. Therefore, job B is expected to spend more waiting time than job A. Hence, even though job A and job B have the same d/p ratio, it will likely be more desirable to give the priority to job B rather than job A.

The modified critical ratio avoids the above conflict by modifying the importance of the processing time in assigning the priority to each job. The importance of the processing time is raised to the power z. Therefore, according to the configuration of the system, the importance of the processing time in deciding which job should have the highest priority is varied.

The critical ratio rule depends heavily on whether the due date of a job has passed or not. If the job's due date has not passed yet, the numerator of the critical ratio rule is positive. Therefore, if two jobs have the same remaining slack time, the priority will be given to the job that has the highest remaining processing time. On the other hand, if the job's due date has already passed, the numerator of the critical ratio rule will be of a negative value. Therefore, if two jobs have the same remaining slack time, the priority will be given to the job that has the lowest remaining processing time.

The same conflict is observed when the modified critical ratio rule is used. Consider a hypothetical case where a z value of α is found to be the best value that yields the best performance for such a configuration. It is not clear whether modifying the weight of the remaining processing time by raising it to the power α gives the priority to the jobs that have small remaining processing time, or whether it gives the priority to the jobs that have large remaining processing time. This numerical sensitivity makes it more difficult to understand and explain at which value of the power factor z, the modified critical ratio will yield the best performance.

Sequencing Using A Quantified Decision Domain

The modified critical ratio has shown improvement over other tested benchmarking rules in this research. This improvement can be explained based on two main factors.

1. The critical ratio rule considers two important characteristics of a job, the remaining slack and the remaining processing time. However, the weight or the importance of each of these characteristics when assigning the priority of each job is fixed. On the other hand, using the modified critical ratio rule, the weight or the importance of each of these characteristics is varied according to system parameters. In traditional sequencing rules, choosing the best sequencing rule involves choosing the information considered in the selected sequencing rule. Therefore, the decision domain will be discrete. On the other hand, choosing the best value of the power factor z involves choosing the weight of information considered in the modified critical ratio rule. Therefore the decision domain is continuous.

2. The modified critical ratio rule can react sensitively to the changes in the system parameters. Traditionally, the sequencing problem is a problem that has a continuous range of system parameters and a discrete domain of available sequencing rules. Consider a system configuration A where EDD is the best sequencing rule. If one or more of the system parameters (utilization, due date tightness, etc.) is changed, the decision-maker will have a decision domain of changing the sequencing rule or sticking with EDD Wu and Wysk (1989), Pierreval and Mebark (1997). On the other hand, using

the modified critical ratio rule, the sequencing problem is a problem that has continuous range and a continuous domain. Therefore, if any change in the system parameters is introduced, the reaction will be changing the power factor z, which is a continuous reaction domain. This is the second reason that contributed into the superiority of the modified critical ratio rule.

Research Contribution

This research has introduced a new sequencing rule, that has been shown to perform statistically better than published sequencing rules in most of the settings experimented in this research. This finding is important for practitioners as it provides a methodology to improve the performance of a manufacturing system.

On a conceptual level, the sequencing rule introduced in this research introduces a new sequencing paradigm. Traditional sequencing is concerned with choosing the best rule that yields the best performance. Sequencing rules differs based on the information content of these rules. Therefore, choosing the best sequencing rule involves choosing the information considered when jobs are prioritized. On the other hand, the sequencing paradigm followed in this research is not concerned with the information that should be considered when jobs are prioritized, rather, it is concerned with the weight or the effect of the information considered when jobs are prioritized.

Future Directions

This research has introduced a new sequencing rule that has introduced an extension of the critical ratio rule, that has shown to perform better than tested sequencing rules. Future directions to follow this research can be divided into two areas. First, the modified critical ratio rule needs to be studied more thoroughly. The second future direction is in generalizing the sequencing paradigm that has been introduced in this research.

Future directions related to the modified critical ratio rule

1. In a previous chapter, we presented one approach that might be followed to determine the best value of z, regression analysis. However, regression did not generate promising results in this research. We have explained the inappropriateness of the regression model by the lack of sufficient data. One of the future directions that can be pursued is conducting more experiments with different settings of system parameters in order to achieve an improved regression model.
2. In this research, the factors that have been studied are due date tightness, utilization level, and penalty tightness factor cost. Future research may consider other factors such as number of machines, alternate routing, due date setting procedure, release mechanism, manufacturing system structure, permitted early shipment environment, and many other job shop factors and their interactions.
3. In this research, the search for the best value of z was restricted by a computational limitation (numeric overflow), therefore, the maximum experimental value of z was 22. Future research may investigate higher values of the power factor z, especially in the case of high system utilization and tight due dates. At this configuration, a value of z higher than 22 may lead to improved performance. It is noticed in Figure 11 that as the value of z is increased, the average relative cost is improved.

4. As discussed previously in this chapter, both critical ratio and modified critical ratio rules give higher priority for jobs of high processing time if there is a late job in the queue, and higher priority for jobs of low processing time if all the jobs in the queue are early. This inconsistency may have a negative impact on the system's performance. A future direction might be to investigate a modification of the modified critical ratio rule to overcome this inconsistency.

Future directions related to generalizing the sequencing paradigm introduced in this research

This research introduced a shift in the sequencing paradigm. The traditional sequencing paradigm is concerned with the selection of the best rule that will yield best performance. Sequencing is no longer concerned with choosing the information content of a sequencing rule, rather it is concerned with choosing the importance or the weight of a job information when prioritizing job is considered. This shift in the objective can be used to explore a more generalized rule that considers more information in a job. Such a rule might consider the number of operations for a job, arrival time of a job, and the financial aspects of a job such as inventory value, job value and accumulated tardiness penalty cost. This might be a promising approach. Previous research findings have found that monetary based sequencing rules do outperform time based sequencing rules. However, by rethinking the importance or the weight of the financial information of a job, monetary based or combined time-monetary based rules might show improved performance.

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Appendix 1 - Interarrival Time Calculations

The system studied in this research is presented in Figure 1. Orders arrive to the system at the rate of λ_0, which is the parameter we need to determine. The arrival rate at machine i is λ_i, i.e., λ_1 is the arrival rate to machine 1. The value of λ_i can be determined by using equation 1:

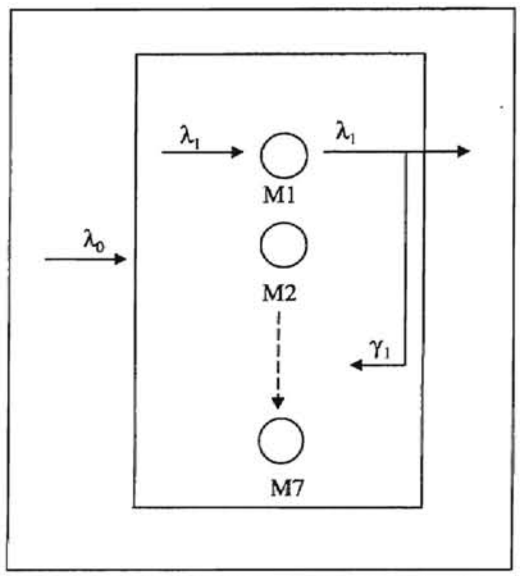

Figure 38 – System Representation

$$\lambda_i = \frac{\mu_i}{\rho} \qquad \text{(Equation 1)}$$

Where;

λ_i: the arrival rate for machine i.

ρ: the desired utilization level.

μ_i: the average processing time at machine i.

The average departure rate from any machine is same as the average arrival rate to the same machine assuming the utilization is less than or equal 1. However, the jobs departing from any machines may either leave the system or stay in the system to be processed by another machine. The rate of jobs staying in the system is denoted as γ_i.

The jobs arriving to machine i consist of two components. The first is the jobs arriving to machine i as the first machine, i.e., the first operation for these jobs is to be performed on machine i. Since each machine has the same probability of being the machine for the first operation for a job, the arrival rate of this component is λ_0 divided by seven (number of machines). The second component is the jobs arriving to machine i after being processed by any machine other than machine i. Therefore, λ_0 can be determined by the following formula:

$$\lambda_i = \lambda_0 / 7 + 1/6 \sum_{k=1, k \neq i}^{7} \gamma_k \qquad \text{(Equation 2)}$$

The first term of the above equation represents the rate of jobs arriving to machine i as their first operation. The second term represents the portion of jobs leaving other machines and arriving to machine i. The value of γ_K is calculated as follows:

$$\gamma_k = \lambda_k \sum_{j=3}^{7} ab \qquad \text{(Equation 3)}$$

Where;

j: operation number

a: the probability of a job leaving machine k has j operations

b: the probability that a job leaving machine k has not completed all its operations

The constant a is determined as follows:

$$a = \frac{j}{\sum_{j=3}^{7} n} \qquad \text{(Equation 4)}$$

The factor a in equation 3 and 4 is the probability that a job leaving machine i has j number of operation. Note that a job that has a higher number of operations circulates more in the system than a job that has a smaller number of operations.

The factor b is determined by the following formula:

$$b = \frac{j-1}{j} \qquad \text{(Equation 5)}$$

The above equation calculates the probability that a job did not finish all its operations. The numerator in equation five consists of the number of visits a job will make to any machine before finishing all its operations. The denominator in equation 5 consists of the number of visits that a job will make to any machine in order to finish its operations.

Combining equations 2 through 5, λ_K is determined as follows:

$$\lambda_k = \frac{\lambda_0}{7} + \frac{1}{6}\sum_{j=1, j\neq k}^{7} \lambda_k \frac{j}{\sum_{n=3}^{7} n} \frac{j-1}{j} \qquad \text{(Equation 6)}$$

Substituting in the above equation, equation 6 reduces to:

$$\lambda_k = \frac{\lambda_0}{7} + 0.8\lambda_k \qquad \text{(Equation 7)}$$

Combining equations 7 and 1, λ_0 can be determined by the following formula:

$$\lambda_0 = \frac{1.4\mu}{\rho} \qquad \text{(Equation 8)}$$

Appendix 2 - Description of the simulation model

The simulation model was coded in the SLAM II simulation language with FORTRAN subroutines inserts (Pritsker, 1995). Figures 39a and b shows the SLAM II network of the simulated system, and the FORTRAN program is shown in Appendix 3, while the attributes and global variables used in this simulation model are shown in Table XI. Jobs arrive to the system at a calculated interarrival rate. The arrival process is modeled in the CREATE node shown in the network graph. After arrival, the following attributes of each job are assigned in the AWAIT node labeled EV1:

1. the number of operation for the job,
2. the sequence of the operation for the job,
3. the processing time of each operation,
4. the value of the job, and
5. the selling price of the job.

After the attributes containing the above information are assigned, the attributes that are specific to next operation are assigned in the AWAIT node labeled EV2. These attributes are the number of the next operation for the job, the machine number of the next operation, and the processing time of the next operation. Then, the job leaves the AWAIT node labeled EV2 to one of the branches that start with one of the ASSIGN nodes labeled MC1 to MC7. These seven branches (starting with ASSIGN nodes MC1 to MC7) represent the queues in front of machines 1 to 7. In each of these branches, there is one ASSIGN node and one AWAIT node. At the ASSIGN node (labeled MC1, MC2 to MC7), the attribute that stores the current time is updated. This attribute (ATRIB (24)) is used to calculate the inventory cost associated with each job. Jobs leave the ASSIGN node in each of these branches and arrive to an AWAIT node that follows each ASSIGN node. At the AWAIT node, a job waits for the machine required for its next operation. The FORTRAN subroutine that starts with the line number 100 is used at each of these AWAIT nodes. The FORTRAN subroutine is called when 1) a job arrives to the Await node or 2) when the resource is freed. In the FORTRAN subroutine, a check is made to determine if a machine is idle and if there are jobs in the queue. Then, there are two possibilities to execute the subroutine depending on the sequencing rule applied. If the modified critical ratio is applied, the modified critical ratio is calculated for each job. The job that has the least ratio is removed from the queue, and is assigned to the idle machine. On the other hand, if the SPT rule is used, the job that has the highest priority in the queue is removed from the queue, and is assigned to the idle machine. The priorities in this case are assigned based on ATRIB (29), which stores the remaining processing time of a job. Jobs leave the AWAIT node and stay in the activity that follows the AWAIT node for the period its operation processing time. After the operation is completed, the resource that represents the machine used by a job is freed in the AWAIT node labeled FREE. Then the attributes that store information about the job value, remaining processing time of the job, and the inventory cost of the job are updated in the AWAIT node labeled EV3. After the jobs attributes are updated, a job is routed again to the AWAIT node labeled EV2 if the job's operations are not completed. Otherwise, if the job's operations are completed, the job is routed to the ASSIGN node labeled LEAVE. At the ASSIGN node labeled LEAVE, the attribute that stores the current time is updated. This attribute (ATRIB (24)) is used to calculate the tardiness penalty cost for tardy jobs, and the inventory holding cost of finished goods. Also, at the

ASSIGN node labeled LEAVE, the value of ATRIB (22), that stores the job's deviation from its due date, is calculated. A job leaves the AWAIT node labeled LEAVE to the branch starting with the AWAIT node labeled EVE5 if it is completed after its due date, and to the branch starting with the AWAIT node labeled EVE4 if it is completed before its due date. If a job is completed after its due date, its tardiness penalty cost is calculated in the AWAIT node labeled. Then the average tardiness of tardy jobs, and average penalty cost of tardy jobs are collected in the COLLECT nodes labeled LAT and PENC respectively. If a job is finished early, it is routed to the AWIAT node EVE4 through an activity that last for the time of its earliness. The inventory cost of storing an early finished jobs is calculated in the AWAIT node labeled EVE4, and is added to the total inventory cost incurred by the job. Then the earliness of early jobs is calculated in the COLLECT node labeled EAR. Both early and tardy jobs are joined at the AWAIT node labeled EVE6 at which the relative cost of each job is calculated. After a job leaves the AWAIT node labeled EVE6, the average inventory cost and the average relative cost statistics for all jobs are collected in the COLLECT nodes labeled INVC and RC respectively. The entity that represents a job is terminated.

Attribute	Description
Attribute(1)	Job's arriving time
Attribute(2)	Number of operations
Attribute(3)	Machine of first operation
Attribute(4)	Machine of second operation
Attribute(5)	Machine of third operation
Attribute(6)	Machine of fourth operation
Attribute(7)	Machine of fifth operation
Attribute(8)	Machine of sixth operation
Attribute(9)	Machine of seventh operation
Attribute(10)	Duration of first operation
Attribute(11)	Duration of second operation
Attribute(12)	Duration of third operation
Attribute(13)	Duration of fourth operation
Attribute(14)	Duration of fifth operation
Attribute(15)	Duration of sixth operation
Attribute(16)	Duration of seventh operation
Attribute(17)	Number of completed operations
Attribute(18)	Machine of next operation
Attribute(19)	Duration of next operation
Attribute(20)	Due Date
Attribute(21)	Selling Price
Attribute(22)	Waiting time in storage area
Attribute(23)	Job's Value
Attribute(24)	Waiting time reference
Attribute(25)	Completed processing time
Attribute(26)	Accumulated holding cost per job
Attribute(27)	Penalty cost per job
Attribute(28)	Relative cost
Attribute(29)	
Attribute(30)	Total Processing Time
DD(1)	Due date tightness
DD(2)	Selling price factor
DD(3)	Factor of inventory cost (H)
DD(4)	The value of power factor (z)
DD(5)	Penalty tightness (pt)
DD(6)	Scale of RC
DD(7)	Scale of processing time

Table XI – Description of attributes and global variables

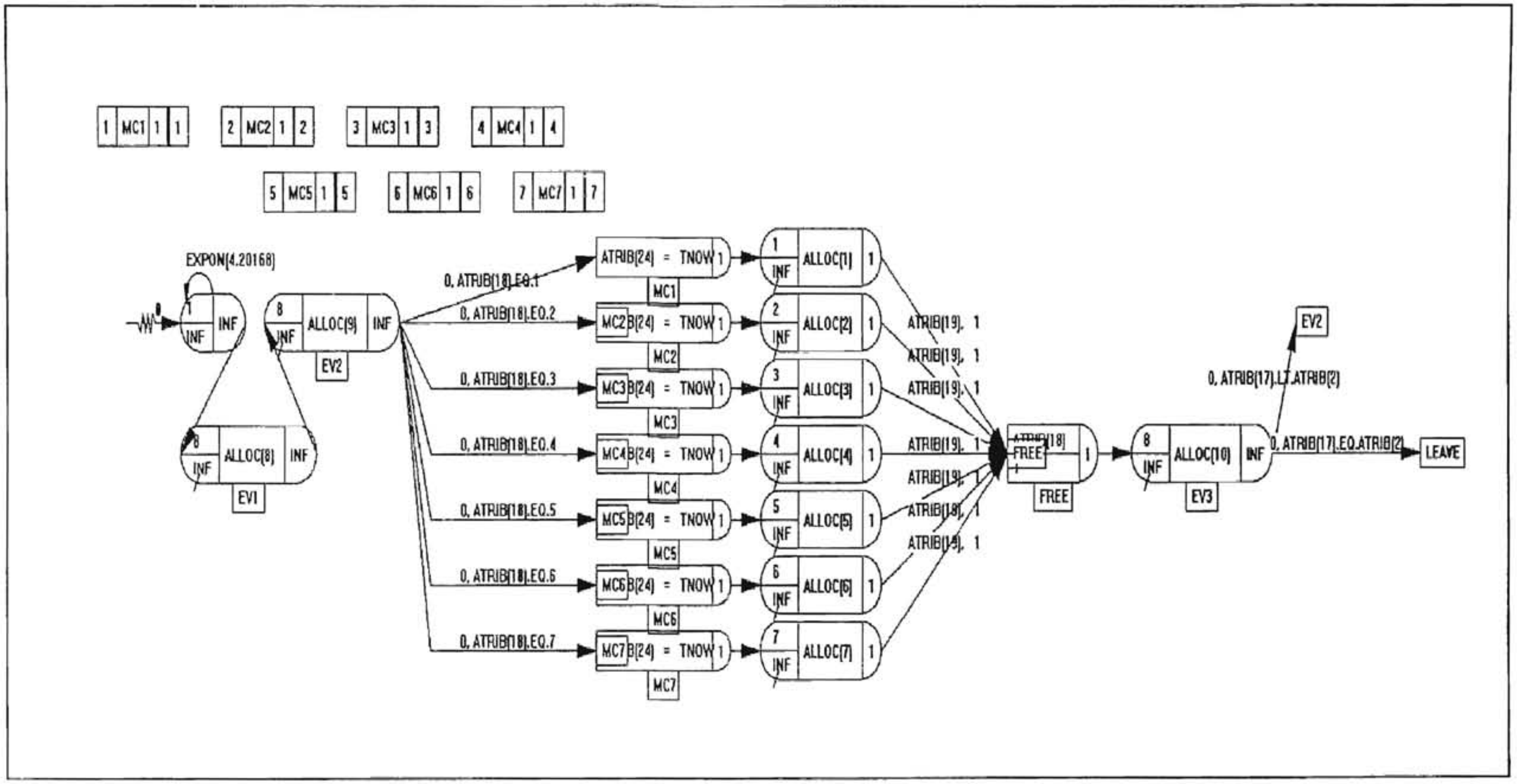

Fig 39. a - SLAMII Network Model (part 1)

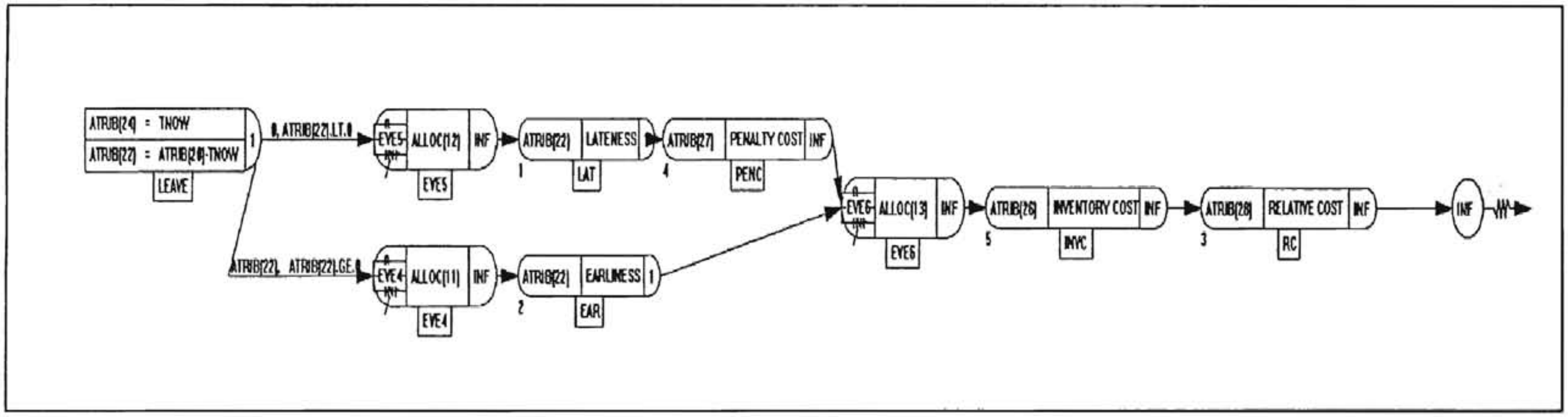

Figure 39.b - SLAMII Newtork Model(part b)

Appendix 3 - Fortran Program

```
SUBROUTINE ALLOC(I,IFLAG)
      COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
     1,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      NA=I
      GOTO(100,100,100,100,100,100,100,1,2,3,4,5,6),I
100   IFLAG=0
      IF(NNRSC(NA).EQ.0) RETURN
      IF(NNQ(NA).EQ.0) RETURN
      IF(DD(8).EQ.1.) GOTO 122
      DO 110 K=1,NNQ(NA)
      CALL COPY(K,NA,ATRIB)
      RNUM=ATRIB(20)-TNOW
      DEN1=ATRIB(30)-ATRIB(25)
      Z=DD(4)
      DEN=DEN1**Z
      CRITL=RNUM/DEN
      IF(K.EQ.1) THEN
      CRITT=CRITL
      NCRIT=1
      ELSE
      IF(CRITL.LT.CRITT) THEN
      CRITT=CRITL
      NCRIT=K
      ENDIF
      ENDIF
110   CONTINUE
      CALL SEIZE(NA,1)
      CALL COPY(NCRIT,NA,ATRIB)
      IFLAG=NCRIT
      IF(IFLAG.EQ.0) CALL ERROR(NCC1)
      RETURN
122   IFLAG=1
      CALL SEIZE(NA,1)
      RETURN
1     IF(NNQ(8).NE.1) CALL ERROR(3)
      CALL COPY(1,8,ATRIB)
      NOP1=UNFRM(3.,8.,8)
      ATRIB(2)=NOP1
      DO 10 LS1=1,ATRIB(2)
13    NF1=UNFRM(1.,8.,9)
      IF (LS1.EQ.1) GOTO 15
      MA11=LS1+1
      IF (NF1.EQ.ATRIB(MA11)) GOTO 13
15    MA12=LS1+2
      ATRIB(MA12)=NF1
10    CONTINUE
      DO 12 LD1=1,ATRIB(2)
      MA19=LD1+9
      ATRIB(MA19)=UNFRM(3.5,6.5,LD1)*DD(7)
      ATRIB(30)=ATRIB(30)+ATRIB(MA19)
12    CONTINUE
      ATRIB(21)=ATRIB(30)*DD(2)
      ATRIB(20)=TNOW+ATRIB(30)*DD(1)
      ATRIB(23)=ATRIB(21)*0.3
      IFLAG=1
      RETURN
2     IF(NNQ(8).NE.1) CALL ERROR(3)
      CALL COPY(1,8,ATRIB)
      NXO1=ATRIB(17)+1
      ATRIB(17)=NXO1
      NA12=NXO1+2
      NA19=NXO1+9
```

```
      ATRIB(18)=ATRIB(NA12)
      ATRIB(19)=ATRIB(NA19)
      IFLAG=1
      RETURN
3     IF(NNQ(8).NE.1) CALL ERROR(3)
      CALL COPY(1,8,ATRIB)
      ATRIB(25)=ATRIB(25)+ATRIB(19)
      ATRIB(23)=(ATRIB(25)/ATRIB(30)*0.2+0.3)*ATRIB(21)
      ATRIB(26)=ATRIB(26)+DD(3)*ATRIB(23)*(TNOW-ATRIB(24))
      ATRIB(29)=ATRIB(30)-ATRIB(25)
      IFLAG=1
      RETURN
4     IF(NNQ(8).NE.1) CALL ERROR(3)
      CALL COPY(1,8,ATRIB)
      ATRIB(26)=ATRIB(26)+0.75*ATRIB(21)*DD(3)*(TNOW-ATRIB(24))
      IFLAG=1
      RETURN
5     IF(NNQ(8).NE.1) CALL ERROR(3)
      CALL COPY(1,8,ATRIB)
      ATRIB(22)=-ATRIB(22)
      ATRIB(27)=ATRIB(21)*ATRIB(22)/(DD(5)*(ATRIB(20)-ATRIB(1)))
      IFLAG=1
      RETURN
6     IF(NNQ(8).NE.1) CALL ERROR(3)
      CALL COPY(1,8,ATRIB)
      ATRIB(28)=(DD(6)*(ATRIB(27)+ATRIB(26)))/ATRIB(21)
      IF(DD(9).EQ.1.) THEN
      WRITE(NPRNT,61) ATRIB(28)
61    FORMAT(F10.2,F10.3)
      ENDIF
      IFLAG=1
      RETURN
      END
```

VITA

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