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Cost performance of simple priority rule combinations

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Abstract

Purpose – Several prior studies have investigated the strategy of concurrently deploying different priority rules at different processing stages of a manufacturing system. The purpose of this paper is to investigate the advantage of using such a strategy over that of using priority rules in their pure forms.

Design/methodology/approach – Three priority rules were combined in all possible ways in a simulated, three-stage, flow-dominated manufacturing system. The performances of these combinations, along with three other simple priority rules in their pure forms, were compared using both mean and variability in waiting, earliness, tardiness, and total costs under two shop load levels and several tardiness to earliness cost ratios.

Findings – The results indicate that the combinations between SI^X and shortest processing time (SPT) rules perform well in reducing both mean and variability of waiting cost but do poorly on tardiness cost. On the other hand, the due date rule in its pure form or in conjunction with SI^X or SPT is effective in reducing both mean and variability of both earliness and tardiness costs. While tardiness cost appears to dominate the total cost data, the shop load level registered little impact on the performance of the combination schemes.

Research limitations/implications – The results of the paper have useful practical implications for textile and ceramic industries. However, the conclusions are limited to the cost structure used, although a wide range of cost ratios is included.

Originality/value – The paper offers insights into whether throughput and due date-related costs can be reduced by using a job sequencing strategy that simultaneously deploys different priority rules at different processing stages of a manufacturing environment.

Keywords Production scheduling, Manufacturing systems, Operating costs

Paper type Research paper

1. Introduction

Most prior research on job or flow shops has focused on the use of one rule at a time at all work centers in the system. Such an approach, which includes a set of simple priority rules or combinatorial rules, is appropriate when the emphasis is in understanding and comparing the performance pattern of these rules individually. Among others, the results clearly indicate that such a strategy does not yield superior results on all important shop performance measures (Blackstone *et al.*, 1982; Ramasesh, 1990; Yeh, 2005). In order to overcome this limitation, researchers recently introduced an alternative strategy that produced the desirable results (Barman, 1997, 1998; Barman and LaForge, 1998; Barrett and Barman, 1986; Dooley, 1990; Hermann *et al.*, 1995; LaForge and Barman, 1989; Mahmoodi *et al.*, 1996). Such a strategy calls

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for a simultaneous deployment of different priority rules at different processing stages of an operating environment and is the focus of this research.

Generally, scheduling research evaluating the shop performance incorporated typical throughput (mean flow time, mean waiting time, etc.) and due date (mean lateness, mean tardiness, etc.) based measures. For example, recent efforts focusing on the tardiness criterion through better algorithms include Li *et al.* (2008) and Ronconi and Henriques (2009). While in most businesses the quality of a decision is measured against its cost consequences, in scheduling research the cost-based performance criteria has received far less than sufficient attention. Perhaps, it is presumed that an improvement in the throughput or due date measures will eventually lead to reduced costs. Second, and more importantly, generalization of cost structures is difficult because they vary widely from firm to firm (Blackstone *et al.*, 1982).

The results of several previous studies (Barman, 1997, 1998; Barman and LaForge, 1998; Barrett and Barman, 1986; Dooley, 1990; LaForge and Barman, 1989; Mahmoodi *et al.*, 1996) clearly indicate that combining priority rules is a better job sequencing strategy than using them in their pure forms with regard to the overall shop performance. However, the comparisons were limited in that they are solely based on time or due date-based measures, and none included any cost-based criteria. This study, a direct extension to two previous studies (Barman, 1997, 1998), addresses the above issues. Specifically, the objective is to investigate whether throughput and due date-related costs can be reduced by using a job sequencing strategy that simultaneously deploys different priority rules at different processing stages of a manufacturing environment.

2. Related research

Blackstone *et al.* (1982) and Ramasesh (1990) provided excellent surveys of the research on shop scheduling over the past few decades. Results indicate that simple priority rules, such as shortest processing time (SPT), earliest due date (EDD), or first in-first out, are ineffective in improving the overall shop performance because they determine job priorities using a single job or shop attribute (Blackstone *et al.*, 1982; Li and Barnes, 2000; Monch *et al.*, 2003). In order to achieve a better shop performance in both throughput and due date-related measures, a new strategy has more recently been introduced (Barman, 1997, 1998; Barman and LaForge, 1998; Barrett and Barman, 1986; Dooley, 1990; Hermann *et al.*, 1995; LaForge and Barman, 1989; Mahmoodi *et al.*, 1996). Such a strategy calls for concurrent deployment of different priority rules at different stages of a processing environment and has been very effective in producing desirable results.

Barrett and Barman (1986), in a simple two-stage processing environment, observed that the combination between SPT and EDD minimized mean tardiness and outperformed the pure SPT rule in both flow time and lateness variances. Elsewhere (LaForge and Barman, 1989), in a three-stage flow-dominant system, it was reported that selective applications of different priority rules at different stages could have a positive impact on shop performance. Dooley (1990) combined three simple priority rules in a three-workstation manufacturing system and reported that SPT at the interim and EDD at the exit workstations produced better results than the benchmark SPT rule. A pure strategy with the EDD rule, however, outperformed all other heuristics in the average tardiness measure.

Improved overall shop performance has also been achieved through the use of combinatorial rules, which combine more than one job attribute in a single rule. Experiments with the SI^{X} rule, a modification of SPT with the job slack information, showed that it can reduce the mean tardiness, and waiting time and lateness variances, which are the inherent disadvantages of the SPT rule (Eilon and Cotterill, 1968; Eilon *et al.*, 1975). Mahmoodi *et al.* (1996) investigated the performance of 28 combination schemes including the SI^{X} rule in a three-structure flow-dominant shop. They observed that the limitations of the pure SPT strategy can be overcome by combining it with either EDD or SI^{X}. Specifically, the combinations using SI^{X} at the intermediate and exit work stations with any rule at the entrance yielded an excellent overall performance under all experimental conditions.

Several recent studies provided further insights in the application of priority rule combination schemes. Barman (1997) combined four simple priority rules in a three-stage manufacturing system under two shop load levels. The results showed that the combinations between SPT and EDD yielded best overall performance on the mean lateness, mean tardiness, and the percent of tardy jobs criteria. In a later study (1998), it was observed that SI^{X} is a better choice than EDD, when combined with SPT, in reducing both mean lateness and the percent of tardy jobs. In addition, the combination schemes involving SPT, EDD, and SI^{X} produced excellent mean and maximum tardiness results. Barman and LaForge (1998) reported that priority rule combinations in a hybrid system are a better strategy than pure priority rules with respect to multiple measures of delivery speed. Furthermore, there exists a trade-off between delivery speed and delivery reliability in that priority rules that are effective for delivery speed are not effective for delivery reliability. Hermann *et al.* (1995) described a global scheduling procedure using an algorithm based upon policies created by combining common dispatching rules.

Use of cost-based performance criteria is also evident in prior research (Agarwal *et al.*, 1973; Agarwal and McCarl, 1974; Benton, 1993; Hoffmann and Scudder, 1983; Scudder and Hoffmann, 1985, 1986, 1987). Agarwal *et al.* (1973) and Agarwal and McCarl (1974) introduced a cost-based composite rule and compared its performance in terms of in-process inventory costs and total cost per job. In addition to time-based measures, Hoffmann and Scudder (1983) and Scudder and Hoffmann (1985, 1986, 1987) considered cost-based measures such as average in-process ($), average profit ($) in queue, and average value added ($) in queue. Elsewhere (Benton, 1993), the performance criteria included the average work-in-process value in the shop and mean lost profit. It needs to be stressed that the primary focus of these studies was to investigate the effectiveness of cost-based sequencing rules, but not to evaluate the cost consequences of simple priority rules.

3. Computer model

The study is based on the same simulated model used in two previous studies (Barman, 1997, 1998). It includes three work centers with two identical, parallel machines in each work center. While both the machines are capable of doing the designated operation at that work center, the operations vary from one work center to another. In other words, the machines in any given work center are identical, but are different across the work centers. All jobs entering the shop have the same routing and require exactly three operations. They are processed at the first work center first, the second work center next, and at the third work center last. Jobs arriving at any work center wait in a single queue if both machines are busy. Whenever a machine becomes free, it selects a job from the queue using the prevailing rule at that time at that work center. Following the operation, the job is routed to the next work center. Additional operational parameters of the system and the conditions under which it was simulated are provided in Barman (1998). The computer program to simulate the model was written in SLAM II (Pritsker, 1986).

4. Cost parameters

The raw material cost for each job entering the shop was sampled from a uniform distribution between $8 and 12. The dollar value of each job at various stages of operations was determined by accumulating the value added to the job at the end of each operation. Following the procedure used by Benton (1993), the value added to a job after each operation was computed by multiplying the processing time with the hourly processing cost at that work center. The processing cost was assumed to $24 per hour at all three work centers. Initially, several levels of processing costs, including their combinations, at the three work centers were considered and their effect on the performance of selected combination schemes evaluated. However, the relative magnitude of the processing costs at the three work centers appeared to be an insignificant factor because it impacted only the dollar values of the jobs at various processing stages. Furthermore, the use of identical cost, instead of different costs, at all three work centers eliminated the possible significance, if any, of any particular work center with regard to its impact on the overall shop performance.

The study included three types of job-related costs: the cost of jobs waiting to be processed, cost of finishing a job early, and the cost of finishing a job late (tardy). The cost of jobs waiting to be processed was assumed to be 400 percent of the dollar value of a job per hour, which translates into $4 per hour. While the earliness cost was held at a fixed level of $4 per hour, five different tardiness costs were included. These are: $4, 6, 8, 12 and 16 per hour, which resulted in five levels, 1, 1.5, 2, 3 and 4, of tardiness to earliness costs ratios. In other words, the tardiness to earliness costs ratios varied from 1:1 to as high as 4:1.

5. Experimental details

5.1 Priority rules combined

The following three priority rules were combined in every possible way at the three work centers, which resulted in 27 (3 × 3 × 3) priority rule combination schemes:

(1) *SPT*. From all jobs waiting to be processed at any given work center, the one with the SPT at that work center is selected next.

(2) *EDD*. The urgency for on-time completion is the rationale behind this rule. The job that has the most imminent due date is selected next for processing.

(3) *Modified SPT* (SI^X). A truncated SPT rule introduced by Eilon and Cotterill (1968) and Eilon *et al.* (1975), it classifies the jobs waiting to be processed according to the slack of each job. Jobs with a zero or negative slack are placed into a priority queue, while the rest into a normal queue. The priority queue is processed first followed by the normal queue; however, the SPT rule is used in both queues to determine the job processing order.

The rationale for choosing these three rules has been stated earlier. In addition, three other combination schemes, the first in-first out, critical ratio, and slack rules in their pure forms (FFF, CCC, and LLL) were included as benchmark for performance comparison. Therefore, the cost performance of 30 (27 + 3) combination schemes was compared in this study.

Furthermore, it needs to be stressed that the use of priority rules in their pure forms or in combinations is frequently found in the textile and ceramic industries, where the factory layout resembles the manufacturing process described herein. While oftentimes EDD is used as the primarily processing rule at different work centers, it is not rare to use truncated or combination rules, especially when the company faces unstable demand coupled with frequent changes in orders sizes and due dates. Consequently, the evaluation of the efficacy of different combinations makes sense because it could provide better information to practicing managers as to the choice of priority rules for a given order size and due date situation.

5.2 Shop load

The experiment was simulated at two shop load levels: high and low. For the high level, the shop utilization level was set at approximately 92 percent, while for the low level it was close to 82 percent. The shop load levels were controlled by manipulating the job arrival rate.

5.3 Due date determination

The job due dates were established endogenously by the total work content method (Blackstone *et al.*, 1982; Ramasesh, 1990). The total processing time of a job multiplied by an allowance factor, K, was added to the job's arrival time to determine its due date. Prior research (Blackstone *et al.*, 1982; Ramasesh, 1990) indicates that such an approach is most rational for setting job due dates in dynamic scheduling environments. The value of K only controls the due date tightness and does not affect the relative performance of the priority schemes as long as the extent of tightness is uniformly maintained under all experimental conditions. Therefore, the value of K was adjusted in a manner that was followed in Barman (1997, 1998), Barman and LaForge (1998) and LaForge and Barman (1989) to maintain the same degree of due date tightness under the high and low-shop load levels.

5.4 Data collection

Multiple observations were collected using the batch means method (Barman, 1997, 1998; Barman and LaForge, 1998; Ragatz and Mabert, 1988) in which one simulation run was subdivided into equal subgroups, treating each subgroup as a single independent observation. As described in Fishman (1978) and Ragatz and Mabert (1988), each subgroup was chosen to be 20,000 hours, based upon the evaluated transient period of the system. For each experimental condition, the shop was simulated from an empty condition for 620,000 hours. Thus, the procedure yielded 30 sample observations, one at the end of each 20,000 hours, excluding the first batch. The cost-related performance data were collected from the completed jobs during each batch and were found to be statistically independent by the procedure delineated by Fishman (1978, pp. 237-40).

5.5 Performance measures

The relative performance of the combination schemes was evaluated using the following cost-based performance measures, mean and standard deviation of the:

- waiting cost;
- earliness cost;
- tardiness cost; and
- total cost.

The waiting cost for each job was computed from the duration of time it spends at each work center queue and its dollar values at those times. The tardiness cost resulted from only those jobs that missed their due dates, while those that were finished early contributed to the earliness cost. Both the costs were based on the dollar value of the completed jobs as well as the length of time by which they were late or early. The total cost was calculated by adding the waiting, tardiness, and earliness costs.

5.6 Experimental design

A complete factorial experiment with three factors was designed to evaluate the relative cost performance of the priority rule combinations. The first factor is the combinations schemes, which has 30 levels. The shop load level is the second factor, which contains two levels: high and low. The relative magnitude of the tardiness and earliness costs is the third factor, which includes five levels, as stated earlier. Therefore, the factorial experiment included 300 ($30 \times 2 \times 5$) experimental conditions, each of which was replicated 30 times. The data for the four mean cost measures were analyzed using the ANOVA. However, the Kruskal-Wallis H-test, a single-factor, non-parametric alternative to ANOVA was used to analyze the standard deviation data.

6. Results

6.1 Mean measures

The ANOVA results indicate that the effects of combination schemes and shop load levels upon all of the four performance measures (mean waiting, earliness, tardiness, and total costs) are statistically significant (p-value $\leq$ 0.01 percent). In addition, the third factor, the relative magnitude of the tardiness and earliness costs, was found to be significant only for the mean tardiness and mean total costs (p-value $\leq$ 0.01 percent). However, as expected, this factor did not cause any significant difference in the mean waiting and mean earliness costs. The reason is that the levels of this factor were generated by varying the tardiness cost while keeping both the waiting and earliness costs at a fixed level.

Furthermore, Duncan's range test for multiple comparisons was conducted to detect the statistical differences, if any, between the factor levels. For the first factor, the test revealed the effectiveness of different combination schemes and grouped them statistically with regard to the four mean cost criteria. These results are presented in Tables I-IV, listing the best and worst ten combination schemes for each of the four performance measures. Note that the cost data of the schemes reported in these tables are an average of 300 observations, stemming from the two load levels, five cost ratios, and the 30 replications for each experimental condition.

Table I. The best and worst ten combination schemes based on mean waiting cost

Rank	Scheme	Mean waiting cost ($)
1	MMM	*1,260.42*
2	SMM	*1,260.68*
3	MSM	*1,263.93*
4	SSM	*1,264.62*
5	SMS	*1,265.27*
6	MMS	*1,265.52*
7	MSS	*1,269.25*
8	SSS	*1,269.67*
9	DSS	*1,348.50*
10	DSM	*1,376.35*
21	SSD	1,887.77
22	DDM	1,995.25
23	DSD	*2,115.90*
24	DMD	*2,170.25*
25	MDD	*2,499.05*
26	SDD	*2,499.82*
27	DDD	*2,904.45*
28	LLL	*2,940.20*
29	FFF	3,139.18
30	CCC	7,593.43

Notes: Italicized figure indicate no significant difference in means at 5 percent level by Duncan's multiple range test; symbols used are: C is critical ratio rule, D is EDD rule, F is first in-first out rule, L is slack rule, M is modified SPT (SI^{X}) rule, S is SPT rule; three symbols in each scheme represent the three rules used at work centers 1, 2 and 3, respectively; for example: SMM represents use of SPT at work center 1 and SI^{X} at work centers 2 and 3, SSS represents use of SPT at all three work centers, DSM represents use of EDD, SPT, and SI^{X} at work centers 1, 2 and 3, respectively, MMS represents SI^{X} at work centers 1 and 2, and SPT at work center 3, etc.

The mean waiting cost results (Table I) show that the best eight schemes are all possible combinations between the SI^{X} and SPT rules, including their pure forms (MMM and SSS). The three schemes at the bottom of the list are CCC, FFF, and LLL, the pure forms of the critical ratio, and the slack rules, respectively. While there is no statistical difference within the best eight combinations, the range of the cost figures between the best and worst schemes is substantial. The results are consistent with (Barman, 1998) in that the same eight combinations under the same conditions yielded the best mean flow time results. Such an occurrence is intuitively obvious because rules that do minimize flow times do so by reducing waiting times, and therefore, are expected to yield low waiting costs.

The earliness costs (Table II) are computed from only those jobs finished early and are a function of the extent to which they are early. Therefore, the best performers, such as DDD and LLL schemes, caused jobs to finish closer to their due dates because of their focus on job due dates or slacks. On the other hand, the schemes that performed poorly were penalized for finishing the jobs too early. The rationale is that the earlier a job is finished before shipping to the customer, the larger is the holding cost, and therefore, the greater is the penalty. While DDD and LLL being the two best, the next best schemes include EDD in two of the three work centers with either SPT or SI^{X} in the third.

Table II.
The best and worst ten combination schemes based on mean earliness cost

Rank	Scheme	Mean earliness cost ($)
1	DDD	5,346.20
2	LLL	5,423.58
3	DDS	5,722.62
4	DSD	*5,804.73*
5	DDM	*5,807.87*
6	DMD	*5,817.07*
7	MDD	*5,865.47*
8	SDD	*5,866.07*
9	DSS	*6,228.45*
10	DMS	*6,254.93*
21	MSS	*6,957.75*
22	SSS	*6,958.07*
23	SSM	*6,959.40*
24	SMS	*6,959.82*
25	MSM	*6,960.33*
26	MMS	*6,960.72*
27	SMM	*6,964.28*
28	MMM	*6,965.08*
29	CCC	8,024.88
30	FFF	9,237.87

Notes: Italicized figure indicate no significant difference in means at 5 percent level by Duncan's multiple range test; symbols used are: C is critical ratio rule, D is EDD rule, F is first in-first out rule, L is slack rule, M is modified SPT (SI^{X}) rule, S is SPT rule; three symbols in each scheme represent the three rules used at work centers 1, 2 and 3, respectively; for example: SMM represents use of SPT at work center 1 and SI^{X} at work centers 2 and 3, SSS represents use of SPT at all three work centers, DSM represents use of EDD, SPT, and SI^{X} at work centers 1, 2 and 3, respectively, MMS represents SI^{X} at work centers 1 and 2, and SPT at work center 3, etc.

However, the eight schemes between SPT and SI^{X}, which were very effective in reducing the mean waiting cost, performed poorly. These combinations, which emphasize on throughput, attempt to complete jobs as soon as possible causing them to finish much earlier than their due dates. Consequently, they yielded excessive earliness costs.

The tardiness costs are computed from only those jobs that are tardy, the jobs that are completed past their due dates. As shown in Table III, the top two schemes are the FFF and DDD, and the due date rules in their pure forms. In addition, some of the best performers contained EDD at two of the three work centers, along with SPT or SI^{X} in the third. It appears that the role of the due date rule is crucial in reducing both earliness and tardiness costs. Furthermore, the schemes that resulted in high mean earliness costs, the eight possible combinations between SPT and SI^{X}, also yielded high mean tardiness costs. These combinations, however, produced significantly low-mean waiting costs.

To many, the performance of FFF and in reducing mean tardiness cost might appear surprising. However, prior research clearly suggests that no rule is capable of minimizing mean tardiness and there is little research on tardiness cost. The results of this study suggest that the tardiness cost performance of scheduling rules and their combinations is contingent upon the cost structure. In addition, the results are consistent with Barman (1998) in which combinations such as SDD, MDD, DMD, DSD, DDM, SMD, SSD, and MMD yielded superior tardiness results.

Table III. The best and worst ten combination schemes based on mean tardiness cost

Rank	Scheme	Mean tardiness cost ($)
1	FFF	11,624.26
2	DDD	*12,879.37*
3	SDD	*12,951.64*
4	MDD	*12,953.95*
5	DMD	*14,639.69*
6	DSD	*14,713.78*
7	DDM	16,671.99
8	SMD	*17,106.20*
9	MMD	*17,146.92*
10	SSD	17,496.67
21	MMM	*27,946.99*
22	SMM	*27,952.28*
23	MSM	*28,816.47*
24	SSM	*28,817.86*
25	MMS	*29,811.43*
26	SMS	*29,815.94*
27	MSS	*30,721.94*
28	SSS	*30,759.91*
29	LLL	39,821.19
30	CCC	40,306.72

Notes: Italicized figure indicate no significant difference in means at 5 percent level by Duncan's multiple range test; symbols used are: C is critical ratio rule, D is EDD rule, F is first in-first out rule, L is slack rule, M is modified SPT (SI^X) rule, S is SPT rule; three symbols in each scheme represent the three rules used at work centers 1, 2 and 3, respectively; for example: SMM represents use of SPT at work center 1 and SI^X at work centers 2 and 3, SSS represents use of SPT at all three work centers, DSM represents use of EDD, SPT, and SI^X at work centers 1, 2 and 3, respectively, MMS represents SI^X at work centers 1 and 2, and SPT at work center 3, etc.

Table IV lists the best and worst ten schemes based on the mean total cost, computed by adding the mean waiting, mean earliness, and the mean tardiness costs. Since the study involved five levels of tardiness cost and one level of earliness and waiting costs, the performance is mostly influenced by the mean tardiness cost rather than the mean waiting or earliness cost. Therefore, the two lists (Tables III and IV) are very similar with regard to the best and worst performers. While the use of EDD at all three work centers resulted in the lowest mean total cost, the combinations between EDD at any two work centers with SPT or SI^X at the third also produced superior results. Specifically, DDD, SDD, and MDD are the three best schemes if the mean total cost is the sole performance criterion. Similarly, the use of slack or critical ratio in its pure form appears to be least desirable. The eight possible combinations between SPT and SI^X did not perform well in the total cost category despite performing well in the waiting cost category.

Regarding the impact of the shop load levels upon the four cost categories, graphically shown in Figure 1, the Duncan's multiple range test reveals that the differences are statistically significant at the 0.05 level. In addition, the schemes were rank ordered based on their cost performances for each load level and presented in Table V. No discernible pattern in their relative performances became apparent

Rank	Scheme	Mean total cost ($)
1	DDD	*21,130.01*
2	SDD	*21,317.49*
3	MDD	*21,318.45*
4	DMD	*22,626.94*
5	DSD	*22,634.37*
6	FFF	24,001.31
7	DDM	*24,475.03*
8	DDS	*25,225.19*
9	SMD	*25,402.02*
10	MMD	*25,443.74*
21	MMM	*36,172.51*
22	SMM	*36,177.16*
23	MSM	*37,040.75*
24	SSM	*37,041.89*
25	MMS	*38,037.62*
26	SMS	*38,041.03*
27	MSS	*38,948.94*
28	SSS	*38,987.75*
29	LLL	48,185.02
30	CCC	55,925.01

Notes: Italicized figure indicate no significant difference in means at 5 percent level by Duncan's multiple range test; symbols used are: C is critical ratio rule, D is EDD rule, F is first in-first out rule, L is slack rule, M is modified SPT (SI^{X}) rule, S is SPT rule; three symbols in each scheme represent the three rules used at work centers 1, 2 and 3, respectively; for example: SMM represents use of SPT at work center 1 and SI^{X} at work centers 2 and 3, SSS represents use of SPT at all three work centers, DSM represents use of EDD, SPT, and SI^{X} at work centers 1, 2 and 3, respectively, MMS represents SI^{X} at work centers 1 and 2, and SPT at work center 3, etc.

Table IV.
The best and worst ten combination schemes based on mean total cost

by altering the load levels. In other words, the schemes that did well under the high-load level also did well under the low-level regardless of the cost criterion.

6.2 Standard deviation measures

The Kruskal-Wallis *H*-test confirmed that the priority rule combinations had a statistically significant impact (p-value $\leq$ 0.01 percent) on each of the four standard deviation measures. Furthermore, as expected, the shop load level was also found to be statistically significant (p-value $\leq$ 0.01 percent) for all of the four criteria. In other words, the lower the shop load level, the smaller is the variance in the cost performance data. The four variability data for the best and worst ten combination schemes are presented in Tables VI-IX. Similar to the mean cost data, the figures in the tables are an average of 300 observations, resulting from the two load levels, five cost ratios, and 30 replications.

It is evident from Table VI that the rule in its pure form, the FFF combination, yielded the lowest variability in the waiting cost category. On the other hand, the critical ratio and the slack rules in their pure forms (CCC and LLL) did the worst. In general, all of the possible combinations between the SPT and SI^{X} rules appeared to be effective in reducing the waiting cost variability. Note that all of these eight combinations yielded very comparable results.

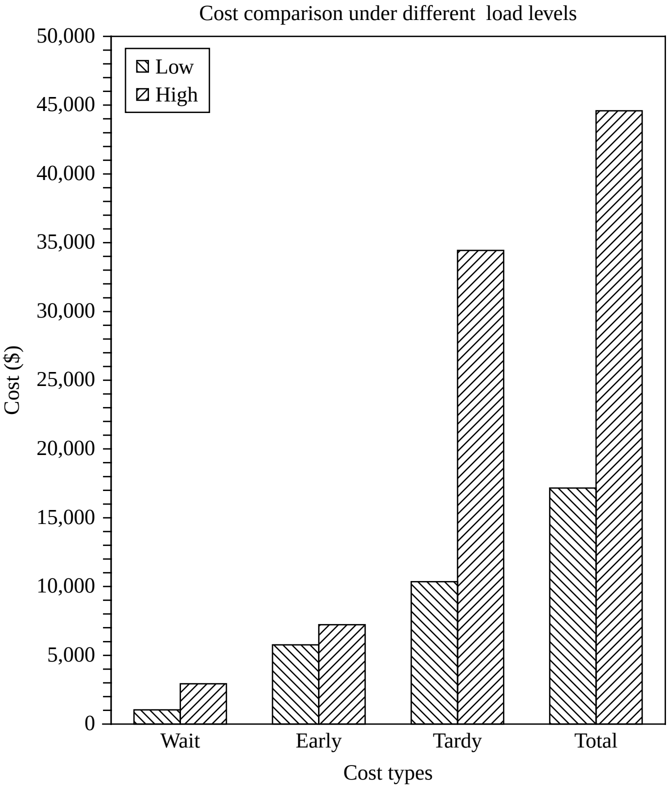

Figure 1.
Comparison of different mean costs under the low- and high-shop loads

The LLL combination, the slack rule in its pure form, yielded the lowest standard deviation in the earliness cost measure, followed by the DDD scheme (Table VII). In fact, most of the best combinations included the due date rule in two of the three work centers. On the other hand, the combinations that included the SPT and SI^X rules yielded poor results, contrary to their performance in the waiting cost category.

The data in Table VIII show that the performance of the schemes as measured by the variability in the tardiness cost varied widely, even within the top ten combinations. The DSM combination did the best, followed by DDD, but the critical ratio, slack and the rules in their pure forms did poorly. The other combinations that performed relatively well are SSS, SDS, DMD, DDS, and MDD. It appears that the role of the due date rule is critical in lessening the tardiness cost variability because several top performers in this category included this rule in two of the three work centers. As was observed for the mean tardiness and total cost criteria, the performance of the schemes appeared nearly identical for the variability in these two measures (Tables VIII and IX). We believe that the rationale provided earlier to explain this phenomenon for the mean cost results still applies to the variability results. With regard to the impact of the shop load levels, no discernible difference was apparent on the performance of the combinations for theses four variability measures.

Table V.
The best ten schemes for different shop loads and cost criteria

	Schemes based on			
Rank	Mean waiting cost ($)	Mean earliness cost ($)	Mean tardiness cost ($)	Mean total cost ($)
Shop load: high				
1	MMM	DDD	FFF	SDD
2	SMM	LLL	SDD	MDD
3	MSM	DDS	MDD	DDD
4	SSM	DSD	DDD	DSD
5	SMS	DMD	DSD	DMD
6	MMS	DDM	DMD	FFF
7	MSS	MDD	DDM	DDM
8	SSS	SDD	SMD	DDS
9	DSS	DSS	MMD	SMD
10	DSM	DMS	DDS	MMD
Shop load: low				
1	MMS	DDD	FFF	DDD
2	SMS	LLL	DDD	MDD
3	MSS	DDS	MDD	SDD
4	MMM	DDM	SDD	FFF
5	SSS	DSD	DMD	DMD
6	SMM	DMD	DSD	DSD
7	MSM	MDD	SMD	DDM
8	SSM	SDD	MMD	SMD
9	DSS	DSS	DDM	MMD
10	DSM	DMS	MSD	DDS

Notes: Symbols used are: C is critical ratio rule, D is EDD rule, F is first in-first out rule, L is slack rule, M is modified SPT (SI^X) rule, S is SPT rule; three symbols in each scheme represent the three rules used at work centers 1, 2 and 3, respectively; for example: SMM represents use of SPT at work center 1 and SI^X at work centers 2 and 3, SSS represents use of SPT at all three work centers, DSM represents use of EDD, SPT, and SI^X at work centers 1, 2 and 3, respectively, MMS represents SI^X at work centers 1 and 2, and SPT at work center 3, etc.

However, as expected, the variability across-the-board increased when the shop load was raised to the higher level.

7. Conclusions

Several previous studies (Barman, 1997, 1998; Barman and LaForge, 1998; Barrett and Barman, 1986; Dooley, 1990; LaForge and Barman, 1989; Mahmoodi *et al.*, 1996) reported that using different priority rules at different work centers is a better job sequencing strategy than using them in their pure forms. This study investigated this issue further by extending the results of two prior studies (Barman, 1997, 1998). Furthermore, instead of using traditional due date and throughput-oriented measures, such as flow time, tardiness, etc. this study explored the efficacy of the combinations using several cost-based performance measures. Three priority rules whose combinations showed promising results in Barman (1998) were combined in all possible ways in a three-stage flow-dominated manufacturing system, resulting in 27 possible combinations. The performances of these combinations, along with three other simple priority rules in their pure forms, were compared using both mean and variability in waiting, earliness, tardiness, and total costs under two shop load levels and various tardiness to earliness cost ratios.

Table VI. The best and worst ten schemes based on standard deviation of waiting cost

Rank	Scheme	SD of waiting cost ($)
1	FFF	3,483.62
2	MMM	3,745.95
3	SMM	3,762.45
4	MSM	3,787.62
5	SSM	3,797.75
6	MSS	3,871.97
7	MMS	3,880.40
8	SSS	3,884.12
9	SMS	3,884.82
10	SMD	3,912.67
21	SDS	4,312.65
22	SDM	4,323.03
23	MDM	4,339.65
24	MDD	4,388.58
25	SDD	4,390.08
26	DDD	4,668.50
27	DDS	4,698.77
28	DDM	4,898.77
29	LLL	10,292.40
30	CCC	22,099.73

Notes: Symbols used are: C is critical ratio rule, D is EDD rule, F is first in-first out rule, L is slack rule, M is modified SPT (SI^{X}) rule, S is SPT rule; three symbols in each scheme represent the three rules used at work centers 1, 2 and 3, respectively; for example: SMM represents use of SPT at work center 1 and SI^{X} at work centers 2 and 3, SSS represents use of SPT at all three work centers, DSM represents use of EDD, SPT, and SI^{X} at work centers 1, 2 and 3, respectively, MMS represents SI^{X} at work centers 1 and 2, and SPT at work center 3, etc.

The results indicate that all the possible combinations between SI^{X} and SPT, including their pure forms, performed well in reducing both mean and standard deviation in waiting costs, but did poorly on the same measures for the tardiness cost. In addition, these combinations caused jobs to be completed much earlier than their due dates, yielding relatively higher mean and variability in earliness costs. It should be stressed that the costs of finishing jobs early may not apply to many manufacturing organizations where early shipment is permissible and that would obviate any additional inventory holding costs. Clearly, the use of the due date rule in its pure form (DDD), or in two of the three work centers in combination with SPT or SI^{X} in the third, was found highly effective in reducing both mean and variability of both earliness and tardiness costs. The results are intuitively consistent with that reported in Barman (1998) in which the same combination schemes were found most effective in reducing maximum tardiness. Furthermore, as was observed in Barman (1997, 1998) and Barman and LaForge (1998), we found little impact of the shop load level on the relative performance of the combination schemes. With regard to the total cost, it was mostly influenced by the tardiness cost because of the cost structure used in this study. Consequently, the combinations that did well in the tardiness cost category exhibited superior total cost performance. The critical ratio (CCC) and slack (LLL) rules, two of the three benchmark combinations used for comparison, produced poor results in most

Table VII.
The best and worst ten schemes based on standard deviation of earliness cost

Rank	Scheme	SD of earliness cost ($)
1	LLL	7,407.20
2	DDD	7,942.17
3	DDS	8,141.00
4	DDM	8,181.23
5	DMD	8,294.07
6	DSD	8,294.80
7	SDD	8,383.65
8	MDD	8,383.85
9	DSS	8,535.02
10	DMS	8,546.28
21	MSS	9,191.58
22	SSS	9,193.15
23	SSM	9,199.48
24	MSM	9,200.15
25	SMS	9,203.45
26	MMS	9,204.83
27	SMM	9,212.70
28	MMM	9,213.73
29	CCC	10,737.32
30	FFF	12,045.30

Notes: Symbols used are: C is critical ratio rule, D is EDD rule, F is first in-first out rule, L is slack rule, M is modified SPT (SI^{X}) rule, S is SPT rule; three symbols in each scheme represent the three rules used at work centers 1, 2 and 3, respectively; for example: SMM represents use of SPT at work center 1 and SI^{X} at work centers 2 and 3, SSS represents use of SPT at all three work centers, DSM represents use of EDD, SPT, and SI^{X} at work centers 1, 2 and 3, respectively, MMS represents SI^{X} at work centers 1 and 2, and SPT at work center 3, etc.

of the cost categories, except that the latter was found effective in reducing the mean earliness cost because of its due date orientation.

By including the variability in cost measures, this study added an important element to the set of shop performance criteria traditionally considered in research on scheduling. While the mean cost is an adequate criterion for cost comparison, the variability is directly linked to the accuracy in estimating it. That is, the lower the variability, the more reliable would be the cost estimation process. On the other hand, high variability could cause the actual costs to be substantially different from the estimated figures. Therefore, strategies with cost high variability should be avoided because they allude to an estimation problem.

We observed that the EDD rule, along with other combination schemes, was highly effective in reducing the mean tardiness cost, given that it was found less effective in reducing mean tardiness in previous research (Blackstone *et al.*, 1982; Ramasesh, 1990). The only plausible explanation is that the cost computation in this study included a multiplicative factor between the dollar value of a job and the duration by which it was late. While in prior studies that are non-cost related, the mean tardiness computation was simply additive in nature, considering only the length of time by which a job is late. A summary of the results is provided in Table X, which lists the best combination schemes when various cost criteria are jointly considered.

Rank	Scheme	SD of tardiness cost ($)
1	DSM	10,556.69
2	DDD	15,166.61
3	SSS	31,735.53
4	SDS	31,756.22
5	DMD	34,644.30
6	DDS	36,585.13
7	MDD	36,770.95
8	DDM	42,710.55
9	SMS	51,129.52
10	MDM	51,233.71
21	SSD	73,438.75
22	MMS	73,572.73
23	CCC	75,362.09
24	SMD	75,429.99
25	SMM	76,423.80
26	MSD	76,519.60
27	FFF	77,906.32
28	MSS	78,102.29
29	LLL	82,530.86
30	DMM	88,994.38

Notes: Symbols used are: C is critical ratio rule, D is EDD rule, F is first in-first out rule, L is slack rule, M is modified SPT (SI^X) rule, S is SPT rule; three symbols in each scheme represent the three rules used at work centers 1, 2 and 3, respectively; for example: SMM represents use of SPT at work center 1 and SI^X at work centers 2 and 3, SSS represents use of SPT at all three work centers, DSM represents use of EDD, SPT, and SI^X at work centers 1, 2 and 3, respectively, MMS represents SI^X at work centers 1 and 2, and SPT at work center 3, etc.

Table VIII.
The best and worst ten schemes based on standard deviation of tardiness cost

While most of prior scheduling research has focused on due date and throughput related performance measures, little effort has been spent on cost-related criteria, despite the fact that cost effectiveness is the primary concern for practicing mangers. What Blackstone *et al.* (1982, p. 28) stated, "… the structure of delay costs differ widely from firm to firm, many researchers have chosen to use non-cost performance measures," is perhaps the most important factor that could be attributed to such a deviation. Therefore, the results of this study are limited to the cost structure used, even though a wide range of cost ratios was included. It should also be stressed that the concept of earliness cost, which has received rare research attention in the past, may not apply to all manufacturing organizations and thus the attendant results have limited implications. More importantly, however, the results of this study do support the findings from previous research (Barman, 1997, 1998; Barman and LaForge, 1998; Barrett and Barman, 1986; LaForge and Barman, 1989) that combining priority rules, instead of using them in their pure forms, can enhance the shop performance.

Future research might focus on the cost performance with different cost structures and components, including other dispatching rules that have been found to be effective in earliness and/or tardiness measures. Efforts to develop new priority rules that simultaneously consider throughput and job due dates, exploiting the main advantage of rule combinations, are also a worthwhile avenue for extending this research.

Rank	Scheme	SD of total cost ($)
1	DSM	23,262.39
2	DDD	27,777.28
3	SDS	44,758.40
4	SSS	44,812.80
5	DMD	47,110.37
6	DDS	49,424.90
7	MDD	49,543.38
8	DDM	55,790.55
9	SMS	64,217.79
10	MDM	64,284.04
21	SSD	86,186.51
22	MMS	86,657.96
23	SMD	88,171.44
24	MSD	89,259.89
25	SMM	89,398.95
26	MSS	91,165.84
27	FFF	93,435.24
28	LLL	100,230.46
29	DMM	101,805.54
30	CCC	108,199.14

Notes: Symbols used are: C is critical ratio rule, D is EDD rule, F is first in-first out rule, L is slack rule, M is modified SPT (SI^{X}) rule, S is SPT rule; three symbols in each scheme represent the three rules used at work centers 1, 2 and 3, respectively; for example: SMM represents use of SPT at work center 1 and SI^{X} at work centers 2 and 3, SSS represents use of SPT at all three work centers, DSM represents use of EDD, SPT, and SI^{X} at work centers 1, 2 and 3, respectively, MMS represents SI^{X} at work centers 1 and 2, and SPT at work center 3, etc.

Table IX. The best and worst ten schemes based on standard deviation of total cost

Waiting and earliness	Waiting and tardiness	Earliness and tardiness
Cost measures: mean		
DSS	None	DDD DDM DMD DSD MDD SDD
Cost measures: SD		
None	SMS SSS	DDD DDM DDS DMD MDD

Notes: Symbols used are: C is critical ratio rule, D is EDD rule, F is first in-first out rule, L is slack rule, M is modified SPT (SI^{X}) rule, S is SPT rule; three symbols in each scheme represent the three rules used at work centers 1, 2 and 3, respectively; for example: SMM represents use of SPT at work center 1 and SI^{X} at work centers 2 and 3, SSS represents use of SPT at all three work centers, DSM represents use of EDD, SPT, and SI^{X} at work centers 1, 2 and 3, respectively, MMS represents SI^{X} at work centers 1 and 2, and SPT at work center 3, etc.

Table X. Best combination schemes when cost measures are jointly considered

Understanding the impact of order review/release strategies in conjunction with priority rule combinations on shop performance might be another potential area for future research.

References

Agarwal, S.C. and McCarl, B.A. (1974), "The development and evaluation of a cost-based composite scheduling rule", *Naval Research Logistics Quarterly*, Vol. 21 No. 1, pp. 155-69.

Agarwal, S.C., Wyman, F.P. and McCarl, B.A. (1973), "An investigation of cost-based rule for job shop scheduling", *International Journal of Production Research*, Vol. 11 No. 3, pp. 247-61.

Barman, S. (1997), "Simple priority rule combinations: an approach to improve both flow time and tardiness", *International Journal of Production Research*, Vol. 35 No. 10, pp. 2857-70.

Barman, S. (1998), "The impact of priority rule combinations on lateness and tardiness", *IIE Transactions on Scheduling and Logistics*, Vol. 30 No. 5, pp. 495-504.

Barman, S. and LaForge, R.L. (1998), "The impact of simple priority rule combinations on delivery speed and delivery reliability in a hybrid shop", *Production and Operations Management*, Vol. 7 No. 4, pp. 402-16.

Barrett, R.T. and Barman, S. (1986), "A SLAM II simulation study of a simplified flow shop", *Simulation*, Vol. 47 No. 5, pp. 181-9.

Benton, W.C. (1993), "Time-and cost-based priorities for job shop scheduling", *International Journal of Production Research*, Vol. 31 No. 7, pp. 1509-19.

Blackstone, J.H. Jr, Phillips, D.T. and Hogg, G.L. (1982), "A state of the art survey of dispatching rules for manufacturing job shop operations", *International Journal of Production Research*, Vol. 20 No. 1, pp. 27-45.

Dooley, K.J. (1990), "Interactions between dispatching rules and workstation location", *Proceedings of the Midwest Decision Sciences Institute, Minneapolis, MN, USA*.

Eilon, S. and Cotterill, D.J. (1968), "A modified SI rule in job shop scheduling", *International Journal of Production Research*, Vol. 7 No. 2, pp. 135-45.

Eilon, S., Chowdhury, I.G. and Serghiou, S.S. (1975), "Experiments with the SI^{X} rule in job-shop scheduling", *Simulation*, Vol. 24, pp. 45-8.

Fishman, G.S. (1978), *Principles of Discrete Event Simulation*, Wiley, New York, NY.

Hermann, J.W., Lee, C.-Y. and Hinchman, J. (1995), "Global job shop scheduling with a generic algorithm", *Production and Operations Management*, Vol. 4 No. 1, pp. 30-45.

Hoffmann, T.R. and Scudder, G.D. (1983), "Priority scheduling with cost considerations", *International Journal of Production Research*, Vol. 21 No. 6, pp. 881-9.

LaForge, R.L. and Barman, S. (1989), "The performance of simple priority rule combinations in a flow dominant shop", *Production & Inventory Management Journal*, Vol. 30 No. 3, pp. 1-4.

Li, C.-L., Mosheiov, G. and Yovel, U. (2008), "An efficient algorithm for minimizing earliness, tardiness, and due-date costs for equal sized jobs", *Computers & Operations Research*, Vol. 35 No. 11, pp. 3612-22.

Li, J.-W. and Barnes, D.J. (2000), "Investigating the factors influencing the shop performance in a job shop environment with kanban-based production control", *International Journal of Production Research*, Vol. 38 No. 18, pp. 4683-99.

Mahmoodi, F., Mosier, C.T. and Guerin, R.E. (1996), "The effect of combining simple priority heuristics in flow-dominant shops", *International Journal of Production Research*, Vol. 34 No. 3, pp. 819-39.

Monch, L., Rose, O. and Sturm, R. (2003), “A simulation framework for the performance assessment of shop-floor control systems”, *Simulation*, Vol. 79 No. 3, pp. 163-70.

Pritsker, A.A.B. (1986), *Introduction to Simulation and SLAM II*, Systems Publishing Corporation, West Lafayette, IN.

Ragatz, G.L. and Mabert, V.A. (1988), “An evaluation of order release mechanisms in a job-shop environment”, *Decision Sciences*, Vol. 19 No. 1, pp. 167-89.

Ramasesh, R. (1990), “Dynamic job shop scheduling: a survey of simulation research”, *Omega*, Vol. 18 No. 1, pp. 43-57.

Ronconi, D.P. and Henriques, L.R.S. (2009), “Some heuristic algorithms for total tardiness minimization in a flow shop with blocking”, *Omega*, Vol. 37 No. 2, pp. 272-81.

Scudder, G.D. and Hoffmann, T.R. (1985), “Composite cost-based rules for priority scheduling in a randomly routed job shop”, *International Journal of Production Research*, Vol. 23 No. 6, pp. 1185-95.

Scudder, G.D. and Hoffmann, T.R. (1986), “The use of value-based rules to avoid shop disruption”, *Omega*, Vol. 14 No. 3, pp. 259-64.

Scudder, G.D. and Hoffmann, T.R. (1987), “The use of cost based priorities in random and flow shops”, *Journal of Operations Management*, Vol. 7 Nos 1/2, pp. 217-32.

Yeh, C.-H. (2005), “Sequencing shop floor operations: a practical approach”, *Journal of Manufacturing Technology Management*, Vol. 16 No. 5, pp. 531-41.

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