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RESEARCH ARTICLE

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Analysis of dispatching rules in a stochastic dynamic job shop manufacturing system with sequence-dependent setup times

Abstract Stochastic dynamic job shop scheduling problem with consideration of sequence-dependent setup times are among the most difficult classes of scheduling problems. This paper assesses the performance of nine dispatching rules in such shop from makespan, mean flow time, maximum flow time, mean tardiness, maximum tardiness, number of tardy jobs, total setups and mean setup time performance measures viewpoint. A discrete event simulation model of a stochastic dynamic job shop manufacturing system is developed for investigation purpose. Nine dispatching rules identified from literature are incorporated in the simulation model. The simulation experiments are conducted under due date tightness factor of 3, shop utilization percentage of 90 % and setup times less than processing times. Results indicate that shortest setup time (SIMSET) rule provides the best performance for mean flow time and number of tardy jobs measures. The job with similar setup and modified earliest due date (JMEDD) rule provides the best performance for makespan, maximum flow time, mean tardiness, maximum tardiness, total setups and mean setup time measures.

Keywords scheduling, stochastic dynamic job shop, sequence-dependent setup times, dispatching rule, simulation

1 Introduction

Production scheduling in a manufacturing system is associated with allocation of a set of jobs on a set of production resources over time to achieve some objectives. In a job shop manufacturing system, a set of jobs is processed on a set of machines and each job has specific operation order. The job shop scheduling problem is a combinatorial optimization problem as well as NP-hard and it is one of the most typical and complex production scheduling problems [1,2]. In dynamic job shop scheduling problems, jobs arrive continuously over time in job shop manufacturing systems. Further, in a stochastic dynamic job shop (SDJS) manufacturing system, at least one parameter of the job (release time, processing time/ setup time) is probabilistic.

In traditional approaches, in order to reduce the complexity of solving job shop scheduling problems, setup time is either neglected or included in the processing time of a job. But this effort does not represent the realistic picture of a manufacturing system. Setup time is a time that is required to prepare the necessary resources such as machines to perform an operation [3]. In many real-life situations, a setup operation often occurs while shifting from one operation type to another. Sequence-dependent setup time depends on both current and immediately previous operation [3]. Sequence-dependent setup time encounters in many industries, such as printing industry, paper industry, auto industry, chemical processing and plastic manufacturing industry. Scheduling problems with sequence-dependent setup times are among the most difficult classes of scheduling problems [4]. It has been pointed out by Manikas and Chang [5] and Defersha and Chen [6] that limited research on job shop scheduling problems considering sequence-dependent setup times is available.

A dispatching rule is used to select the next job to be processed from a set of jobs awaiting processing in the input queue of a machine. Dispatching rules are also termed as sequencing rules or scheduling rules. Dispatching rules are classified into broad four categories namely as process time based rules, due date based rules, combination rules and rules that are neither process time based nor due date based [7]. This paper focuses the performance of nine dispatching rules identified from literature in a SDJS manufacturing system with consideration of sequence-dependent setup times.

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The remainder of the paper is organized as follows: The review of relevant literature is shown in Section 2; Section 3 describes salient aspects of configuration of the SDJS scheduling problem; the outline for development of simulation model is explained in Section 4; Section 5 presents details of simulation experimentations; Section 6 provides analysis of experimental results; finally, Section 7 gives concluding remarks and directions for future research.

2 Literature review

Ramasesh [8] provided a review of simulation research in dynamic job shop scheduling problems. Allahverdi et al. [9] provided a comprehensive survey of literature on scheduling problems with setup times (costs). Panwalkar et al. [10] provided a survey of scheduling rules used in manufacturing systems. Blackstone et al. [11] presented a state-of-the-art review of scheduling rules used in job shop scheduling problems. Holthaus and Rajendran [12] proposed two new dispatching rules for dynamic job shop scheduling problems to minimize mean flow time, mean tardiness and percentage of tardy jobs performance measures. These rules combine process time and work content in queue for the next operation on a job by making use of additive (Rule 1) and alternative approaches (Rule 2). The authors concluded that Rule 1 is quite superior in minimizing mean flow time performance measure. Jayamohan and Rajendran [13] proposed seven dispatching rules for minimization of mean flow time, maximum flow time, variance of flow time and tardiness performance measures in dynamic shops. The proposed rules are found to be very much effective in minimizing different performance measures. Jain et al. [14] proposed and assessed the performance of four new dispatching rules for makespan, mean flow time, maximum flow time and variance of flow time measures in a flexible manufacturing system. The authors found that the proposed dispatching rules provided better performance than the existing rules. Dominic et al. [15] developed two better scheduling rules viz. longest sum of work remaining and arrival time of a job (MWRK_FIFO) and shortest sum of total work and processing time of a job (TWKR_SPT) for dynamic job shop scheduling problems. These rules are tested against six existing scheduling rules, i.e., first-in-first-out (FIFO), last-in-first-out (LIFO), shortest processing time (SPT), longest processing time (LPT), most work remaining (MWRK) and total work (TWKR) for mean flow time, maximum flow time, mean tardiness, tardiness variance and number of tardy jobs performance measures.

There have been a few attempts to address dynamic job shop scheduling problems with sequence-dependent setup times. To the best of authors' knowledge, Wilbrecht and Prescott [16] were the first among researchers to study the influence of setup time on dynamic job shop manufacturing systems performance. They proposed and tested a setup oriented scheduling rule, job with shortest setup time (SIMSET). The authors concluded that SIMSET rule outperformed other six existing scheduling rules, i.e., random, earliest due date, shortest run, longest run, shortest process and longest process for value of work-in-progress, number of processes completed in a week, number of jobs sent out of the shop in one week, number of processes completed late in one week, distribution of completion time, queue wait time of a job in a shop, number of jobs waiting in a shop, shop capacity utilized, number of jobs waiting in a queue for more than one week and size of jobs waiting in a queue for more than one week performance measures. Kim and Bobrowski [17] studied the impact of sequence-dependent setup time on a dynamic job shop manufacturing system performance. The authors concluded that setup oriented scheduling rules, i.e., SIMSET and job with similar setup and critical ratio (JCR), outperforms ordinary scheduling rules, i.e., SPT and critical ratio (CR) for mean flow time, mean work-in-process inventory, mean finished good inventory, mean tardiness, proportion of tardy jobs, mean machine utilization, mean setup time per job, mean number of setups per job and mean total cost per day performance measures when a manufacturing system with sequence-dependent setup times is considered. Kim and Bobrowski [18] extended their earlier research [17] to investigate the impact of setup times variation on sequencing decisions with normally distributed setup times. The authors concluded that setup times variation had a negative impact on a manufacturing system performance. Recently, Vinod and Sridharan [19] proposed and assessed the performance of five setup oriented scheduling rules viz. shortest sum of setup time and processing time (SSPT), job with similar setup and shortest processing time (JSPT), job with similar setup and earliest due date (JEDD), job with similar setup and modified earliest due date (JMEDD) and job with similar setup and shortest sum of setup time and processing time (JSSPT) for dynamic job shop scheduling problems with sequence-dependent setup times. The authors concluded that the proposed rules provided better performance than the existing scheduling rules, i.e., FIFO, SPT, earliest due date (EDD), modified earliest due date (MEDD), CR, SIMSET and JCR for mean flow time, mean tardiness, mean setup time and mean number of setups performance measures.

Literature review clearly reveals that there is a need to evaluate the performance of dispatching rules in a SDJS manufacturing system with sequence-dependent setup times. The present paper is an attempt in this direction. It assesses the performance of existing nine best performing dispatching rules identified from literature using simulation modeling for makespan, mean flow time, maximum flow time, mean tardiness, maximum tardiness, number of tardy jobs, total setups and mean setup time performance measures in an SDJS manufacturing system with sequence-dependent setup times.

3 Job shop configuration

In the present study, a job shop manufacturing system with ten machines is selected. The configuration of the manufacturing system is determined based on the configuration of job shop considered by previous researchers [12,19]. It has been pointed out by researchers that six machines are sufficient to represent the complex structure of a job shop manufacturing system [16,20] and variations in job shop size do not significantly affect the relative performance of dispatching rules [12,20]. For the same reason, most of the researchers addressed a job shop scheduling problem with less than ten machines [15,21,22].

3.1 Job data

Six different types of jobs, i.e., job type A, job type B, job type C, job type D, job type E and job type F, arrive at the manufacturing system. All the job types have equal probability of arrival. Job types A, B, C, D, E and F require 5, 4, 4, 5, 4 and 5 operations, respectively. Table 1 shows the machines visited by different job types in their routes. The processing times and setup times of each job are stochastic and assumed to be uniformly distributed on each machine. Processing time changes according to job type and route of the job. The processing times of each job on the machines according to their routes are shown in Table 2. The pattern of processing times on different machines is selected based on the research work carried out by previous researcher [23]. Sequence-dependent setup times which encounters while shifting from one job type to another are given in Table 3.

Table 1 Routes of job types

Job type	Number of operations	Route of the job (machine number)
A	5	1-6-10-2-4
B	4	8-3-5-10
C	4	7-9-3-1
D	5	5-7-9-2-4
E	4	2-8-1-10
F	5	6-9-1-3-5

Table 2 Processing times of jobs on machines according to routes

Job type	Processing times of jobs according to machines
A	U(10,11), U(14,15), U(17,18), U(16,17), (18,19)
B	U(17,18), U(10,11), U(19,20), U(13,14)
C	U(17,18), U(11,12), U(16,17), U(13,14)
D	U(12,13), U(19,20), U(16,17), U(10,11), U(17,18)
E	U(13,14), U(19,20), U(10,11), U(16,17)
F	U(19,20), U(13,14), U(15,16), U(10,11), U(14,15)

3.2 Inter-arrival time

Inter-arrival time is an average time between arrivals of two jobs. Rangsaritratsamee et al. [24] reported that average arrival rate of jobs must be selected to have utilization of the machine less than 100%. Otherwise, the number of jobs in the queues in front of each machine will grow without bound. Thus, inter-arrival time of the jobs is established using percentage utilization of the manufacturing system and processing requirements of the jobs. It is observed in the literature that arrival process of the jobs follows a Poisson distribution [8,19,24]. Thus, inter-arrival time is exponentially distributed. Mean inter-arrival time of the jobs is calculated using the following relationship [19,21]

$$b=\frac{1}{\lambda}=\frac{\mu_p\mu_g}{UM} \quad (1)$$

Here

b — Mean inter-arrival time;

λ — Mean job arrival rate;

μ_p — Mean processing time per operation (including setup time);

μ_g — Mean number of operations per job;

U — Shop utilization;

M — Number of machines in the shop.

Table 3 Job types/sequence-dependent setup times data

Preceding job type	Following job type					
	A	B	C	D	E	F
A	0	U(5,5.25)	U(5,5.75)	U(5,5.50)	U(5,5.50)	U(5,5.25)
B	U(5,5.50)	0	U(5,5.25)	U(5,5.75)	U(5,5.25)	U(5,5.50)
C	U(5,5.25)	U(5,5.50)	0	U(5,5.50)	U(5,5.75)	U(5,5.25)
D	U(5,5.75)	U(5,5.25)	U(5,5.50)	0	U(5,5.25)	U(5,5.50)
E	U(5,5.50)	U(5,5.75)	U(5,5.25)	U(5,5.50)	0	U(5,5.25)
F	U(5,5.25)	U(5,5.50)	U(5,5.75)	U(5,5.25)	U(5,5.50)	0

In the present work, μ_p is computed by taking the mean of mean processing times of all operations (from Table 2) plus the mean of mean setup times (from Table 3). Thus, $\mu_p = 19.45$. For the taken input data, μ_g is 4.5 with $M = 10$. In the present work, experiments are carried out at $U = 90\%$. Van Parunak [25] reported that due to stochastic nature of input processes (processing times and setup times) actual shop load is approximated and fall within a range of $\pm 1.5\%$ of the target value.

3.3 Due date of jobs

The due date of a job indicates the time at which job order must be completed. The due date of the arriving job could be either externally or internally determined. In case of externally determined due date, due date is either established by the customer or set for a specific time in the future. In case of internally determined due date, due date is based on total work content (sum of processing times and setup times) of the job or number of operations to be performed on the job. The total work content (TWK) method is used by most of the researchers to assign due date of a job [12,19,21,26].

$$d_i = a_i + k(p_i + n_i u_i) \tag{2}$$

Here

d_i — Due date of job i;

a_i — Arrival time of job i;

k — Due date tightness factor;

p_i — Mean total processing times of all the operations of job i;

n_i — Number of operations of job i;

u_i — Mean of mean setup times of all the changeover of job i.

In the present study, $k = 3$ is considered.

4 Structure of simulation model

The study of large and complex manufacturing systems is possible only with simulation modeling. In the present study, using PROMODEL software, a discrete event simulation model for the operations of SDJS manufacturing system with each dispatching rule is developed. The job flow in the modeled SDJS manufacturing system is shown in Fig. 1. The assumptions made while developing a simulation model are as follows: 1) Each machine can perform only one operation on any job at a time. An operation cannot be performed until its predecessor operation is completed. 2) The jobs arrival in the system is dynamic. A type of job is unknown until it arrives in the system. 3) Unlimited capacity buffer is considered before and after each machine. 4) Processing times and setup times of each job are stochastic and known in priori with their distribution. 5) For processing of the jobs, alternate routings is not allowed.

In the present study, a conceptual model of a job shop manufacturing system is developed. In order to ensure that the simulation model is correctly developed, a multilevel verification exercise is performed. For this, the simulation model is debugged and internal logics are checked. The output obtained from simulation model is compared with that obtained from a manual exercise by using the same input data. Finally, the simulation model is run under different settings in order to check that the model behaves in a logical manner.

4.1 Dispatching rules

The dispatching rules (DRLs) are used to select a next job to be processed on the machine from a set of jobs awaiting machining in the input queue of the machine. In the present work, the following DRLs as identified from the literature are used to make job sequencing decision [16,19]:

1) FCFS: first come first served. Highest priority is given to the job which arrives first in the input queue of the machine.

2) SPT: shortest processing time. Highest priority is given to the job having the shortest processing time for the imminent operation.

3) SIMSET: shortest setup time. Highest priority is given to the job having the shortest setup time for the imminent operation.

4) EDD: earliest due date. Highest priority is given to the job having earliest due date.

5) SSPT: shortest (setup time + processing time). Highest priority is given to the job having smallest value of the sum of setup time and processing time.

6) JSPT: job with similar setup and shortest processing time. The job identical to the job that just finishes operation on the machine is selected for processing. When there is no identical job, highest priority is given to the job having shortest processing time for the imminent operation.

7) JEDD: job with similar setup and earliest due date. The job identical to the job that just finishes operation on the machine is selected for processing. When there is no identical job, highest priority is given to the job having earliest due date.

8) JMEDD: job with similar setup and modified earliest due date. The job identical to the job that just finishes operation on the machine is selected for processing. When there is no identical job, highest priority is given to the job having modified earliest due date.

9) JSSPT: job with similar setup and shortest (setup time + processing time). The job identical to the job that just finishes operation on the machine is selected for processing. When there is no identical job, highest priority is given to the job having smallest value of the sum of setup time and processing time.

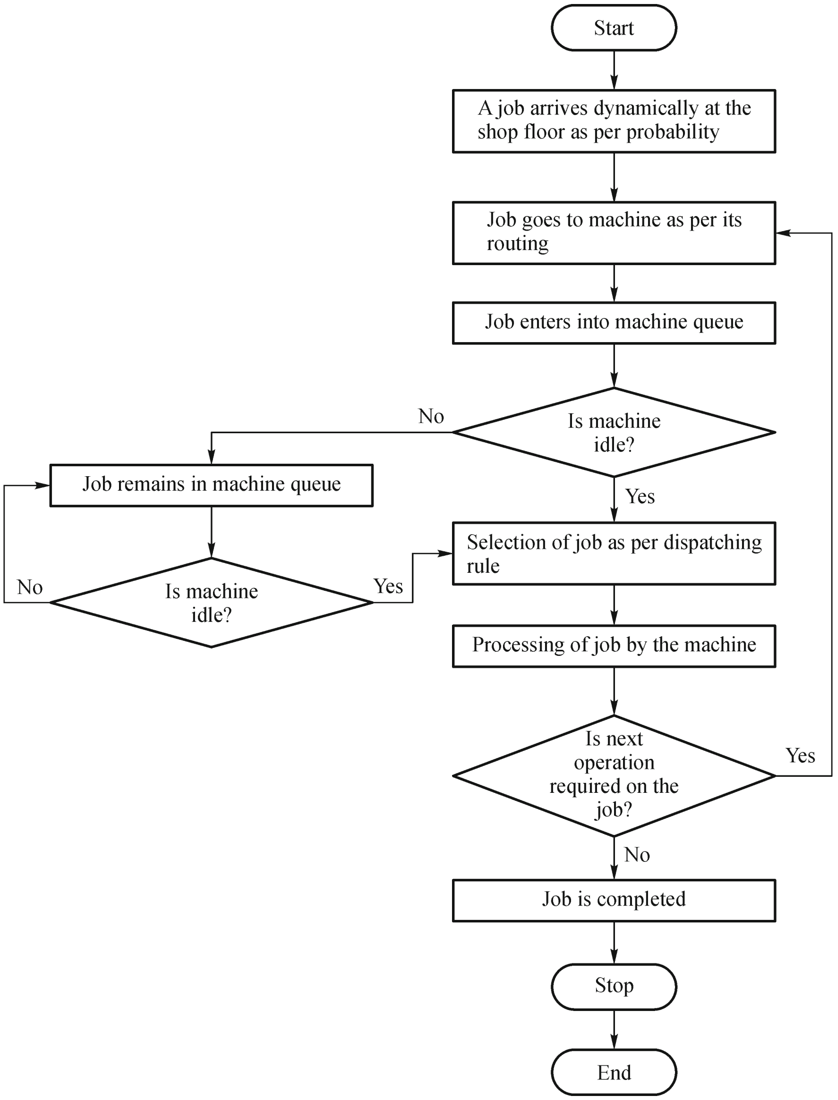

Fig. 1 Job flow in a modeled job shop

4.2 Performance measures

The performance measures used for evaluation purpose in the experimental investigations are as follows:

1) Makespan (M): It is a time of completion of last job in a manufacturing system.

2) Mean flow time ($\overline{F}$): It is an average time that a job spends in a manufacturing system during processing.

$$\overline{F} = \frac{1}{n}\left[\sum_{i=1}^{n} F_i\right] \tag{3}$$

where, F_i is the flow time of job i, $F_i = c_i - a_i$; c_i is the completion time of job i; a_i is the arrival time of job i; n is the number of jobs produced during simulation period (during steady state period).

3) Maximum flow time ($F_{\max}$): It is a maximum value of flow time that encounters during processing of jobs in a manufacturing system.

$$F_{\max} = \max\{F_i\}, 1 \leqslant i \leqslant n \tag{4}$$

4) Mean tardiness ($\overline{T}$): It is an average tardiness of a job in a manufacturing system during processing.

$$\overline{T} = \frac{1}{n}\left[\sum_{i=1}^{n} T_i\right] \tag{5}$$

Here, T_i is the tardiness of job i, $T_i = \max\{0, L_i\}$; L_i is the lateness of job i, $L_i = c_i - d_i$; d_i is the due date of job i.

5) Maximum tardiness ($T_{\max}$): It is a maximum value of tardiness that encounters during processing of jobs in a manufacturing system.

$$T_{\max} = \max\{T_i\}, 1 \leqslant i \leqslant n \tag{6}$$

6) Number of tardy jobs (NTJ): It is a value of the number of jobs which are completed after their due dates.

$$NTJ = \sum_{i=1}^{n} \delta(J_i) \tag{7}$$

where, if $J_i > 0$, $\delta(J_i) = 1$; otherwise, $\delta(J_i) = 0$.

7) Total setups (*TSP*): It is a value of the number of setups that encounters during processing of jobs in a manufacturing system.

$$TSP = \sum_{i=1}^{n} \delta(P_i) \tag{8}$$

Here, if $P_i > 0$, $\delta(P_i) = 1$; otherwise, $\delta(P_i) = 0$. P_i is the *i*th setup.

8) Mean setup time (*MST*): It is an average time that a job spends for the setup during processing in a manufacturing system.

$$MST = \frac{1}{n}\left[\sum_{i=1}^{n} S_i\right] \tag{9}$$

Here, S_i is the setup time of job *i*.

5 Experimental design for simulation study

Using simulation modeling, a number of experiments on SDJS scheduling problem have been conducted. The first stage in simulation experimentation is to identify steady state period, i.e., end of the initial transient period. The Welch's procedure as described by Law and Kelton [27] is used for this purpose. A pilot study for SDJS manufacturing system is conducted with FCFS dispatching rule. Thirty replications are considered for simulation experimentation. The simulation for each replication is made to run for 20000 jobs completion. It is observed that the manufacturing system reaches steady state at the completion of 5000 jobs. Finally, the experimental investigation is carried out to assess the performance of nine dispatching rules identified from literature in a SDJS manufacturing system for 20000 jobs completion (after warm up period of 5000 jobs).

6 Results and discussions

In SDJS manufacturing system, the performance of nine dispatching rules identified from literature is assessed. For each performance measure under each dispatching rule, the simulation output of 30 replications is averaged. The average values of various performance measures are shown in Figs. 2–9.

6.1 Makespan

It represents completion time of the last job. The makespan values for different dispatching rules are shown in Fig. 2. It clearly indicates that JMEDD rule is the best performing dispatching rule for makespan measure. This is followed by other dispatching rules, i.e., EDD, JEDD, JSSPT, JSPT, SSPT, SPT, SIMSET and FCFS dispatching rules in that order.

6.2 Mean flow time

The performance of different dispatching rules for mean flow time measure is shown in Fig. 3. It indicates that the SIMSET rule is the best performing dispatching rule for mean flow time performance measure. This is followed by other dispatching rules, i.e., SSPT, JMEDD, SPT, JEDD, EDD, JSSPT, JSPT and FCFS dispatching rules in that order. Thus, SIMSET rule is the best performing dispatching rule for mean flow time performance measure when a stochastic dynamic job shop scheduling problem with sequence-dependent setup times is considered.

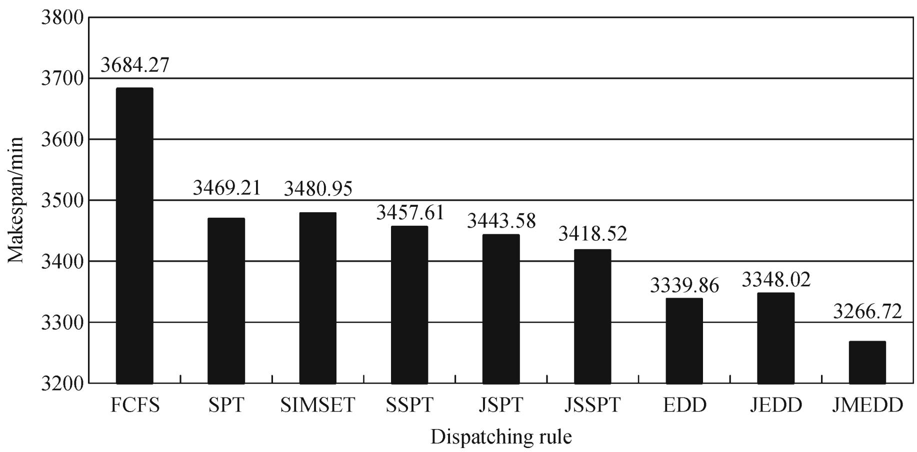

Fig. 2 Performance of dispatching rules for makespan

6.3 Maximum flow time

Figure 4 depicts the performance of various dispatching rules for maximum flow time measure. It is observed that the JMEDD dispatching rule provides the best performance for maximum flow time measure. This is followed by JEDD, EDD, JSSPT, JSPT, SSPT, SIMSET, SPT and FCFS rules in that order as the next best performing dispatching rules. Thus, for maximum flow time performance measure, JMEDD rule is the best performing dispatching rule.

6.4 Mean tardiness

Mean tardiness is due date based performance measure and related to better customer service and satisfaction. Figure 5 shows the performance of various dispatching rules for mean tardiness measure. It clearly indicates that the JMEDD rule is the best performing dispatching rule and it is followed by SPT, SIMSET, SSPT, JEDD, EDD, JSSPT, JSPT and FCFS dispatching rules in that order. Thus, JMEDD dispatching rule ranks first in minimizing mean tardiness of jobs.

6.5 Maximum tardiness

Figure 6 depicts the performance of various dispatching rules for maximum tardiness measure, which indicates that the JMEDD dispatching rule is the best performing dispatching rule. The performance pattern of different dispatching rules for maximum tardiness measure is similar to the performance of different dispatching rules with respect to maximum flow time measure.

6.6 Number of tardy jobs

The performance of different dispatching rules for number of tardy jobs measure is shown in Fig. 7. This figure indicates that the SIMSET dispatching rule provides the best performance for number of tardy jobs measure. The

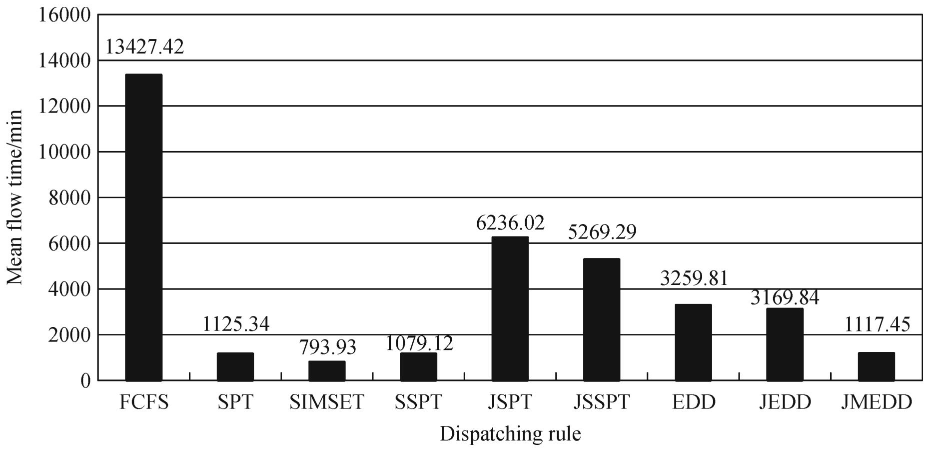

Fig. 3 Performance of dispatching rules for mean flow time

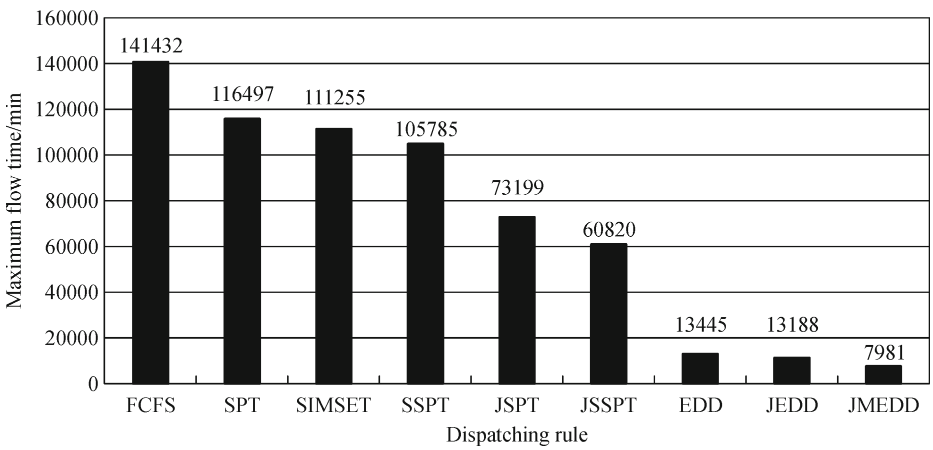

Fig. 4 Performance of dispatching rules for maximum flow time

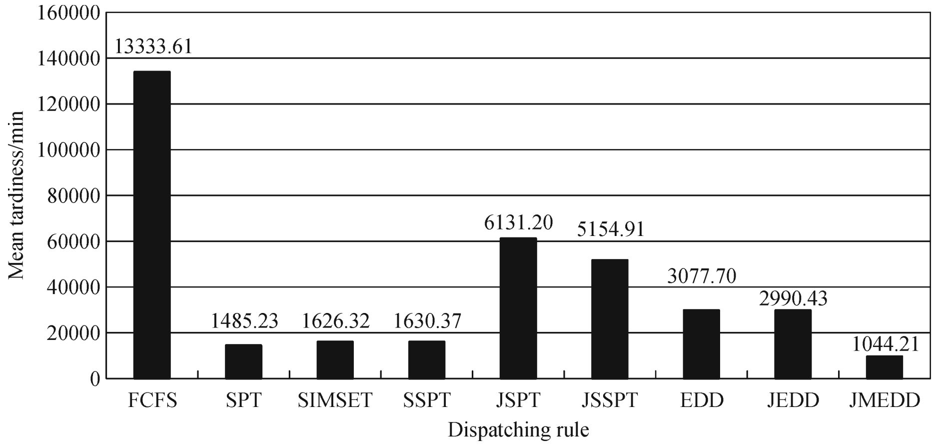

Fig. 5 Performance of dispatching rules for mean tardiness

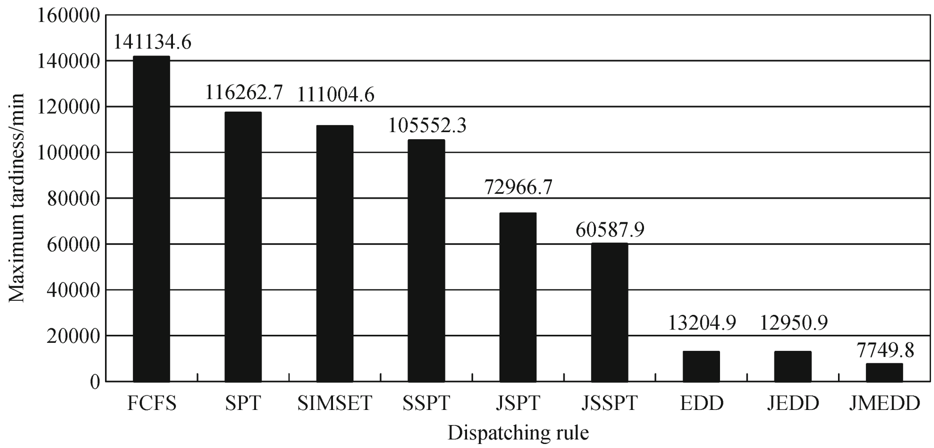

Fig. 6 Performance of dispatching rules for maximum tardiness

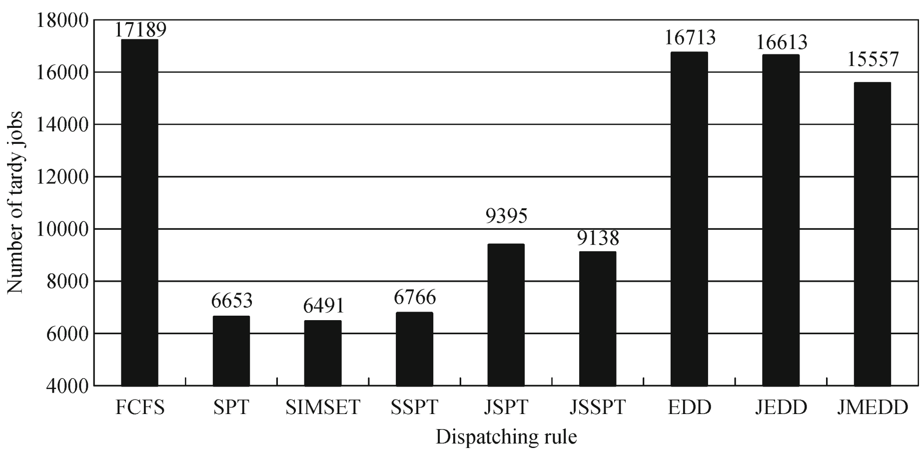

Fig. 7 Performance of dispatching rules for number of tardy jobs

other dispatching rules, i.e., SPT, SSPT, JSSPT, JSPT, JMEDD, JEDD, EDD and FCFS dispatching rules rank second to ninth respectively in minimizing number of tardy jobs performance measure.

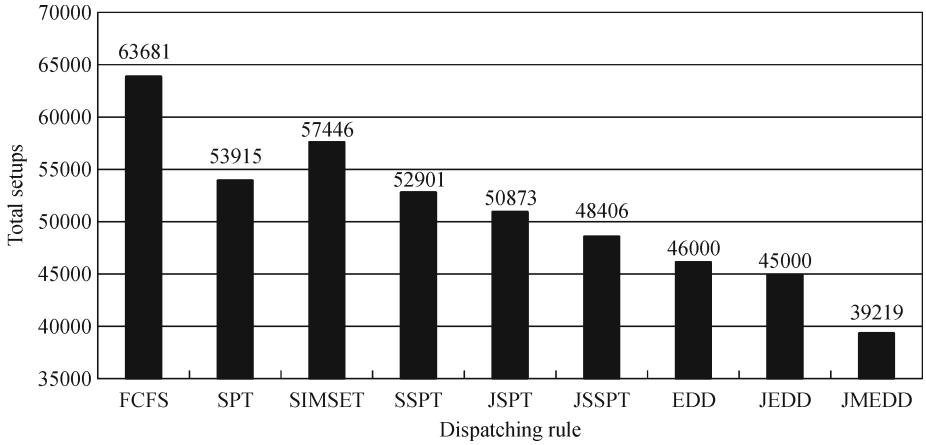

Fig. 8 Performance of dispatching rules for total setups

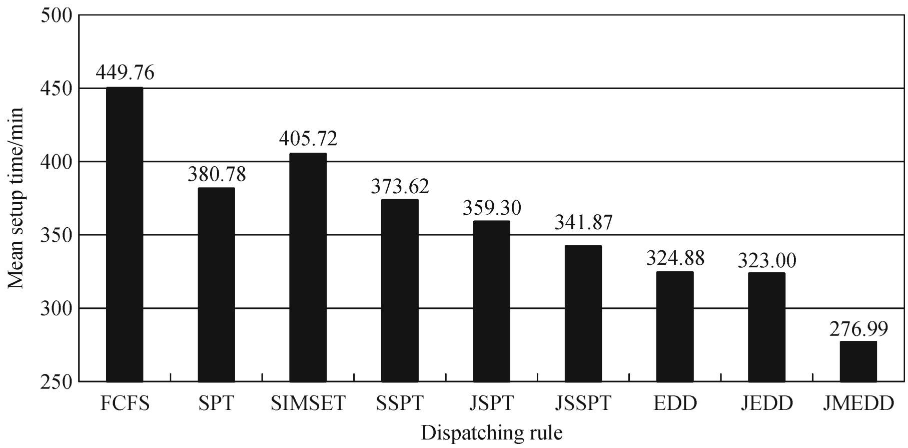

Fig. 9 Performance of dispatching rules for mean setup time

6.7 Total setups and Mean setup time

The total setups and mean setup time values for different dispatching rules are shown in Figs. 8 and 9**,** respectively. The figures clearly indicate that the JMEDD dispatching rule is the best performing dispatching rule. It is followed by JEDD, EDD, JSSPT, JSPT, SSPT, SPT, SIMSET and FCFS dispatching rules in that order. Thus, the JMEDD dispatching rule ranks first in minimizing both performance measures. As expected, the rules with job with similar setup, i.e., JSPT, JSSPT, JEDD, and JMEDD provides the smaller values than their respective counterparts for these performance measures.

7 Conclusions

The present work addresses an SDJS scheduling problem while considering sequence-dependent setup times. The performance of nine dispatching rules taken from literature is assessed. The experimental results indicate that SIMSET rule provides the best performance for mean flow time and number of tardy jobs measures. The JMEDD rule is the best performing dispatching rule for makespan, maximum flow time, mean tardiness, maximum tardiness, total setups and mean setup time performance measures.

The present work can be extended in a number of ways. The future research could be directed towards addressing the SDJS scheduling problems with sequence-dependent setup times and involving situations like buffer of limited capacity between machines, machine breakdown, batch mode schedule and external disturbances such as order-cancellation and job pre-emption. A better dispatching rule is needed to develop.

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