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# SCHEDULING WITH SEQUENCING FLEXIBILITY

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# SCHEDULING WITH SEQUENCING FLEXIBILITY


## Abstract

We examine the effects of <u>sequencing flexibility</u> on the performance of scheduling rules. Our findings show that using sequencing flexibility even to a small extent significantly improves the performance of scheduling rules. Interestingly, at high levels of sequencing flexibility, some competing rules outperform the shortest processing time rule for the mean flowtime criterion. Also, the performance differences between various rules diminish significantly. Similar effects were also observed in case of two due date related performance measures. When a high degree of sequencing flexibility is available, job based rules outperform operation based rules. For example, using operation milestones with due date based rules can lead to a deterioration in tardiness performance. We also discuss implications of our findings for manufacturing systems design.

# SCHEDULING WITH SEQUENCING FLEXIBILITY

## 1.0 INTRODUCTION

Global competitive pressures in the manufacturing sector have resulted in renewed efforts to improve manufacturing operations. Recently, attention has focussed on flexibility and its beneficial effects on manufacturing at both strategic and operational levels. Not surprisingly, technologies such as Flexible Manufacturing Systems(FMS), Computer Integrated Manufacturing(CIM), and Robotics have gained a good deal of attention. However, a review of the literature on flexibility indicates that there are various types of flexibilities, and some of these flexibilities can be advantageously used without necessarily investing in capital intensive hardware technologies such as FMSs. In this paper we investigate the effects of one such type of flexibility, namely sequencing flexibility, on the performance of a manufacturing system. Sequencing flexibility is a measure of alternate feasible sequences which can be used to schedule the operations of a job in a manufacturing system, even though each operation of the job can be performed on only one of the machines in the shop. This type of flexibility exists in conventional manufacturing systems as well as in new technologies such as FMSs. Our evaluative studies show that using this flexibility can significantly improve the performance of scheduling rules and of manufacturing systems. A surprising finding, which is contrary to most early job shop studies, is that the shortest processing time rule need not necessarily outperform competing nonparametric dispatching rules for reducing the mean flowtime. This phenomenon occurs when a large amount of sequencing flexibility is present in the system, and it is appropriately used for scheduling purposes. Also, there is substantial reduction in the performance differences between various rules when sequencing flexibility is used. This is true for the mean flowtime criterion, as well as for due date related measures such as average tardiness and proportion of tardy jobs. Also, earlier research indicated that using operation milestones generally improves the performance of due date based rules such as the earliest due date rule, critical ratio rule, and the modified due date rule. Our studies here show that these conclusions do not necessarily carry over when sequencing flexibility is available in the system. These findings have implications for both manufacturing system design and product design.

Our paper is organized as follows. In section 2 we discuss the concept of sequencing flexibility in detail and show how it can be quantitatively measured. In section 3 we review the prior literature on using sequencing flexibility in making scheduling decisions. In section 4 we describe the procedures and competing rules used in our study to schedule jobs in flexible environments. Section 5 discusses simulation modeling issues, and also provides details on how the operation graphs for the jobs are generated. Section 6 provides experimental design details. In section 7 we analyze the simulation results. Finally, in section 8 we discuss implications of our study for manufacturing system design, and conclude with future research directions. Notation and acronyms used in the paper are shown in Table 1.

## 2.0 SEQUENCING FLEXIBILITY

The term "flexibility" has been used widely in prior research studies. It encompasses various types of flexibilities such as volume flexibility, variety flexibility, sequencing flexibility, material handling flexibility, product flexibility, expansion flexibility, and machine (or routing) flexibility. Some earlier studies addressed the issue of classifying various types of flexibility (Zelenovic [26], Chatterjee, Cohen, Maxwell and Miller[1984], and Sethi and Sethi [25]). Also, researchers addressed the issue of measuring various types of flexibility (Buzacott [7], Chatterjee et al.[1984], Browne, Dubois, Rathmill, Sethi, and Stecke [6], Carter [8],Brill and Mandelbaum [5], and Ettlie[11]).

In this paper we study in detail the effects of sequencing flexibility on the performance of scheduling rules. Sequencing flexibility refers to the number of alternate sequences in which the operations of a job can be performed.

| | | |
|---|---|---|
| $n_i$ | : | number of operations for job i |
| $a_i$ | : | arrival time of job i |
| $SFM_i$ | : | sequencing flexibility measure for job i. (the subscript is not used when reference is made to the concept) |
| $TPA_i$ | : | the number of transitive precedence arcs in the operation graph of job i |
| SPT | : | shortest processing time rule |
| FIQ | : | first in queue rule (also known as FCFS) |
| FIS | : | first in system rule |
| SPT | : | shortest processing time rule |
| LWR | : | least work remaining rule |
| EDD | : | earliest due date rule |
| CR | : | critical ratio rule |
| EODD | : | earliest operation due date rule |
| MODD | : | modified operation due date rule |
| OCR | : | operation critical ratio rule |
| MSUC | : | maximum successor ratio rule |
| $I_i$ | : | set of remaining operations of job i |
| $REM_i$ | : | number of remaining operations of job $i(=\|I_i\|)$ |
| $IMM_i$ | : | number of immediate successors to the current operation of job i |
| FAF | : | flow allowance factor |
| $D_i$ | : | due date for job i |
| $p_{ji}$ | : | processing time for the jth operation of the ith job |
| $ODD_{ji}$ | : | operation due date for the jth operation of job i |

**NOTATION**

**TABLE 1**

It can easily be seen that sequencing flexibility is inherent in product structure rather than machine hardware. Sequencing flexibility does not depend on the types of machines. Even when each operation of a job can be performed on no more than one specific machine in the shop, there can be many alternate feasible operation sequences. The number of alternate feasible sequences can range from 1 (when operations have strict serial precedence) to $n_i!$ (when no precedence exists at all among the operations). Hence sequencing flexibility is present in conventional machining systems as well as with modern technologies such as FMSs and CIM. However, material handling facilities may sometimes restrict the use of sequencing flexibility. In most conventional systems, material handling is largely manual and/or centralized. Hence jobs can be transported between any pair of machines in either direction, directly or indirectly. But in automated manufacturing systems, material handling may restrict certain operation sequences if access from one machine to another machine is difficult or impossible.

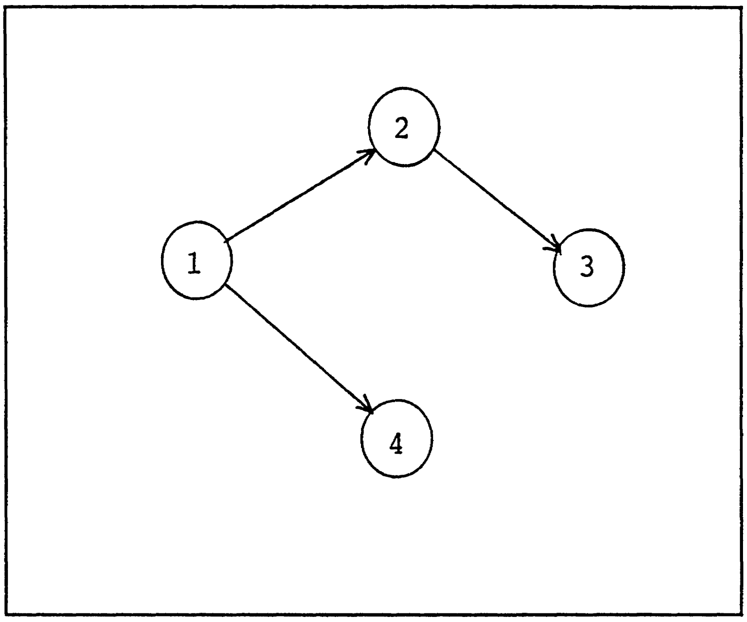
In order to study the effects of sequencing flexibility on the performance of scheduling rules, it is necessary to quantify sequencing flexibility. One measure of sequencing flexibility is the number of feasible operation sequences in a job (Gerwin [13] and Sethi and Sethi [25]). The number of alternate feasible sequences is dependent partly on the number of operations to be performed. Clearly, if two jobs have the same number of feasible sequences, the one with a smaller number of operations is more flexible than the one with a larger number of operations. Hence it is appropriate to scale the number of feasible sequences with respect to the number of operations in a job. Rachamadugu and Schriber [20] derived a measure of flexibility, called the Sequencing Flexibility Measure (SFM) which takes into consideration both the number of operations, and the number of feasible operation sequences. The sequencing flexibility measure is defined as follows:

$$SFM_i = 1.0 - \frac{2*TPA_i}{n_i(n_i-1)} \qquad (1)$$

where $n_i$ is the number of operations in job i, $TPA_i$ is the number of transitive precedence arcs in the operation graph of job i, and $SFM_i$ is the sequencing flexibility measure for job i. The term transitive precedence arcs is used to represent precedence relations, both explicit and implicit, between all pairs of operations of a job. The denominator in the above expression is twice the potential number of acyclic precedence arcs that can exist in an operation graph of a job. For example, consider the operation graph of a job shown in Figure 1. Though the figure shows only three explicit precedence arcs, an arc representing the implicit precedence between operations 1 and 3 is not shown. Hence the total number of precedence relationships (both explicit and implicit), known as transitive precedence arcs, is four. The SFM for the job shown in Figure 1 is therefore 0.333. In the case of classical job shops, each job has a preassigned operation sequence, and hence the SFM value is zero. Gonzalez and Sahni [14], and Bitran, Dada and Sison [4] denote situations in which there are no precedence restrictions at all as open shops. The SFM value for open shops is 1. Clearly, the SFM value for most practical situations falls between 0 and 1. We use SFM as the measure of sequencing flexibility in this paper.

## 3.0 LITERATURE REVIEW

Earlier research studies in job shop scheduling were reviewed by Baker [1], Conway, Maxwell, and Miller[1967], and French [12]. Most studies in job shop research treated the operation sequence of a job as given, and fixed. Very few studies specifically addressed the impact of sequencing flexibility on the performance of scheduling rules in job shops. Russo [22] studied the effects of using sequencing flexibility on the performance of scheduling rules. He used both flowtime, and due date (mean tardiness) related criteria to evaluate the performance of scheduling rules. His study identifies different levels at




**OPERATION GRAPH**

**Figure 1**

which sequencing flexibility can be utilized. He showed that greater the use of flexibility, the larger is the improvement in the performance of scheduling rules. His studies were performed at a shop utilization level of 80%. Neimeier [17] studied the effect of sequencing flexibility on the performance of First Come First Serve (FCFS) and Shortest Processing Time (SPT) rules at various levels of sequencing flexibility. His study assigned operations to machines earlier than necessary, and hence did not fully exploit sequencing flexibility inherent in the jobs. He concluded that using sequencing flexibility improved the performance of the rules, and narrowed the performance differences between SPT and FCFS. However, SPT performed better than FCFS in all his studies. His conclusions were similar to Russo[1965].

Rachamadugu [19], Rachamadugu and Schriber [20] and Schriber [24] investigated the effectiveness of sequencing flexibility on the performance of scheduling rules in job shops and <u>generalized open shops</u>. In a generalized open shop, while operations of a job can be performed in any order, a job need not visit all the machines in the shop. These studies show that, while SPT performs better than competing rules in conventional job shop studies, better results can be obtained by using the Least Work Remaining (LWR) rule in generalized open shops. However, in most practical situations, manufacturing systems are neither as restrictive as the classical job shop studied in the literature (SFM value of 0), nor as flexible as the generalized open shop (SFM value of 1) studied by Rachamadugu and Schriber [20]. Exploratory studies by Rachamadugu and Schriber [20] and Schriber [23] were conducted using GPSS/H (Schriber [24]).

Lin and Solberg [16] recently studied flexibility issues in the context of flexible manufacturing systems. They concluded that utilizing both software and hardware flexibilities inherent in the system significantly improves the performance of scheduling rules. However, their study involved combinations of routing flexibility, sequencing flexibility, and process flexibility. Also, their findings were based on a specific flexible manufacturing system configuration. They observed that SPT and FIQ performed better than competing rules. Their study provides interesting insights into how the managerial control system can influence the effectiveness of flexibility. Their study did not explore the effects of flexibility on due date related criteria.

Our research extends earlier studies in the following ways. First, we isolate and control for the effects of sequencing flexibility. This is important because sequencing flexibility is independent of the manufacturing system hardware (unless there are severe material handling restrictions). Hence it can be used in conventional systems as well as FMSs to improve system performance. Second, we address the effect of due date allowance (or flow allowance) on the performance of various rules when sequencing flexibility is present. Third, we study the effects of using operation due dates (milestones) in the presence of sequencing flexibility. This extends the earlier works of Kanet and Hayya [15], Baker and Kanet [2], and Baker [3] on operation milestones to more general situations. We evaluate the performance based on three criteria which are of practical importance. They are mean flowtime, average tardiness, and proportion of tardy jobs.

## 4.0 SCHEDULING WITH SEQUENCING FLEXIBILITY

We studied the performance of eleven scheduling rules at various levels of sequencing flexibility. These rules were chosen based on their use in the literature and their relevance to flexible situations. They are described below:

1) FIQ - first in queue rule. Whenever a machine is available, highest priority is assigned to the job which arrived at this machine earliest. It should be noted that for prioritization purposes, the latest time at which a "copy" of the job entered the queue is used. This rule is also known as the FCFS rule.

2) FIS - first in system rule. Highest priority is assigned to eligible operations of the job which entered the system earliest.

3) SPT - shortest processing time rule. Highest priority is assigned to the job which requires the least processing time at the machine.

4) LWR - least work remaining rule. Highest priority is assigned to the job which has the least total remaining work to be performed in the system.

5) EDD - earliest due date rule. Highest priority is assigned to the job with the earliest due date.

6) MDD - modified due date rule. Highest priority is assigned to the job with the earliest modified due date, where modified due date equals the maximum of the job's due date, and the earliest finish time of the job (Baker [1984]).

7) CR - critical ratio rule. Highest priority is assigned to the job with the least ratio of remaining time until due date (dynamic slack) to the remaining processing time.

8) EODD - earliest operation due date rule. Highest priority is assigned to the job with the earliest operation due date.

9) MODD - modified operation due date rule. Highest priority is assigned to the job with the earliest modified operation due date.

10) OCR - operation critical ratio rule. Highest priority is assigned to the operation which has the least ratio of operation slack to the operation time.

11) MSUC - maximum successor ratio rule. MSUC value for each queued operation is determined as follows:

$$MSUC_j = \frac{IMM_j + 1}{REM_i} \tag{2}$$

where $IMM_j$ is the number of immediate successors of operation j, and $REM_i$ is the total number of remaining operations of the job i. Numerator is incremented by 1 to ensure that the last operation of a job is not orphaned. Since an operation with large ratio tends to make eligible for assignment a large proportion of its successors, it is anticipated that it will lead to faster completion of the job.

Earlier job shop studies found that using operation milestones instead of job due dates resulted in improvement of scheduling rules. We extended this scheme to flexible sequencing situations. In job shop studies, the operation sequences for jobs are fixed, and hence the operation due dates could be set at the time of job arrival (Kanet and Hayya [15], Baker [3]). When sequencing flexibility is used in scheduling the jobs, it is not known apriori in which sequence the operations will be executed. Hence the operation due date for an operation needs to be computed whenever it becomes eligible for assignment. Also, Baker [3] found a total work content procedure to perform better than competing alternatives for setting due dates. We used this scheme to set the job due dates, as well as operation due dates. Operation due date for the j<u>th</u> operation of job i ($ODD_{ji}$) is given by the following expression-

$$ODD_{ji} = a_i + \frac{D_i - a_i}{\sum_{k=1}^{n_i} p_{ki}} \left(p_{ji} + \sum_{l \notin I_i} p_{li}\right) \tag{3}$$

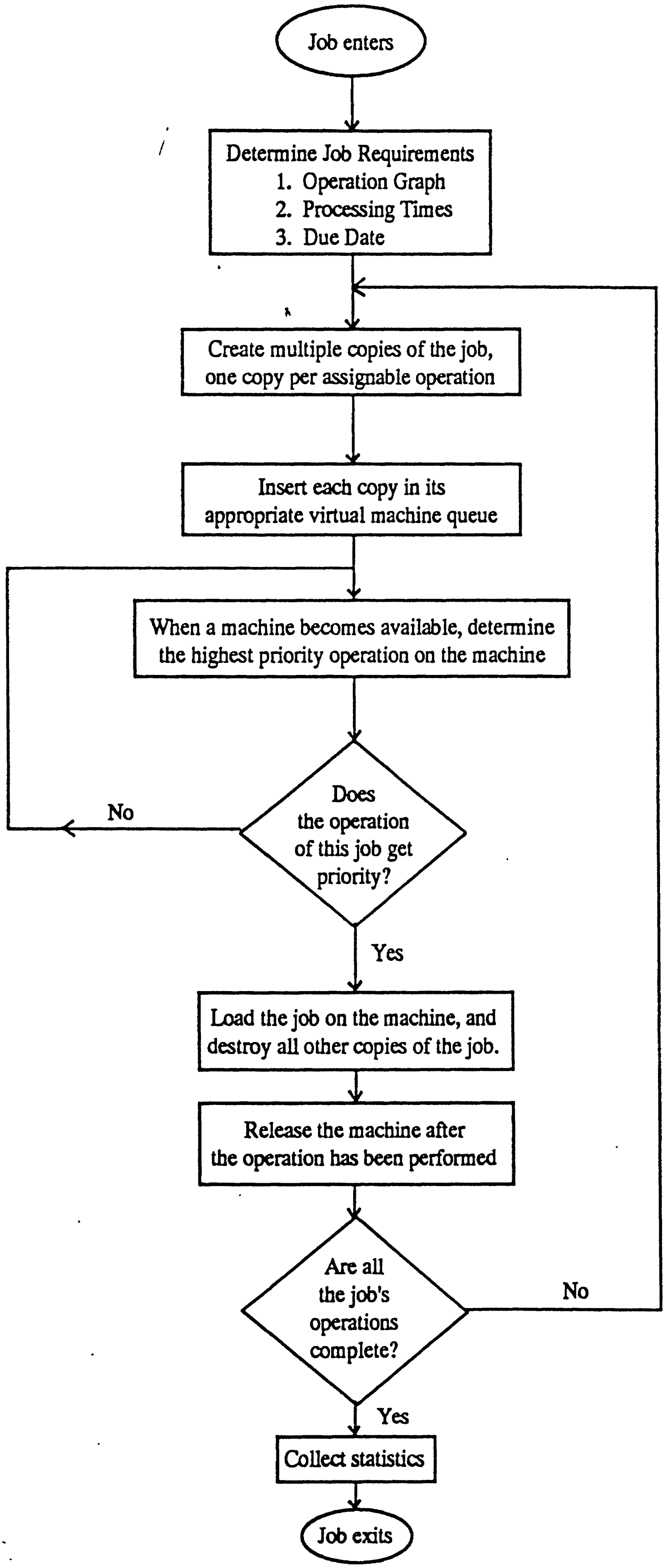
where $a_i$ is the arrival time of job i, $I_i$ represents the set of remaining operations of job i, $D_i$ is the due date of job i, and $p_{ji}$ represents the processing time for the jth operation of job i. Clearly, schedules generated using operation due dates and job due dates need not be identical. Note that (3) results in the same operation milestones as those suggested by Kanet and Hayya[15] and Baker [3] for classical job shops. However, (3) extends those concepts to more general situations in which we have no apriori knowledge of the sequence to be used in dispatching the jobs. Other operation due date setting procedures are possible, but they are not explored here.

## 5.0 MODELING ISSUES

Modeling sequencing flexibility proved challenging. In our approach, whenever a job had more than one eligible operation (an operation whose predecessor operations had been completed), a copy of the job was created for each of the eligible operations. Each copy joined the virtual queue at the machine at which the corresponding operation had to be performed. When processing began on any one of these operations, all other copies of the job were destroyed. This accommodated the assumption that no two operations of a job can be carried out simultaneously. Later, when the ongoing operation was completed, copies of the job were then created for each remaining eligible operation, and so on, until all operations had eventually been completed. The set of steps followed in moving a job through its life cycle is summarized in the flowchart in Figure 2.

Next we describe the generation of operation graphs. First we determine the number of operations for a job. Each operation of a job is assigned a number. Next we randomly sample two integers x and y in $[1,n_i]$ such that $x \neq y$. Without loss of generality assume that $x<y$. If a transitive precedence arc already exists between x and y, then x and y are discarded, and a new random pair of operations is sampled. Else, a direct precedence is imposed between the operations x and y, with x preceding y. This ensures that the operation graph is acyclic. Also, implicit precedence arcs are recognized by making x (and all its predecessors) be predecessors of y (and all its successors). This process is repeated until enough transitive precedence arcs are generated, as needed by the sequencing flexibility measure value (equation 1, section 2).

As an example, consider how we can derive the operation graph shown in Figure 1. Its SFM value is 1/3. Hence we need to generate four transitive precedence arcs (equation (1), section 2). Suppose that the first chosen random pair is (4,1). We set a precedence restriction that 1 should be done before 4.




**JOB LIFE CYCLE IN THE SIMULATION MODEL**

**Figure 2**

Let the next chosen random pair be (2,3). We set a precedence restriction that 2 should precede 3. Let the next randomly chosen pair be (1,4). Since a precedence relation exists between (1,4), we discard this pair, and sample again. Let (2,1) be the next chosen pair. We set a precedence restriction that 1 should precede 2. Since a precedence already exists between 2 and 3, this results in an additional transitive precedence arc, (1,3). Now we have four transitive precedence arcs, (1,2), (2,3), (1,3), and (1,4). Hence the operation graph is now complete.

## 6.0 EXPERIMENTAL DESIGN

We modeled a shop with 10 machines. Each arriving job consisted of a set of operations to be performed, the number chosen from a discrete [4,8] uniform distribution. Every operation of a job is assigned randomly to a machine. Hence, a job may visit a machine more than once. Operation processing times were sampled from a negative exponential distribution with mean of 5.0 time units. Rachamadugu and Schriber [20] and Lin and Solberg [16] found that performance differences between scheduling rules were not significant at low utilization levels. Hence the mean interarrival time was set at 10/3 time units so that the shop utilization was high (90%). Interarrival times were also sampled from a negative exponential distribution.

There are three factors in the experiment: the level of sequencing flexibility (expressed as the SFM), the flow allowance factor(FAF), and the scheduling rule. SFM values can range from 0 to 1, the former representing no sequencing flexibility (almost all classical job shop studies fall in this category) while the latter permits operations of a job to be performed in any order (open shops and generalized open shops). Because product structures in practice do not necessarily fall at the two extremes, we varied SFM values from 0 to 1, in increments of 0.2. Hence we have six SFM values. Flow allowance factors were set at 0.25k, 0.5k, 1k, 2k, and 4k, where k is the ratio of the mean flowtime to the mean processing time in an M/M/1 system. Since interarrival times and processing times are negative exponentially distributed, it can easily be verified that k equals 10 in an M/M/1 system.

A full factorial design was used to study the performance of the various scheduling rules. With six SFM values, five flow allowance factors and eleven scheduling rules, this resulted in 330 experimental settings. A single replication was performed for each experimental setting. For purposes of testing for steady state, a replication was partitioned into a sequence of 12 consecutive, nonoverlapping batches, each corresponding to 20,000 time units (approximately 6,667 jobs). The performance measures of interest were then averaged over the last 10 batches, giving the results reported here.

Common random numbers were used in each experiment so that matched-pair comparisons of the performance measures for any two scheduling rules could be made. This was done by dedicating independent random number generators to each source of randomness in the model. The net effect was that from experiment to experiment, any given job moving through the system had the same time of arrival, the same number of operations, the same set of required machines, and the same set of operation times. This approach sharpens the contrast in the performance measures achieved by the alternate scheduling rules.

The model used to produce the results reported here was written in SIMAN (Pegden, Shannon, and Sadowski [18]) and was supported in part by subroutines coded in Fortran 77. The experiments were run on an Hitachi Data Systems 9080 computer.

## 7.0 SIMULATION VERIFICATION AND VALIDATION

We used three aspects of our study to verify and validate the simulation results. First, we compared the realized overall machine utilization with the expected overall utilization. While the expected machine utilization was 90%, the realized mean machine utilization was 90.1%, and the range was 89.2-91.6%.

Second, we tested the batch mean flowtimes in each experiment for autocorrelation using the Durbin-Watson statistic. In all cases, the existence of autocorrelation could not be confirmed for the batch mean flowtimes at a significance level of 5%. Details are shown in table IA, Appendix A. Similar results were observed for the mean tardiness and proportion of tardy jobs, with some exceptions. These exceptions occurred when the tardiness and the proportion of tardy jobs were driven to very small values (close to 0, when flow allowances are large). Also, in cases where measures were identical, the Durbin-Watson statistic could not be computed. Third, the special cases of zero SFM value correspond to classical job shop studies. Our results for these special cases are similar to those derived by earlier researchers.

### 7.1 ANALYSIS OF RESULTS

Now we analyze the simulation results. Detailed results are provided in Appendix B. First, we discuss how flexibility affects the mean flowtime performance of the rules, and then we discuss the implications for due date related criteria.

Figure 3 compares the mean flowtimes for scheduling rules at different flexibility levels. FIQ was excluded from Figure 3 since it performed worse than FIS under all settings. Also, the MSUC rule was eliminated from the figure since its performance was worse than well known rules from the prior literature. Results for due date based rules are shown at a flow allowance level of 1, which corresponds to the average flowtime for a job with average processing time. Note the beneficial effects of using sequencing flexibility. All rules included in our study improve their flowtime performance as the SFM value increases. It is also clear that even a some sequencing flexibility provides improvements in the mean flowtime performance. Relative to classical job shops, Table 2 lists the reduction in flowtimes for various rules at SFM values of 0.2 and 1. With the exception of the operation critical ratio rule(OCR), rules which perform poorly at 0 flexbility level achieve large improvements at an SFM

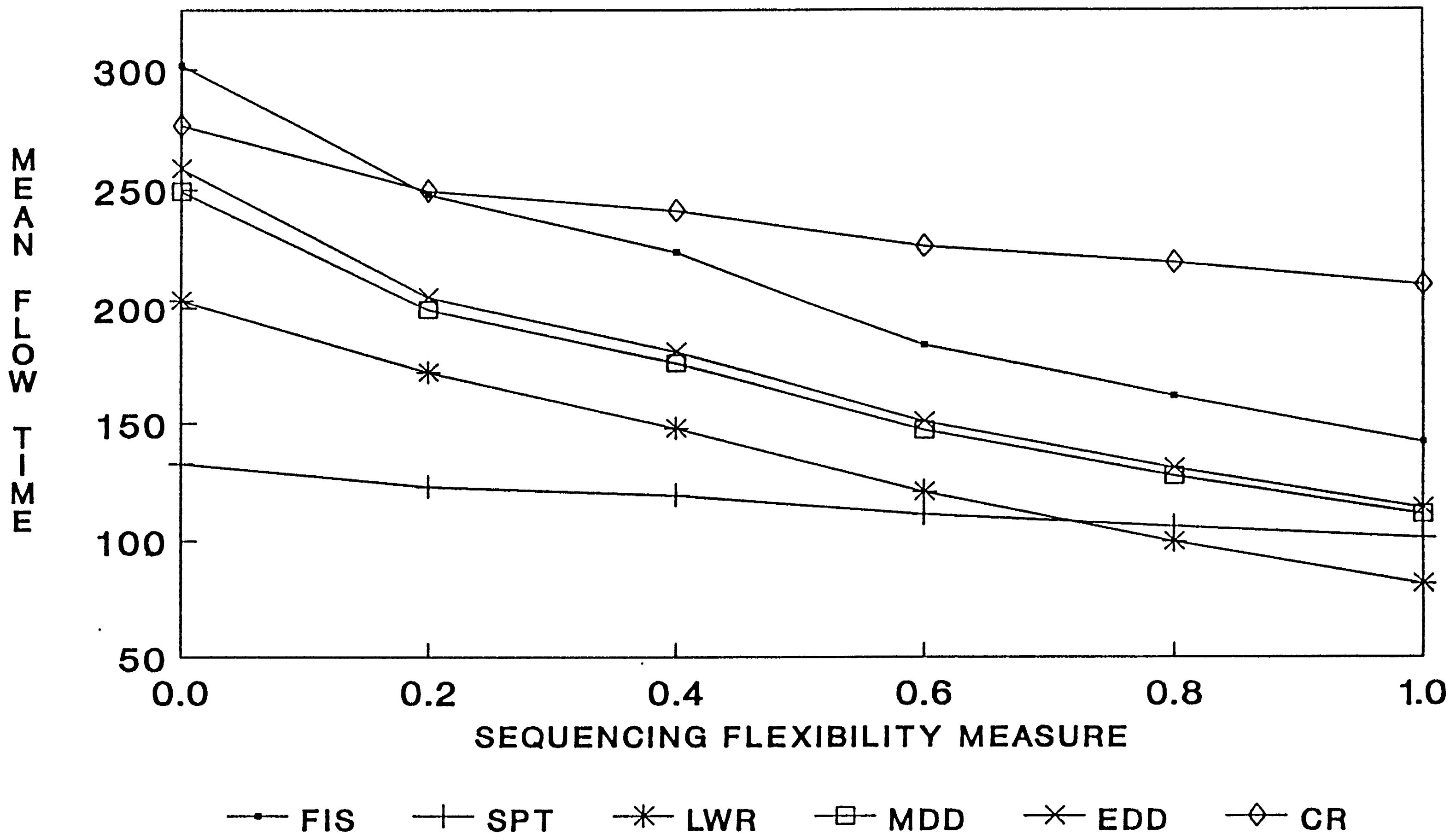



Figure 3: Mean Flow Time as a Function of Sequencing Flexibility Measure for Selected Scheduling Rules

level of 1.0. For example, an arbitrary rule such as FIS improves its mean flowtime by 52.25% while the improvement for SPT is only 23.68%.

| Scheduling Rule | Mean flowtime at SFM=0 (job shops) | Reduction in mean flowtime in comparison with no flexibility (in percent) | |
|---|---|---|---|
| | | SFM = 0.2 | SFM = 1.0 |
| FIS | 301.68 | 17.78 | 52.25 |
| MAX SUC RATIO | 297.62 | 24.42 | 63.84 |
| CR* | 276.41 | 9.73 | 24.07 |
| EDD* | 258.63 | 20.82 | 55.91 |
| OCR | 254.83 | 4.84 | 10.83 |
| MDD* | 249.23 | 19.99 | 55.35 |
| EODD* | 213.96 | 11.82 | 36.84 |
| LWR | 203.21 | 15.57 | 59.93 |
| MODD* | 196.76 | 9.34 | 32.53 |
| SPT | 132.80 | 7.28 | 23.68 |

Note: the performance of rules marked * is reported at a flow allowance factor of 1

PERCENT REDUCTION IN MEAN FLOWTIMES

TABLE 2

Classical job shops have an SFM value of 0. While SPT performs better than competing rules in classical job shops (see a recent survey by Ramasesh [21]), least work remaining rule provides superior performance at high SFM values. Earlier job shop studies did not address perfect sequencing flexibility (SFM=1). Hence those studies did not uncover the superior performance of LWR at high SFM values.

We also studied the interaction between the flowtime performance of due date related rules and various FAF values. As flow allowance increases, due date based rules improve their due date performance. However, earlier research did not focus on the effects of flow allowance on flowtime performance of due date based rules. First, we consider the EDD rule. Clearly, at very low flow allowances, priorities assigned by EDD and FIS are similar. If FAF is zero, EDD reduces to FIS. However, EDD imitates LWR at very large flow allowances. Hence the flowtime performance of EDD improves as FAF increases, and is also bounded by LWR and FIS, as shown in Figure 4.

Now we consider the performance of the CR rule for the mean flowtime criterion (Figure 5). At any SFM value, CR performs worse as the FAF increases. It is interesting to note that EDD and CR perform in opposite ways for the flowtime criterion as FAF increases (compare Figures 4 and 5). As FAF decreases, jobs tend to have negative slack, and hence CR assigns jobs with a small amount of remaining work higher priority. When FAF values are large, slack tends to be positive, and hence jobs with the most remaining work are assigned higher priority, unless the queue at the machine has some tardy jobs. This explains the deteriorating performance of CR at high FAF values. Though large FAF values improve the tardiness performance of the CR rule, those benefits are partly offset by an increase in inventories. This aspect of CR merits further investigation.

Next we consider the flowtime performance of the modified due date rule. By definition, it is clear that MDD tends to imitate LWR at low FAF values. However, at high FAF values, MDD behaves more like the EDD rule. These patterns are evident from Table 3, which compares the performance of these rules at different SFM values.

Kanet and Hayya [15] noted that using operation due dates reduces the flowtime for job due date based rule such as EDD and the slack based rules in classical job shops. Our results lead to somewhat different conclusions, as shown in Figure 6, 7, and 8. In the case of EDD and EODD (Figure 6), our study reaffirms Kanet and Hayya [15] conclusions for the classical job shop. However, where flow allowances are large, setting operation due dates results in deteriorating performance even when small amounts of sequencing flexibility

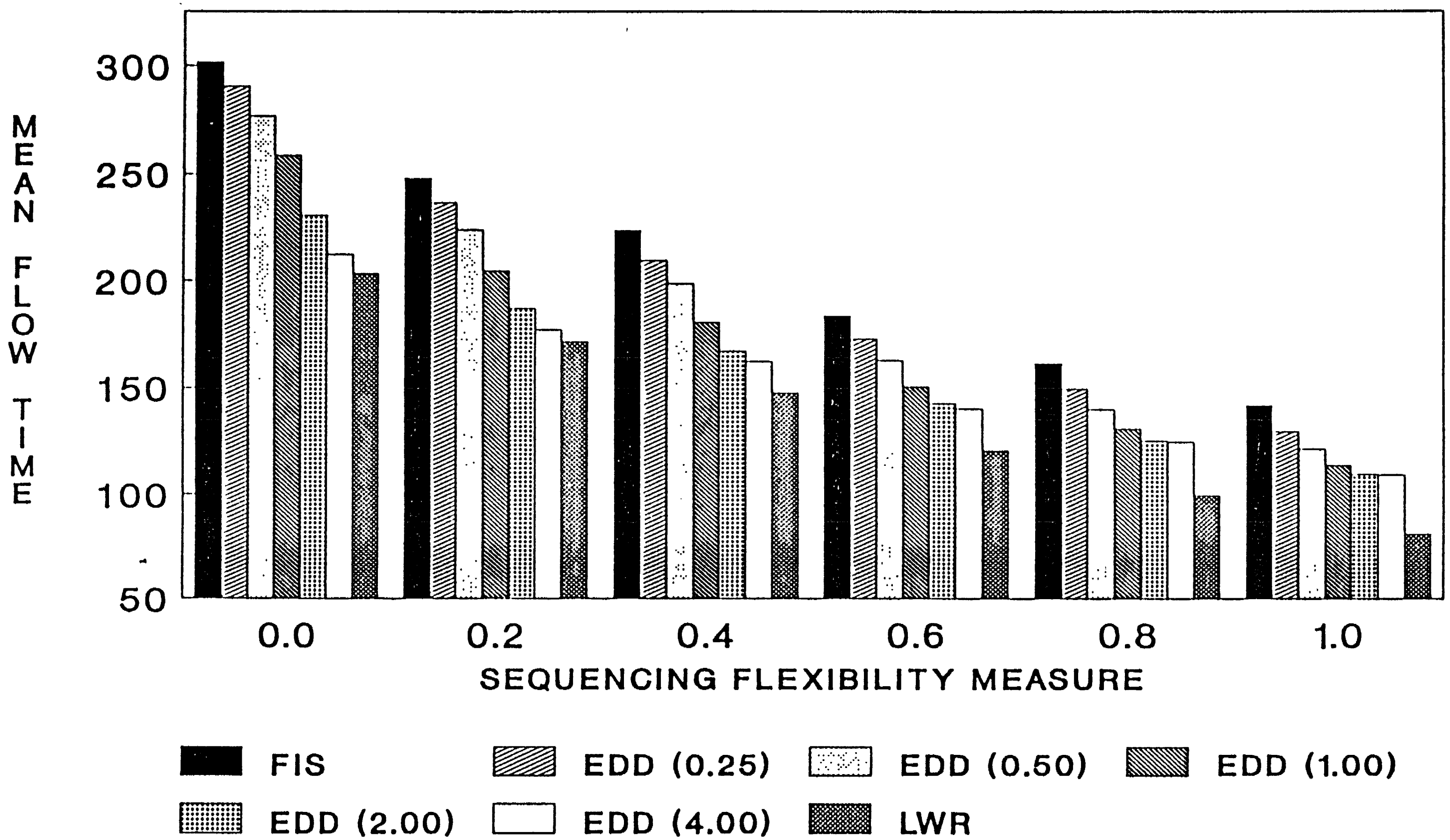



Figure 4: Variation in Mean Flow Time for Earliest Due Date Rule (With FIS and LWR as Bounding Cases)

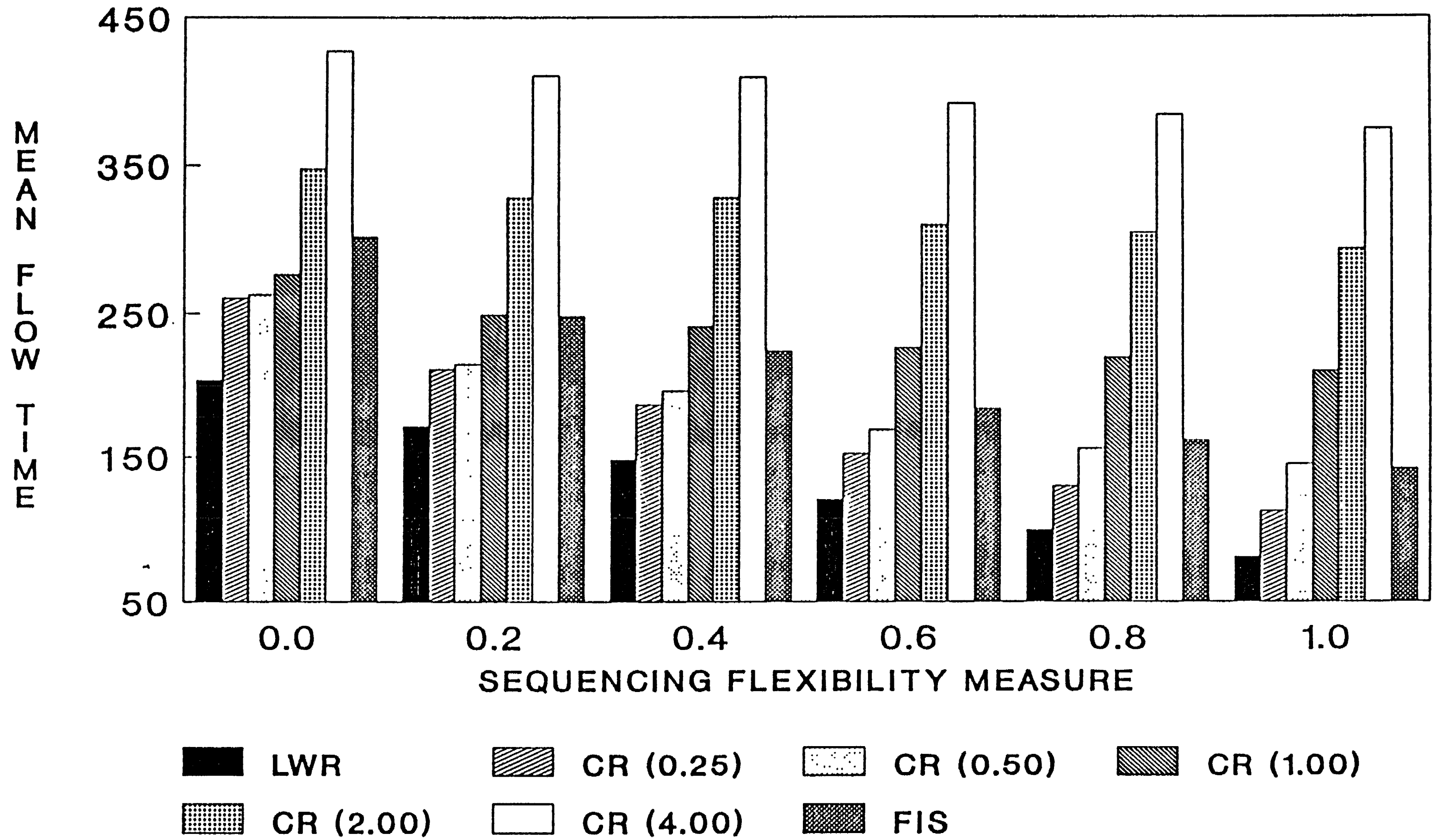



Figure 5: Variation in Mean Flow Time for the Critical Ratio Rule (With LWR and FIS Shown for Comparison)

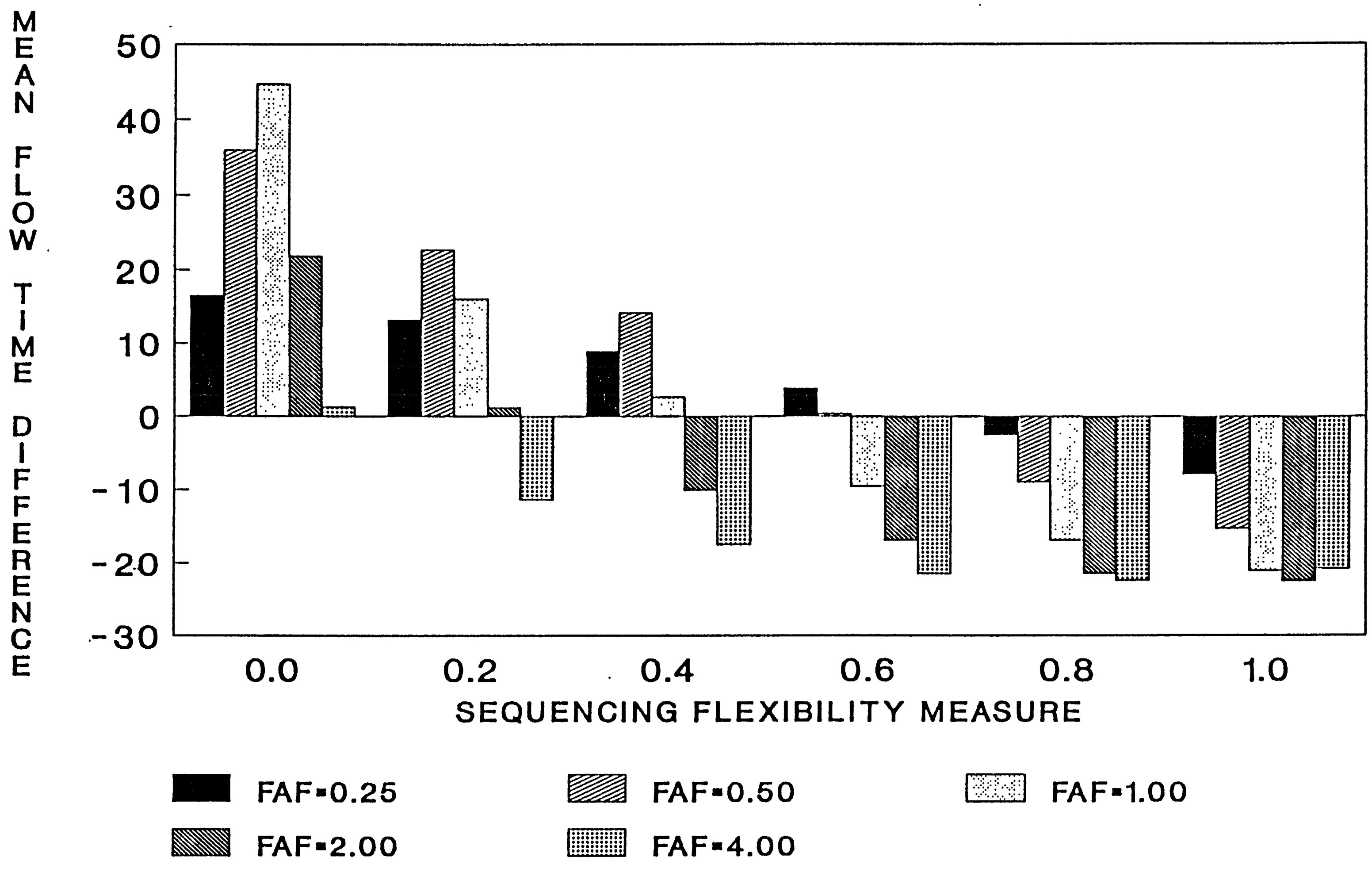



Figure 6: Mean Flow Time Difference,
EDD-EODD

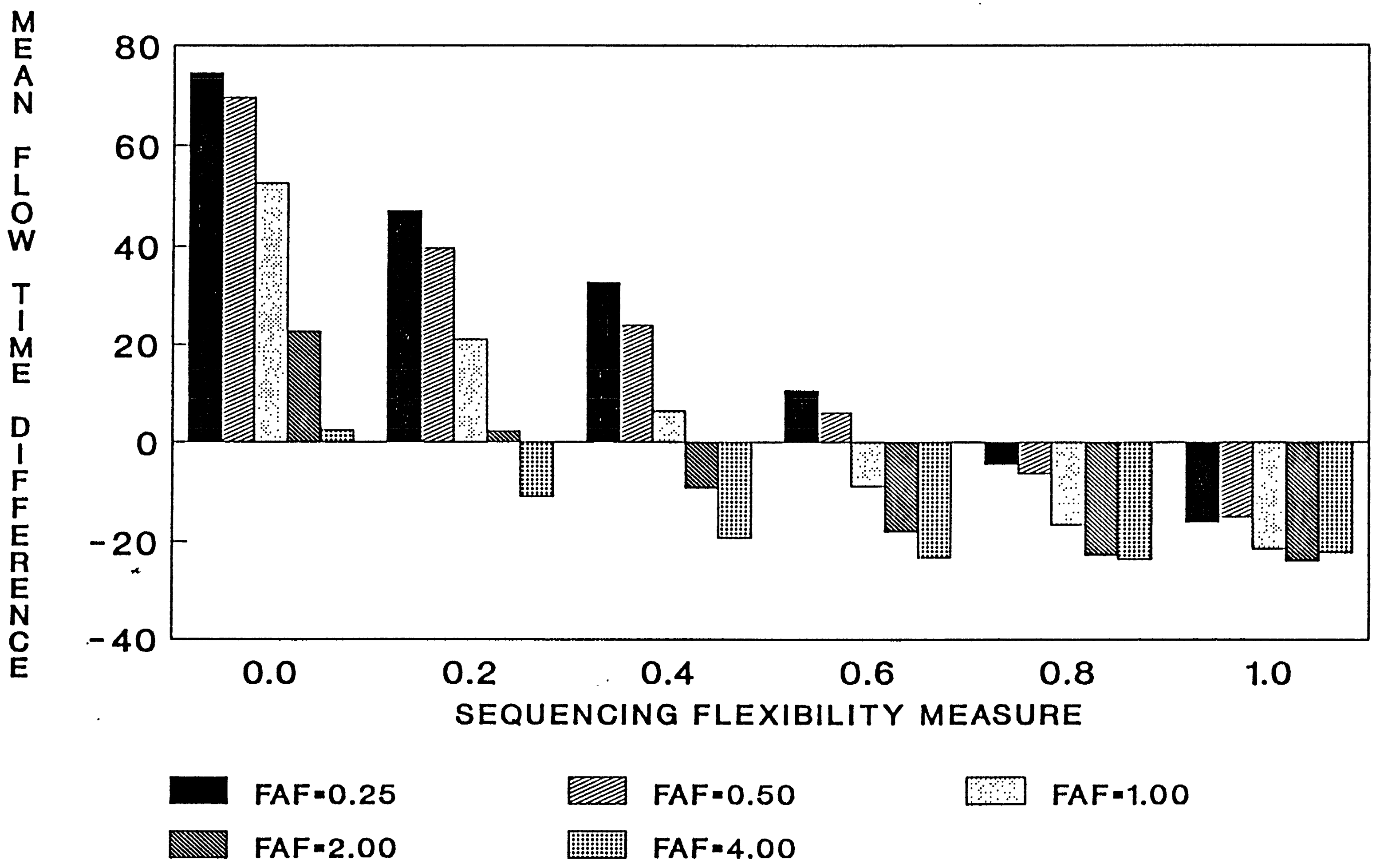



Figure 7: Mean Flow Time Difference,
MDD-MODD

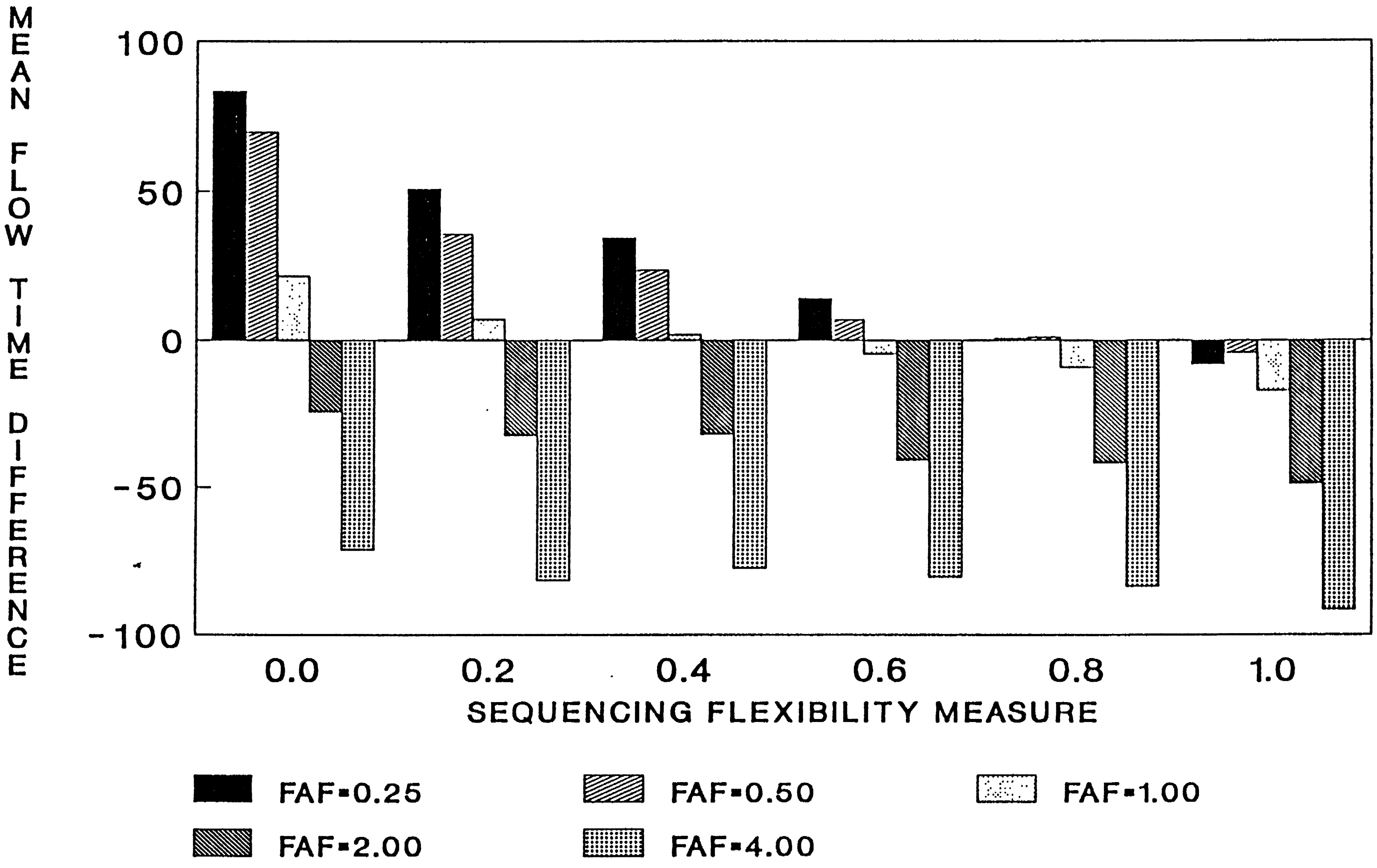



Figure 8: Mean Flow Time Difference,
CR-OCR

| Flow Allowance | | SFM VALUE | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 |
| Low (0.25) | LWR | 203.21 | 171.55 | 147.81 | 120.75 | 99.71 | 81.43 |
| | MDD | 209.37 | 173.27 | 154.74 | 124.96 | 104.65 | 87.59 |
| High (4.0) | EDD | 212.24 | 177.23 | 162.37 | 140.29 | 124.87 | 109.41 |
| | MDD | 213.51 | 177.60 | 160.61 | 138.57 | 123.70 | 107.99 |

Comparison of MDD with LWR and EDD

(mean flowtime)

**Table 3**

is present. At extremely high SFM values, operation milestones worsen the performance of EDD for all FAF values in our study. Similar patterns can also be observed for MDD (Figure 7). In the case of critical ratio rule, using operation due dates can increase mean flowtimes even in classical job shops (Figure 8). This has implications for tardiness performance as well, as discussed below.

Next we discuss the performance of rules for due date related criteria. Since FIS, FIQ and MSUC performed significantly worse than competing rules, their tardiness performance is excluded from further analysis. Figure 9 shows the average tardiness results for competing rules at a low FAF value of 0.25. We note that as the SFM value increases, performance differences between the rules diminish significantly. At low SFM values SPT and MODD perform extremely well. However, when the SFM value is high, MDD outperforms competing rules. This is not surprising, since in tight due date settings MODD and MDD emulate SPT and LWR respectively. Our prior analysis indicates that while SPT yields the smallest flowtimes at low SFM values, LWR results in the least flowtime at

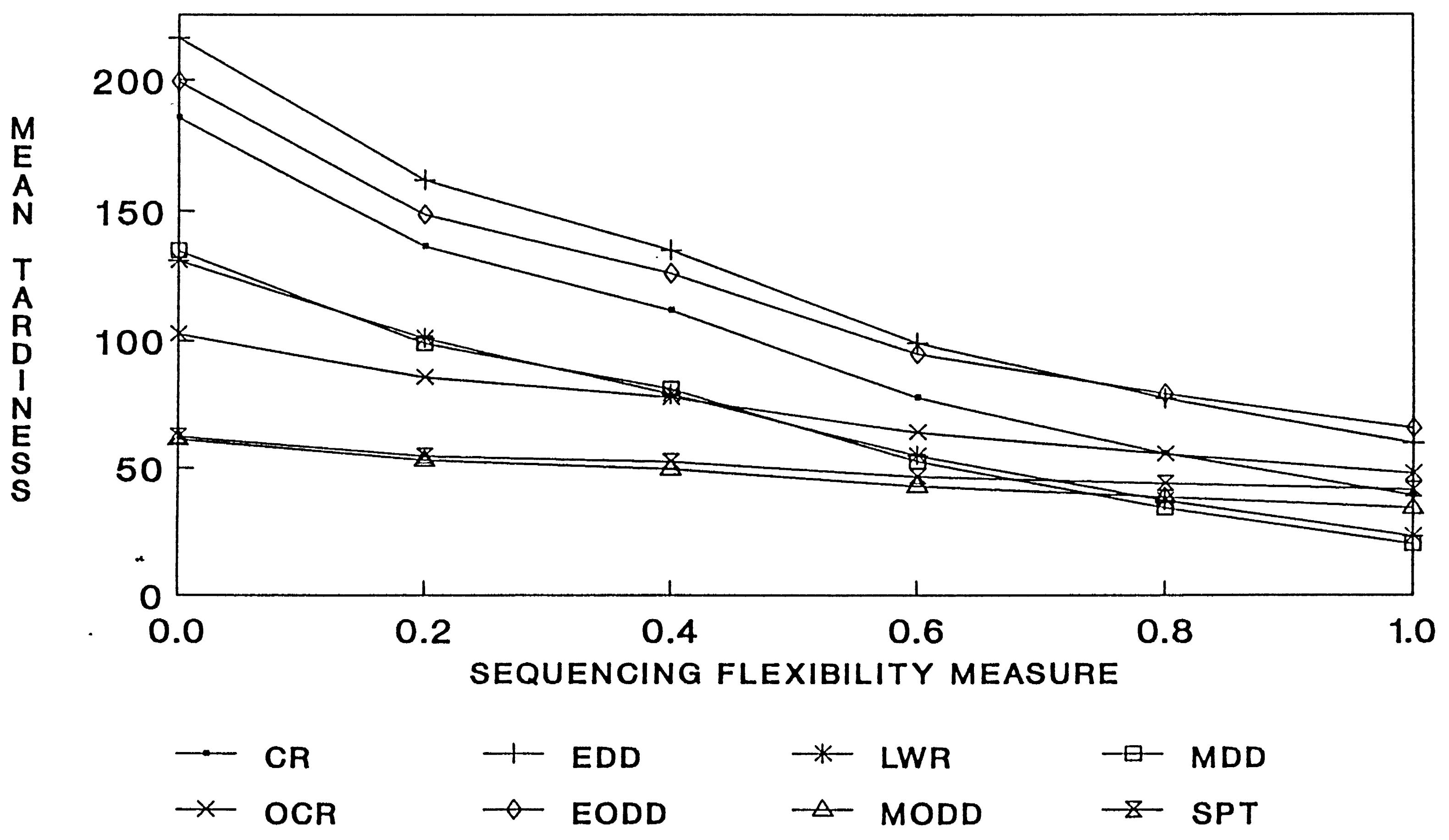



Figure 9: Tardiness Performance of Selected Scheduling Rules, Flow Allowance Factor, 0.25

high SFM values. This explains the superior performance of MODD at low SFM and MDD at high SFM values. Similar patterns can also be observed for the CR and EDD rules. While operation due date versions perform well at low SFM values (classical job shops), job due date versions dominate at high SFM values.

Figure 10 shows the tardiness performance of rules when FAF raised to 1. Whereas SPT and LWR were competitive at the low FAF of 0.25, they are clearly dominated by due date based rules when the FAF is 1. Once again, we note that performance differences between various due date related rules diminsh rapidly as the SFM increases. MODD performs the best at low SFM values, while MDD dominates the other rules at high SFM values (also see shaded cells in Table IIB, Appendix B). In open shops, MDD outperforms other rules. However, performance differences between MDD and MODD at this SFM value are insignificant. Increasing flow allowances beyond 1 results in all due date rules performing well, with the differences becoming insignificant from a practical point of view. For details, see Table IIB, Appendix B. However, at high flow allowance values (FAF = 2 or 4), operation milestone versions are clearly dominated by job due dates versions of rules for all SFM values. Earlier, this was commented on by Baker and Kanet [1983] for job shops. Our study shows that those conclusions can be generalized to precedence constrained job networks.

MODD is a good choice for reducing tardiness at all flow allowance values when sequencing flexibility is low. However, at high sequencing flexibility levels, better results can be achieved by using the MDD rule. Our study not only reaffirms earlier research conclusions that MODD is a good choice for classical job shops, but also extends its usefulness to situations where sequencing flexibility exists in the system. At extremely high SFM values, MDD is a better choice than MODD.

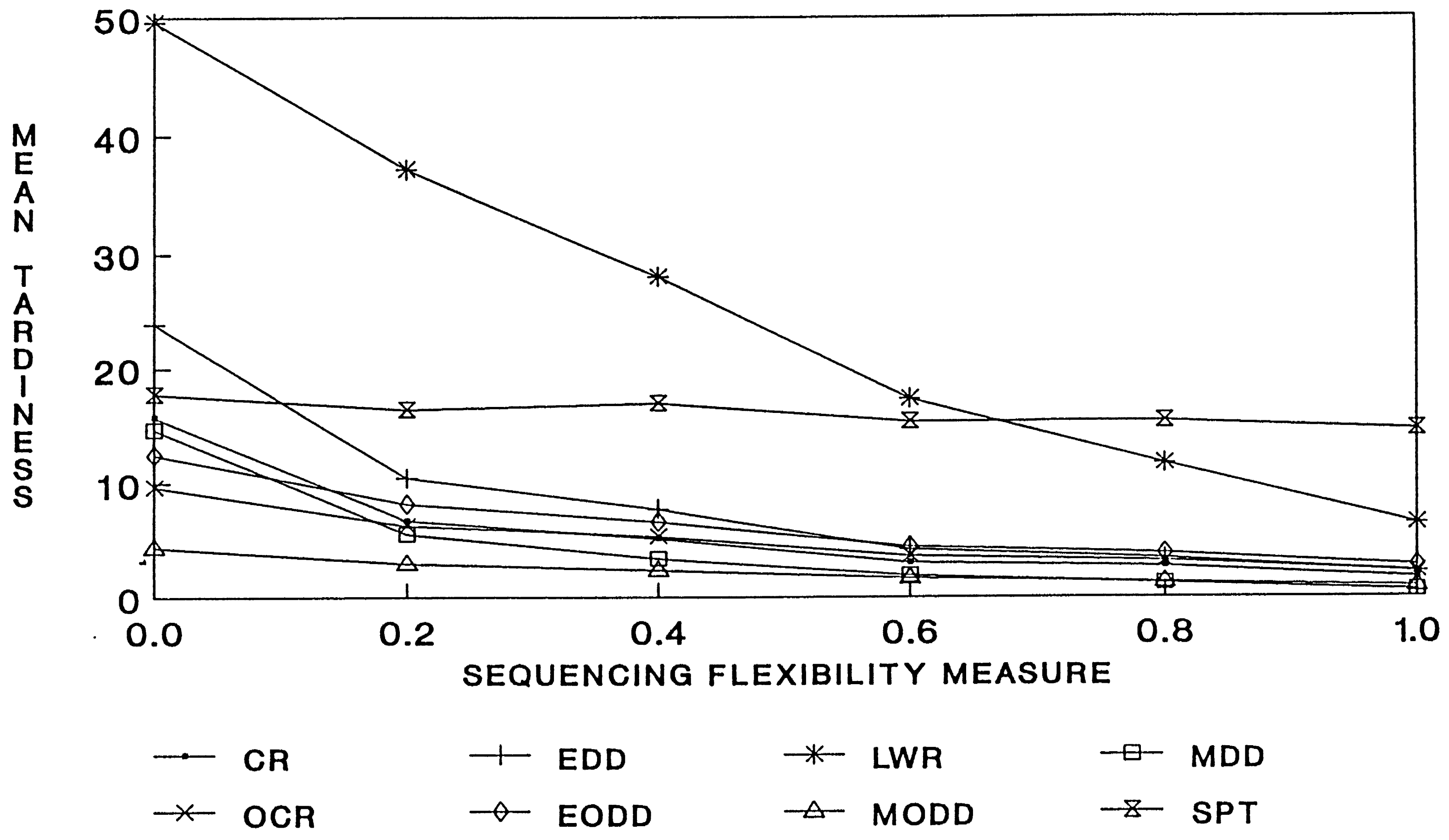



Figure 10: Tardiness Performance of Selected Scheduling Rules, Flow Allowance Factor, 1.00

We evaluated the performance of the scheduling rules for the proportion of tardy jobs. This measure is also of interest to practitioners. For example, in some industries such as the furniture industry, it is a common practice for the manufacturer to incur freight expense if the delivery is late. Then the proportion of tardy jobs is a better surrogate for profits than tardiness. Figure 11 shows the proportion of tardy jobs for the rules at a low FAF value of 0.25. It is clear that all rules improve their performance as the SFM increases. SPT outperforms all other rules at low SFM values (≤0.6), and LWR performs the best at high SFM values. Superior performance of SPT for the proportion tardy criterion was noted earlier by Baker [3] for classical job shops. Our study extends its validity for low sequencing flexibility situations as well. In fact, while operation based rules perform better at low SFM values (job shop situations), job based rules perform better at high SFM values. However, we note that, unlike other measures, there is little convergence in the performance of rules as the SFM is increased. Figure 12 shows the results for a flow allowance value of 1. Clearly, SPT dominates the other rules for job shop situations here. However, the reader will note that MODD provides not only comparable performance for job shops, but dominates other rules for low SFM values (≤0.6). However, MDD provides superior performance for high SFM values (≥0.8). Though slack based rules are known to perform well at large flow allowances for job shops (for the proportion tardy criterion), absolute magnitudes of the values are already so small that the performance differences between MDD/MODD and slack based rules are of little practical importance. At higher flow allowances, performance differences between the rules diminish rapidly. Details are shown in Table IIIB, Appendix B.

## 8.0 CONCLUSIONS

We investigated the effects of sequencing flexibility on the performance of scheduling rules. The performance measures included mean flowtime, average tardiness, and proportion of tardy jobs. When sequencing flexibility is used, the least work remaining rule performs better than the SPT rule to reduce the

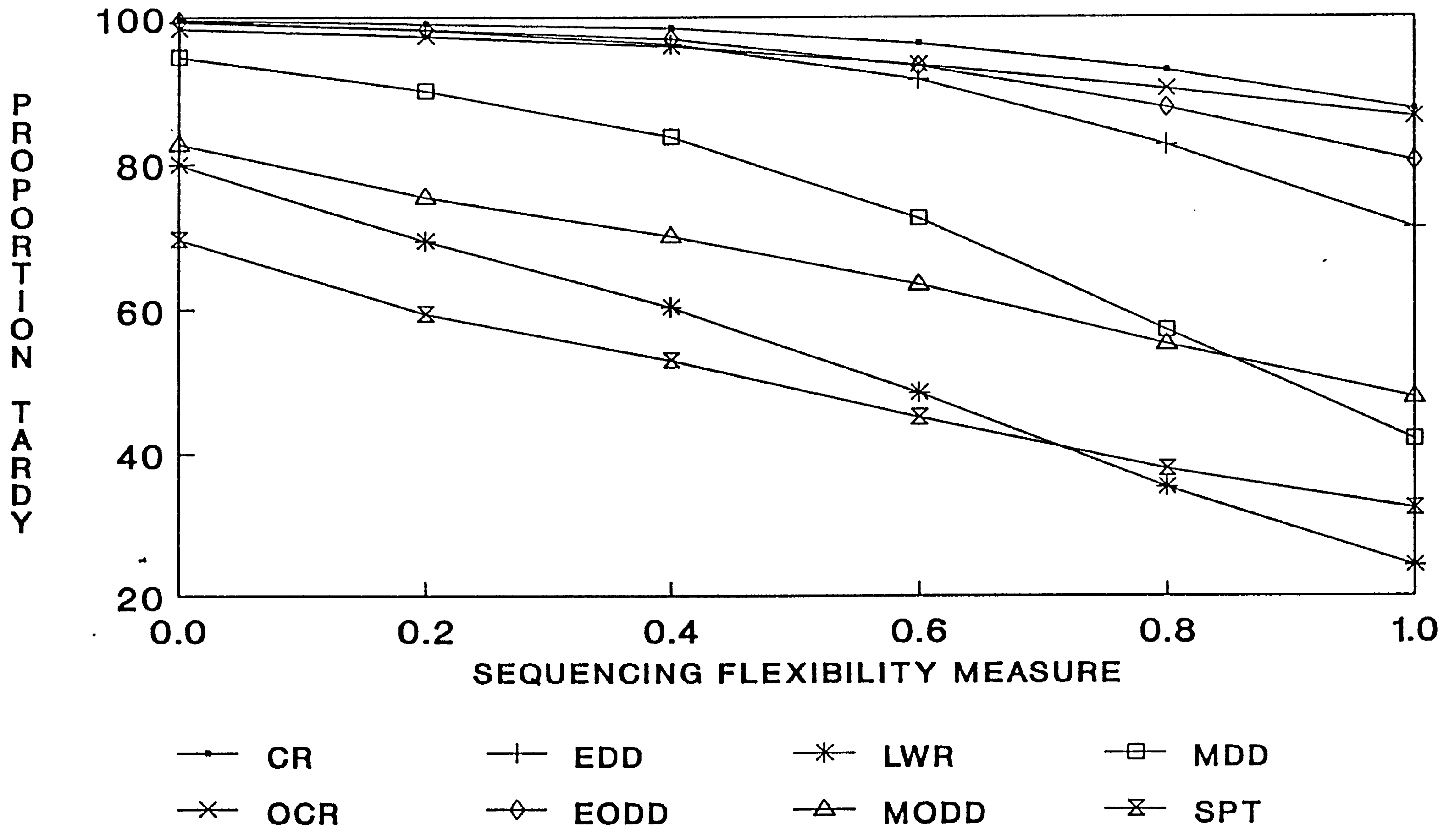



Figure 11: Proportion of Tardy Jobs for Selected Scheduling Rules, Flow Allowance Factor, 0.25

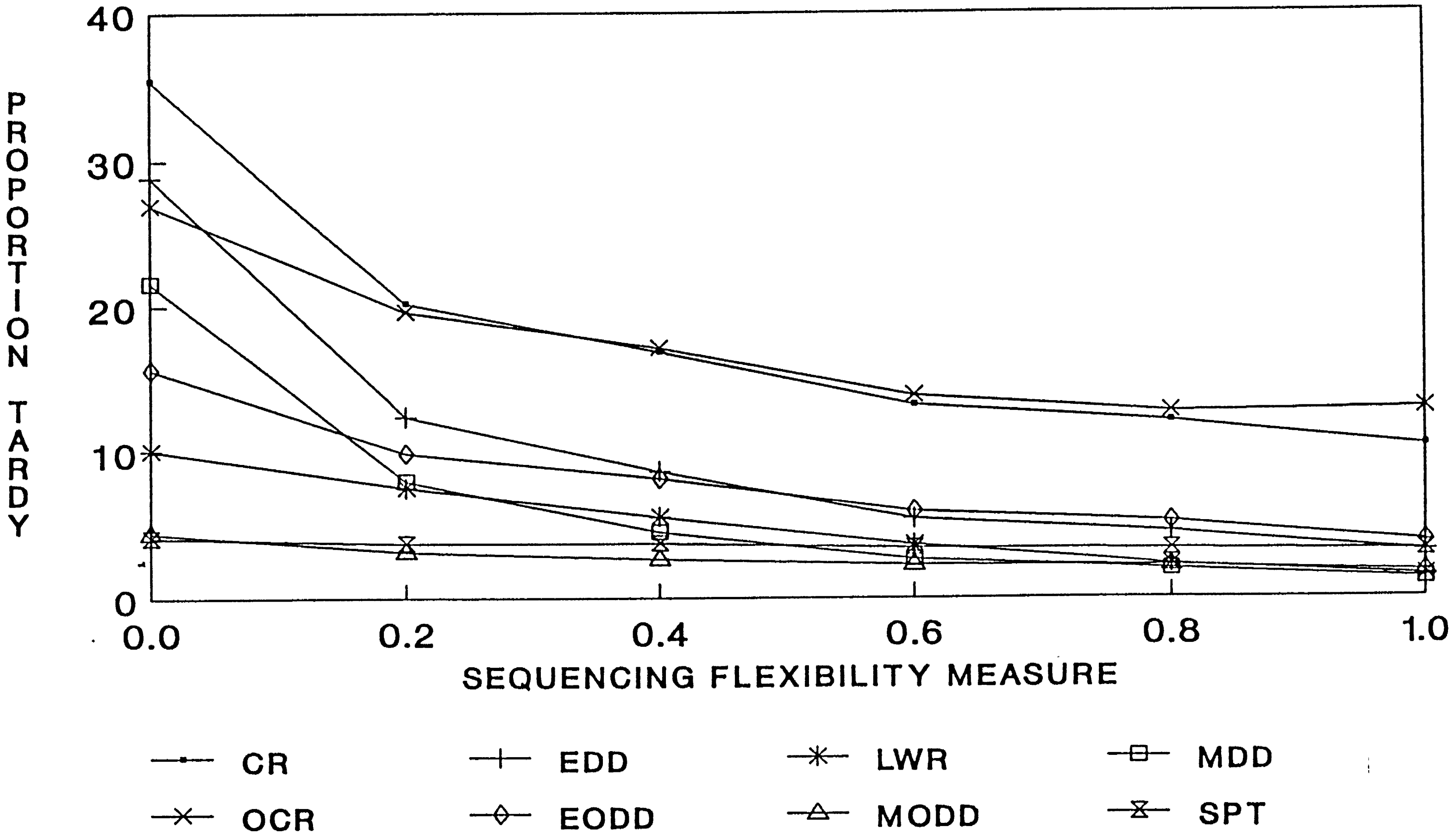



Figure 12: Proportion of Tardy Jobs for Selected Scheduling Rules, Flow Allowance Factor, 1.00

mean flowtime (and inventories). The practical importance of this criterion warrants its investigation using an approximate analytical model if an exact model is mathematically or computationally intractable. Though it is intuitively clear that using flexibility would improve the performance of the rules, our study found that the differences between the rules also diminish significantly at high flexibility values. Our investigations also highlighted the effects of flow allowance on the flowtime performance of EDD and CR. While the earliest due date rule improves its performance as flow allowance is increased, critical ratio rule performance worsens.

Our analysis also included performance of the rules for the mean tardiness criterion. All rules improve their performance as more sequencing flexibility is used. While our study reaffirmed conclusions of earlier researchers that MODD performs well for job shops, we found that this performance carries over to situations where sequencing flexibility is also used. However, at high SFM values, MDD performs better than its operation due date version. We also analyzed the performance of rules for the proportion tardy criterion. For this measure, there was no distinct choice. Depending on the flexibility and flow allowance parameters, one of four rules (SPT, LWR, MODD, and MDD) performed best in our studies.

Our study also has implications for the design of production planning and control systems, manufacturing information system design, and product design. We elaborate on these issues below.

A major factor in the design of shopfloor control systems is the choice of appropriate dispatching rules. Our study indicated that when sequencing flexibility is present and used, differences between various dispatching rules diminish significantly. Hence, when shopfloor control systems use sequencing flexibility, the focus can shift to other relevant criteria such as load control, predictablility of flowtimes, schedule stability, etc.

Evaluative results provided in this paper are also useful in economic justification of investments in manufacturing information systems. In order to use sequencing flexibility, it is necessary to have a realtime manufacturing information system which is capable of assessing machine and job status, and to make choices among alternatives. Our study indicates that using sequencing flexibility results in inventory reduction (through decrease in mean flowtime) and improved customer service through decreases in tardiness. These benefits can be quantified and used in the economic justification of investments in manufacturing information systems.

Finally, our analysis has interesting implications for product design. If the density of operation graph can be reduced at the product design stage, it can lead to improvements in shop floor operations. Product designers need to take this into consideration while choosing among alternate product plans.

## REFERENCES

[1] Baker, K.R. (1974), "Introduction to Sequencing and Scheduling," John Wiley and Sons, Inc., New York, New York.

[2] Baker, K.R. and J.J. Kanet (1983), "Job Shop Scheduling with Modified Due Dates," Journal of Operations Management 3, 1, 37-42.

[3] Baker, K.R. (1984), "Sequencing Rules and Due Date Assignments in a Job Shop," Management Science 3, 2, p1093-1104.

[4] Bitran, G.R., M. Dada, and L.O. Sisan (1982), "A Simulation Model for Job Shop Scheduling," Working Paper, A.P. Sloan School of Management, Massachusetts Institute of Technology, Cambridge, MA.

[5] Brill, P.H. and M. Mandelbaum (1987), "On Measures of Flexibility in Manufacturing Systems," Working Paper W87-08, University of Windsor, Windsor, Ontario, Canada.

[6] Browne, J., D. Dubois, K. Rathmill, S. Sethi, and K. Stecke (1984), "Classification of Flexible Manufacturing Systems," The FMS Magazine 2, 2, 116-117.

[7] Buzacott, J. (1982), "The Fundamental Principles of Flexibility in Manufacturing Systems," Proceedings of the First International Conference on Flexible Manufacturing Systems, Brighton, UK, Elsevier Publications, Amsterdam, Netherlands.

[8] Carter, M.F. (1986), "Designing Flexibility into Automated Manufacturing Systems," in Proceedings of the Second ORSA/TIMS Conference on Flexible Manufacturing systems, edited by K.E. Stecke and R. Suri, Elsevier Publications, Amsterdam, Netherlands, 107-118.

[9] Chatterjee, A., M. Cohen, W. Maxwell, and L. Miller (1984), "Manufacturing Flexibility: Models and Measurements," In Proceedings of the First ORSA/TIMS Special Interest Conference on Flexible Manufacturing Systems, K.E. Stecke and R. Suri, Eds. The University of Michigan, Ann Arbor, MI, 49-64.

[10] Conway, R.W., W.L. Maxwell, and L.W. Miller (1967), Theory of Scheduling, Addison-Wesley Publishing Company, Reading, MA.

[11] Ettlie, J.E. (1988), "Implementation Strategies for Discrete Parts Manufacturing Technologies," Final Report, The University of Michigan, Ann Arbor, Michigan.

[12] French, S. (1982), "Sequencing and Scheduling: An Introduction to the Mathematics of the Job-Shop," Ellis Horwood Limited, Chichester, U.K

[13] Gerwin, D. (1987), "An Agenda for Research on the Flexibility of Manufacturing Processes," International Journal of Production and Operations Management, 7, 1, 38-49.

[14] Gonzalez, M.J. and S. Sahni (1976), "Open-Shop Scheduling to Minimize Finish Time," Journal of the Association for Computing Machinery 23, 655-679.

[15] Kanet, J.J., and J.C. Hayya (1982), "Priority Dispatching with Opeartion Due Dates in a Job Shop," Journal of Operations Management 2, 3, 167-175.

[16] Lin, Y.J. and J.J. Solberg (1991), "Effectivenss of Flexible Routing Control," The International Journal of Flexible Manufacturing Systems 3, 3/4, 189-211.

[17] Neimeier, H. (1967), "An Investigation of Alternate Routing in a Job Shop," Master's Thesis, Cornell University, Ithaca, NY.

[18] Pegden, C.D., R.E. Shannon and R.P. Sadowski (1990), Introduction to Simulation Using SIMAN, McGraw-Hill, New York, NY.

[19] Rachamadugu, R. (1989), "Impact of Flexibility on Scheduling," Talk presented at the TIMS/ORSA National Conference - May 1989, Vancouver, British Columbia, Canada.

[20] Rachamadugu, R. and T.J. Schriber (1990), "Performance of Dispatching Rules Under Perfect Sequencing Flexibility," Proceedings of the Winter Simulation Conference, New Orleans, LA, 653-658.

[21] Ramasesh, R. (1990), "Dynamic Job Shop Scheduling: A Survey of Simulation Research," OMEGA: International Journal of Management Science 18, 1, 43-57.

[22] Russo, T.F. (1965), "A Heuristic Approach to Alternate Routing in a Job Shop," Master's Thesis, Massachusetts Institute of Technology, Cambridge, MA.

[23] Schriber, T.J. (1991), "The Modeling of Perfect Sequencing Flexibility in a Scheduling Environment," Proceedings of the 1991 Winter Simulation Conference, Society for Computer Simulation, San Diego, CA.

[24] Schriber, T.J. (1991), An Introduction to Simulation Using GPSS/H, John Wiley & Sons, New York, NY.

[25] Sethi, A.K. and S.P. Sethi (1990), "Flexibility in Manufacturing: A Survey," International Journal of Flexible Manufacturing Systems 2, 4, 289-328.

[26] Zelenovic, D.M. (1982), "Flexibility - A Condition for Effective Production Systems," International Journal of Production Research 20, 3, 319-337.

**APPENDIX A**

Table IA: Durbin-Watson Statistic for Mean Flow Time

| Scheduling Rule* | Sequencing Flexibility Measure | | | | | |
|---|---|---|---|---|---|---|
| | 0.00 | 0.20 | 0.40 | 0.60 | 0.80 | 1.00 |
| FIQ | 2.684 | 2.650 | 2.501 | 2.650 | 2.445 | 2.495 |
| FIS | 2.959 | 2.546 | 2.503 | 2.651 | 2.491 | 2.523 |
| SPT | 2.958 | 2.499 | 2.438 | 2.623 | 2.491 | 2.509 |
| LWR | 2.955 | 2.294 | 2.324 | 2.523 | 2.271 | 2.581 |
| EDD(.25) | 2.856 | 2.615 | 2.446 | 2.600 | 2.428 | 2.482 |
| EDD(.50) | 2.873 | 2.316 | 2.353 | 2.676 | 2.397 | 2.456 |
| EDD(1.0) | 2.857 | 2.156 | 2.346 | 2.559 | 2.472 | 2.347 |
| EDD(2.0) | 2.806 | 2.374 | 2.423 | 2.508 | 2.438 | 2.302 |
| EDD(4.0) | 3.113 | 2.418 | 2.466 | 2.426 | 2.424 | 2.354 |
| OCR(.25) | 2.830 | 2.679 | 2.322 | 2.570 | 2.535 | 2.353 |
| OCR(.50) | 2.680 | 2.620 | 2.289 | 2.478 | 2.497 | 2.304 |
| OCR(1.0) | 2.776 | 2.365 | 2.227 | 2.443 | 2.373 | 2.444 |
| OCR(2.0) | 2.619 | 2.386 | 2.266 | 2.409 | 2.315 | 2.533 |
| OCR(4.0) | 2.858 | 2.389 | 2.155 | 2.489 | 2.393 | 2.543 |
| CR(.25) | 2.873 | 2.264 | 2.501 | 2.545 | 2.398 | 2.376 |
| CR(.50) | 2.769 | 2.236 | 2.303 | 2.500 | 2.322 | 2.349 |
| CR(1.0) | 2.852 | 2.306 | 2.315 | 2.566 | 2.427 | 2.494 |
| CR(2.0) | 2.798 | 2.648 | 2.251 | 2.576 | 2.547 | 2.505 |
| CR(4.0) | 2.845 | 2.614 | 2.431 | 2.615 | 2.395 | 2.537 |
| EODD(.25) | 2.864 | 2.674 | 2.430 | 2.648 | 2.585 | 2.465 |
| EODD(.50) | 2.911 | 2.683 | 2.594 | 2.732 | 2.600 | 2.437 |
| EODD(1.0) | 2.730 | 2.645 | 2.485 | 2.618 | 2.566 | 2.415 |
| EODD(2.0) | 2.462 | 2.616 | 2.235 | 2.561 | 2.456 | 2.212 |
| EODD(4.0) | 2.312 | 2.402 | 2.340 | 2.532 | 2.383 | 2.359 |
| MODD(.25) | 2.841 | 2.511 | 2.399 | 2.629 | 2.544 | 2.433 |
| MODD(.50) | 2.895 | 2.600 | 2.393 | 2.472 | 2.388 | 2.395 |
| MODD(1.0) | 2.823 | 2.561 | 2.437 | 2.648 | 2.573 | 2.441 |
| MODD(2.0) | 2.514 | 2.495 | 2.272 | 2.561 | 2.456 | 2.212 |
| MODD(4.0) | 2.612 | 2.402 | 2.340 | 2.532 | 2.383 | 2.359 |

| | | | | | | |
|---|---|---|---|---|---|---|
| MSUC | 2.515 | 2.581 | 2.566 | 2.803 | 2.491 | 2.779 |
| MDD(.25) | 2.832 | 2.429 | 2.420 | 2.695 | 2.580 | 2.558 |
| MDD(.50) | 2.940 | 2.141 | 2.400 | 2.458 | 2.391 | 2.464 |
| MDD(1.0) | 2.784 | 2.169 | 2.392 | 2.595 | 2.432 | 2.425 |
| MDD(2.0) | 2.744 | 2.282 | 2.390 | 2.440 | 2.432 | 2.277 |
| MDD(4.0) | 2.980 | 2.312 | 2.465 | 2.512 | 2.415 | 2.347 |

**Note:** **The numbers in parenthesis indicate flow allowance factors used to determine due dates.**

**APPENDIX B**

Table IB: Mean Flow Time

| Scheduling Rule* | Sequencing Flexibility Measure | | | | | |
|---|---|---|---|---|---|---|
| | 0.00 | 0.20 | 0.40 | 0.60 | 0.80 | 1.00 |
| FIQ | 309.80 | 262.23 | 241.90 | 206.67 | 181.44 | 156.55 |
| FIS | 301.68 | 248.02 | 223.64 | 183.72 | 161.67 | 142.06 |
| MSUC | 297.62 | 224.92 | 187.58 | 150.60 | 127.08 | 107.63 |
| SPT | 132.80 | 123.12 | 119.40 | 111.30 | 106.29 | 101.36 |
| LWR | 203.21 | 171.55 | 147.81 | 120.75 | 99.72 | 81.43 |
| OCR(.25) | 177.34 | 160.43 | 152.26 | 138.27 | 129.24 | 121.14 |
| CR(.25) | 260.45 | 211.23 | 186.65 | 152.20 | 129.69 | 112.77 |
| EODD(.25) | 274.24 | 223.36 | 200.65 | 169.07 | 152.18 | 137.72 |
| EDD(.25) | 290.74 | 236.64 | 209.52 | 172.87 | 149.66 | 129.77 |
| MODD(.25) | 134.95 | 126.09 | 122.36 | 114.39 | 109.14 | 103.69 |
| MDD(.25) | 209.37 | 173.27 | 154.74 | 124.96 | 104.65 | 87.59 |
| OCR(.50) | 193.19 | 179.06 | 172.54 | 162.41 | 155.04 | 149.63 |
| CR(.50) | 262.87 | 214.76 | 196.07 | 169.15 | 156.02 | 145.31 |
| EODD(.50) | 241.01 | 201.19 | 184.37 | 162.58 | 149.21 | 137.07 |
| EDD(.50) | 276.93 | 223.94 | 198.60 | 162.89 | 140.22 | 121.74 |
| MODD(.50) | 159.84 | 149.64 | 144.89 | 134.98 | 127.84 | 120.68 |
| MDD(.50) | 229.39 | 189.26 | 168.85 | 140.92 | 121.45 | 105.65 |
| OCR(1.0) | 254.83 | 242.51 | 239.42 | 231.04 | 228.89 | 227.22 |
| CR(1.0) | 276.41 | 249.49 | 241.17 | 226.24 | 219.39 | 209.89 |
| EODD(1.0) | 213.96 | 188.67 | 178.28 | 160.26 | 148.06 | 135.15 |
| EDD(1.0) | 258.63 | 204.77 | 180.89 | 150.70 | 131.15 | 114.03 |
| MODD(1.0) | 196.73 | 178.36 | 169.44 | 155.98 | 144.30 | 132.72 |
| MDD(1.0) | 249.23 | 199.40 | 175.72 | 147.10 | 127.63 | 111.28 |
| OCR(2.0) | 371.97 | 360.46 | 360.14 | 350.54 | 346.18 | 342.27 |
| CR(2.0) | 347.37 | 328.11 | 328.22 | 309.88 | 304.43 | 293.61 |
| EODD(2.0) | 280.76 | 187.19 | 177.42 | 159.62 | 147.09 | 132.40 |
| EDD(2.0) | 230.63 | 187.37 | 167.35 | 142.77 | 125.57 | 109.88 |
| MODD(2.0) | 207.85 | 186.55 | 177.19 | 159.62 | 147.09 | 132.40 |
| MDD(2.0) | 230.60 | 188.80 | 167.90 | 141.63 | 124.32 | 108.49 |

| Scheduling Rule* | Sequencing Flexibility Measure | | | | | |
|---|---|---|---|---|---|---|
| | 0.00 | 0.20 | 0.40 | 0.60 | 0.80 | 1.00 |
| OCR(4.0) | 498.22 | 492.07 | 486.64 | 471.85 | 467.70 | 465.44 |
| CR(4.0) | 426.83 | 410.24 | 409.03 | 391.16 | 383.82 | 373.78 |
| EODD(4.0) | 210.99 | 188.58 | 179.87 | 161.82 | 147.32 | 130.25 |
| EDD(4.0) | 212.24 | 177.23 | 162.37 | 140.29 | 124.87 | 109.41 |
| MODD(4.0) | 210.99 | 188.58 | 179.87 | 161.82 | 147.32 | 130.25 |
| MDD(4.0) | 213.51 | 177.60 | 160.61 | 138.57 | 123.70 | 107.99 |

**Note:** **The numbers in parenthesis indicate flow allowance factors used to determine due dates.**

**Shaded cells indicate minimum values for each column.**

Table IIB: Mean Tardiness

| Scheduling Rule* | Sequencing Flexibility Measure | | | | | |
|---|---|---|---|---|---|---|
| | 0.00 | 0.20 | 0.40 | 0.60 | 0.80 | 1.00 |
| FIQ(.25) | 235.14 | 187.79 | 167.55 | 133.06 | 108.68 | 85.22 |
| FIS(.25) | 226.90 | 173.56 | 149.50 | 110.71 | 90.29 | 73.01 |
| MSUC(.25) | 225.26 | 154.65 | 118.53 | 83.44 | 62.26 | 45.79 |
| SPT(.25) | 62.33 | 54.74 | 52.54 | 46.57 | 44.04 | 41.48 |
| LWR(.25) | 131.00 | 101.06 | 79.15 | 54.87 | 37.44 | 23.28 |
| OCR(.25) | 102.54 | 85.80 | 77.62 | 64.20 | 55.62 | 47.97 |
| CR(.25) | 185.61 | 136.44 | 111.85 | 77.74 | 55.69 | 39.46 |
| EODD(.25) | 199.40 | 148.72 | 126.11 | 95.15 | 79.17 | 65.99 |
| EDD(.25) | 215.92 | 161.99 | 135.07 | 99.20 | 77.48 | 59.95 |
| MODD(.25) | 61.28 | 53.04 | 49.59 | 42.82 | 38.66 | 34.53 |
| MDD(.25) | 134.87 | 99.08 | 81.09 | 52.63 | 34.45 | 20.21 |
| FIQ(.50) | 166.79 | 123.73 | 104.94 | 76.28 | 58.17 | 42.28 |
| FIS(.50) | 156.64 | 108.21 | 88.73 | 58.73 | 46.05 | 35.69 |
| MSUC(.50) | 173.73 | 113.78 | 82.69 | 53.52 | 37.91 | 26.75 |
| SPT(.50) | 33.68 | 30.66 | 30.89 | 27.89 | 27.29 | 26.27 |
| LWR(.50) | 87.18 | 65.70 | 49.95 | 32.72 | 21.79 | 12.89 |
| OCR(.50) | 49.21 | 37.63 | 32.77 | 25.45 | 20.70 | 16.49 |
| CR(.50) | 114.43 | 68.38 | 51.29 | 28.83 | 19.86 | 13.38 |
| EODD(.50) | 96.62 | 62.32 | 50.11 | 35.54 | 29.02 | 23.49 |
| EDD(.50) | 130.28 | 82.08 | 62.29 | 37.71 | 27.20 | 19.81 |
| MODD(.50) | 26.29 | 20.59 | 18.60 | 14.37 | 12.03 | 9.87 |
| MDD(.50) | 83.69 | 49.23 | 35.01 | 18.07 | 10.43 | 5.60 |
| FIQ(1.0) | 76.99 | 49.92 | 39.82 | 25.32 | 18.53 | 12.56 |
| FIS(1.0) | 64.58 | 38.38 | 30.15 | 17.82 | 14.04 | 10.44 |
| MSUC(1.0) | 114.14 | 73.88 | 50.95 | 29.73 | 20.31 | 13.78 |
| SPT(1.0) | 17.79 | 16.43 | 16.99 | 15.41 | 15.44 | 14.73 |
| LWR(1.0) | 49.64 | 37.20 | 28.00 | 17.38 | 11.76 | 6.55 |

| Scheduling Rule* | Sequencing Flexibility Measure | | | | | |
|---|---|---|---|---|---|---|
| | 0.00 | 0.20 | 0.40 | 0.60 | 0.80 | 1.00 |
| OCR(1.0) | 9.67 | 6.34 | 5.40 | 3.65 | 3.21 | 2.30 |
| CR(1.0) | 15.80 | 6.77 | 5.19 | 3.07 | 2.72 | 1.75 |
| EODD(1.0) | 12.48 | 8.12 | 6.69 | 4.48 | 3.93 | 2.85 |
| EDD(1.0) | 23.88 | 10.45 | 7.74 | 4.26 | 3.49 | 2.21 |
| MODD(1.0) | 4.39 | 2.96 | 2.36 | 1.70 | 1.33 | 0.95 |
| MDD(1.0) | 14.70 | 5.59 | 3.40 | 1.95 | 1.23 | 0.59 |
| FIQ(2.0) | 18.23 | 10.42 | 7.71 | 4.47 | 3.14 | 2.13 |
| FIS(2.0) | 12.47 | 6.76 | 5.08 | 2.74 | 2.20 | 1.61 |
| MSUC(2.0) | 59.48 | 40.51 | 26.76 | 13.79 | 9.28 | 6.25 |
| SPT(2.0) | 7.64 | 7.29 | 7.64 | 6.84 | 7.12 | 6.55 |
| LWR(2.0) | 21.65 | 16.51 | 12.54 | 7.03 | 5.32 | 2.66 |
| OCR(2.0) | 0.54 | 0.27 | 0.16 | 0.14 | 0.14 | 0.18 |
| CR(2.0) | 0.12 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| EODD(2.0) | 0.20 | 0.05 | 0.01 | 0.00 | 0.00 | 0.00 |
| EDD(2.0) | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MODD(2.0) | 0.09 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 |
| MDD(2.0) | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| FIQ(4.0) | 2.10 | 1.20 | 0.83 | 0.42 | 0.31 | 0.16 |
| FIS(4.0) | 1.17 | 0.57 | 0.47 | 0.21 | 0.16 | 0.10 |
| MSUC(4.0) | 22.62 | 17.29 | 11.22 | 5.23 | 3.59 | 2.53 |
| SPT(4.0) | 2.23 | 2.27 | 2.49 | 2.09 | 2.35 | 2.02 |
| LWR(4.0) | 5.87 | 4.78 | 3.99 | 1.60 | 1.76 | 0.81 |
| OCR(4.0) | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.05 |
| CR(4.0) | 0.03 | 0.03 | 0.02 | 0.03 | 0.03 | 0.03 |
| EODD(4.0) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| EDD(4.0) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MODD(4.0) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MDD(4.0) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

**Note:** **The numbers in parenthesis indicate flow allowance factors used to determine due dates.**

**Shaded cells indicate minimum values for each flow allowance setting.**

Table IIIB: Proportion Tardy (%)

| Scheduling Rule* | Sequencing Flexibility Measure | | | | | |
|---|---|---|---|---|---|---|
| | 0.00 | 0.20 | 0.40 | 0.60 | 0.80 | 1.00 |
| FIQ(.25) | 98.5 | 97.2 | 96.5 | 93.8 | 89.8 | 83.6 |
| FIS(.25) | 99.2 | 97.9 | 96.2 | 91.7 | 85.5 | 77.7 |
| MSUC(.25) | 87.1 | 78.3 | 73.0 | 66.2 | 58.6 | 48.6 |
| SPT(.25) | 69.7 | 59.4 | 52.9 | 45.1 | 37.9 | 32.4 |
| LWR(.25) | 79.9 | 69.5 | 60.3 | 48.4 | 35.4 | 24.3 |
| OCR(.25) | 98.4 | 97.3 | 96.0 | 93.5 | 90.2 | 86.3 |
| CR(.25) | 99.6 | 99.1 | 98.5 | 96.4 | 92.7 | 87.3 |
| EODD(.25) | 99.5 | 98.3 | 97.0 | 93.3 | 87.6 | 80.3 |
| EDD(.25) | 99.3 | 98.2 | 96.3 | 91.5 | 82.6 | 71.3 |
| MODD(.25) | 82.7 | 75.6 | 70.2 | 63.5 | 55.2 | 47.7 |
| MDD(.25) | 94.5 | 89.9 | 83.7 | 72.7 | 57.2 | 42.0 |
| FIQ(.50) | 86.4 | 80.0 | 75.1 | 66.6 | 56.7 | 46.6 |
| FIS(.50) | 90.3 | 81.3 | 73.6 | 60.3 | 50.5 | 42.0 |
| MSUC(.50) | 58.8 | 44.9 | 38.1 | 30.9 | 24.7 | 18.3 |
| SPT(.50) | 16.5 | 13.8 | 12.6 | 10.9 | 10.1 | 9.7 |
| LWR(.50) | 32.1 | 23.4 | 17.7 | 12.3 | 7.9 | 5.0 |
| OCR(.50) | 79.7 | 71.7 | 65.8 | 57.5 | 49.3 | 44.4 |
| CR(.50) | 94.7 | 86.3 | 78.8 | 64.3 | 53.3 | 45.1 |
| EODD(.50) | 83.5 | 69.6 | 59.8 | 48.0 | 38.5 | 32.3 |
| EDD(.50) | 90.3 | 77.1 | 64.6 | 45.9 | 32.8 | 24.5 |
| MODD(.50) | 33.5 | 26.9 | 24.6 | 20.0 | 17.3 | 15.5 |
| MDD(.50) | 78.4 | 59.9 | 44.8 | 28.1 | 17.0 | 10.9 |
| FIQ(1.0) | 49.7 | 38.7 | 33.4 | 24.7 | 18.9 | 13.9 |
| FIS(1.0) | 51.1 | 36.7 | 30.5 | 20.5 | 16.2 | 12.7 |
| MSUC(1.0) | 31.3 | 21.1 | 16.2 | 12.0 | 9.0 | 6.1 |
| SPT(1.0) | 4.2 | 3.8 | 3.8 | 3.5 | 3.4 | 3.3 |
| LWR(1.0) | 10.1 | 7.6 | 5.6 | 3.7 | 2.3 | 1.5 |

| Scheduling Rule* | Sequencing Flexibility Measure | | | | | |
|---|---|---|---|---|---|---|
| | 0.00 | 0.20 | 0.40 | 0.60 | 0.80 | 1.00 |
| OCR(1.0) | 27.0 | 19.6 | 17.1 | 13.8 | 12.7 | 12.9 |
| CR(1.0) | 35.4 | 20.2 | 16.8 | 13.2 | 12.1 | 10.4 |
| EODD(1.0) | 15.6 | 9.9 | 8.2 | 6.0 | 5.3 | 3.9 |
| EDD(1.0) | 28.9 | 12.4 | 8.7 | 5.5 | 4.6 | 3.2 |
| MODD(1.0) | 4.5 | 3.2 | 2.7 | 2.3 | 2.2 | 1.8 |
| MDD(1.0) | 21.6 | 8.0 | 4.6 | 2.7 | 2.0 | 1.3 |
| FIQ(2.0) | 13.4 | 8.7 | 7.0 | 4.4 | 3.2 | 2.3 |
| FIS(2.0) | 11.9 | 7.4 | 5.7 | 3.5 | 2.8 | 2.1 |
| MSUC(2.0) | 12.9 | 8.5 | 6.1 | 3.9 | 2.7 | 1.7 |
| SPT(2.0) | 1.2 | 1.1 | 1.1 | 1.1 | 1.1 | 1.0 |
| LWR(2.0) | 3.0 | 2.2 | 1.6 | 1.0 | 0.7 | 0.4 |
| OCR(2.0) | 3.4 | 2.8 | 2.6 | 2.6 | 2.8 | 3.3 |
| CR(2.0) | 2.2 | 2.0 | 2.0 | 1.9 | 1.9 | 1.9 |
| EODD(2.0) | 0.5 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| EDD(2.0) | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| MODD(2.0) | 0.2 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| MDD(2.0) | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| FIQ(4.0) | 1.7 | 1.0 | 0.8 | 0.5 | 0.3 | 0.2 |
| FIS(4.0) | 1.3 | 0.7 | 0.6 | 0.3 | 0.2 | 0.2 |
| MSUC(4.0) | 4.0 | 2.8 | 1.8 | 1.0 | 0.6 | 0.4 |
| SPT(4.0) | 0.3 | 0.3 | 0.3 | 0.2 | 0.3 | 0.2 |
| LWR(4.0) | 0.6 | 0.5 | 0.4 | 0.2 | 0.2 | 0.1 |
| OCR(4.0) | 0.5 | 0.6 | 0.6 | 0.7 | 0.7 | 1.0 |
| CR(4.0) | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| EODD(4.0) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| EDD(4.0) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| MODD(4.0) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| MDD(4.0) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

**Note:** **The numbers in parenthesis indicate flow allowance factors used to determine due dates.**

**Shaded cells indicate minimum values for each flow allowance setting.**