

New Routing Rules for Dynamic Flexible Job Shop Scheduling with Sequence-Dependent Setup Times

Mohamed A. Shalaby and Tamer F. Abdelmaguid
Department of Mechanical Design and Production
Faculty of Engineering, Cairo University, Giza 12613, Egypt

Zakaria Y. Abdelrasol
Industrial Engineering Department, Faculty of Engineering
Fayoum University, Fayoum, Egypt

Abstract

Flexible job shops are characterized by the existence of alternative –not necessarily identical- machines, which permits parts to have different alternative routes in the shop. In a dynamic scheduling situation in which jobs continuously arrive over time, part routing rules are needed to deal with such routing flexibility as much as sequencing rules which define the order by which parts are admitted to machines. This paper considers a dynamic flexible job shop scheduling in which there are sequence-dependent setup times and machines are prone to failure. Three new routing rules are proposed and compared with another two rules from the literature through simulation experiments.

Keywords

Dynamic scheduling, flexible job shops, sequence-dependent setup, machine breakdown, routing rules.

1. Introduction

In order to increase the responsiveness of manufacturing systems to market demand, and to maximize the utilization of manufacturing resources, the concept of flexible process planning was introduced. This was contemporary with the emergence of flexible manufacturing systems (FMSs). In flexible process planning, there is a set of alternative process plans for each part, and the decision of selecting a process plan or a part route is integrated with the scheduling decisions. There are two levels by which flexible process planning can be implemented. The first is the full flexibility level in which different process plans are generated for each part such that both the types of manufacturing processes and machine selection decisions are allowed to vary among the different process plans [1, 2]. The second level is the machine flexibility level in which each part route is fixed in terms of the types of manufacturing processes, while a set of alternative machines that can be used to perform a given manufacturing operation of a part is defined [3]. This paper focuses on the latter level of implementing flexible process planning.

Low-volume, high-variety production systems in which products are made to order and alternative machines exist are referred to as flexible job shops. The scheduling problem in those systems, referred to in the literature as flexible job shop scheduling problem (FJSP), is a generalization of the traditional job shop scheduling problem (JSP) in which there are no alternative machines. The JSP is known to be NP-hard [4], and so is the FJSP. Therefore, in a dynamic environment in which scheduling decisions need to be made quickly, it is not a practical option to look for an optimal solution for the FJSP. Rather, heuristic scheduling rules are more reasonable and convenient.

As indicated by Allahverdi et al. [5], most of the research work in scheduling either neglects setup times or include them in the processing times to simplify the scheduling problems. Nevertheless, the experience of many industries shows that setup time is a significant factor that cannot be neglected. Setup time may be sequence-dependent or sequence-independent, depending on whether its value varies with the sequence of operations being processed on the same machine. This paper is concerned with a dynamic version of the FJSP in which parts or manufacturing orders arrive continuously over time. Both sequence-dependent setup times and random machine breakdowns are

taken into consideration. Scheduling decisions are to be taken in a stochastic environment in which inter-arrival time, processing times, setup times and machine downtimes are random variables with known probability distributions. In the studied problem, there are two types of scheduling decisions to be made: (i) the routing of parts which determines to which machine a part will be moved next from among the set of alternative machines, and (ii) the sequencing of the parts waiting in queue in front of a given machine which determines the order by which parts will be processed.

To the best of our knowledge, there has not been any previous attempt to compare the routing rules when sequence-dependent setup times exist in dynamic flexible job shop scheduling. This paper contributes to the literature by developing new routing rules that are suitable for the situations in which sequence-dependent setup times exist in dynamic FJSP, and compare them with traditional routing rules from the literature via simulation experiments. The rest of this paper is organized as follows. A literature review of related research is presented in section 2. Section 3 provides a description of the considered routing rules. Section 4 provides details of the studied flexible job shop configuration and simulation model used in the experiments. In Section 5, the detailed experimental results are presented, followed by the conclusions and future research suggestions in Section 6.

2. Literature Review

The problems that are most relevant to this research are dynamic JSP, dynamic JSP with sequence-dependent setup times and dynamic FJSP. Sequencing or dispatching rules are developed to deal with all three problem types, while routing rules appear in the literature for dynamic FJSP as well as for the studied problem. Simulation is the dominant tool used to analyze and compare the different rules used in this kind of dynamic scheduling problems. For the dynamic JSP, the literature is full of different sequencing rules. Literature reviews and classifications for the different types of sequencing rules can be found in [6, 7]. For the case of dynamic JSP with machine breakdowns, an experimental comparison between different combinations of sequencing rules is provided in [8]. The literature review in this paper focuses on the sequencing rules developed for the dynamic JSP with sequence-dependent setup times which are basically the same rules that are applicable to the studied problem, in addition to the routing rules developed for the dynamic FJSP and the studied problem.

Historically, different sequencing rules have been developed for the dynamic JSP with sequence-dependent setup times. Wilbrecht and Prescott [9] developed three different sequencing rules that take into consideration the effect of sequence-dependent setup times; namely similar setup (SIMSET), shortest process and longest process. SIMSET rule is based on the idea of selecting the job with the shortest setup time regardless of its processing time; while the other two rules take into consideration the processing time. The new rules were compared with other selected conventional rules such as shortest processing time (SPT) and earliest due date (EDD) through a simulation experiment, and it was concluded that the SIMSET rule gives the best overall performance. Hershauer and Ebert [10] developed a sequencing rule that takes the form of a linear combination of weighted decision factors, where one of them is the sequence dependency. Flynn [11, 12] investigated the effect of sequence-dependent setup times on the performance of batch production systems, and employed a special sequencing rule, named repetitive lots (RL) procedure, to sequence lots. Kim and Bobrowski [13] studied the impact of sequence dependent setup time on the performance of job shop scheduling and illustrated the importance of taking into consideration the sequence-dependent setup time in the scheduling process. Kim and Bobrowski [14] simulated a nine-machine shop and compared two sequence-dependent sequencing rules, namely job of identical setup (JIS) and SIMSET, with other two traditional sequencing rules; namely shortest processing time (SPT) and critical ratio (CR). They concluded that setup times have a negative effect on the overall shop performance; however, this can be mitigated by using sequencing rules that take into consideration the sequence-dependent setup times.

Different objectives and more recent comparisons were presented in the literature. Missbauer [15] developed an approximate queuing model to demonstrate the benefits that can be achieved by using a setup-saving sequencing rule as related to reducing the work-in-process (WIP) inventory level. Sun and Noble [16] studied a dynamic JSP with sequence-dependent setup times in a deterministic environment and developed a heuristic approach based on the shifting bottleneck heuristic [17]. They compared it with a simple sequencing rule-based heuristic that implements three different sequencing rules including SIMSET. They demonstrated the effectiveness of their heuristic for the objective of minimizing the weighted sum of squared tardiness. Vinod and Sridharan [18] proposed five setup-oriented sequencing rules and compared them with seven sequencing rules from the literature through simulation experiments. From among the seven sequencing rules, five traditional rules do not count for setup times.

The other two rules are SIMSET and job with similar setup critical ration (JCR) which was proposed earlier in [19] for a deterministic case of the problem. Their results indicate that setup-oriented rules provide better performance than ordinary rules. The difference in performance between these two groups of rules increases with the increase in shop load and setup time ratio.

Routing rules are employed in dynamic FJSP systems. Wilhelm and Shin [20] investigated the influence that routing flexibility might have on the performance of FMSs. Their simulation results showed the benefit of using alternative machines and routing rules in reducing flow time, makespan and storage space, while increasing system utilization. Choi and Malstrom [21] evaluated combinations of seven sequencing rules and four routing rules using an FMS physical simulator for a line-type FMS with buffers. The simulation results indicated that the WINQ/SPT (work in queue/ shortest processing time) and WINQ/SLACK outperformed the other rules. O'Keefe and Kasirajan [22] investigated the interaction between nine sequencing and four routing rules in an FMS. They found that a combination of WINQ/(SIO/TOT) (shortest imminent operation time/total operation time) outperforms the other combinations for the weighted flow time performance measure. Chan et al. [23] presented a fuzzy approach for routing decisions. They compared it with both WINQ and SNQ (shortest number of jobs in queue) via simulation experiments.

Balancing workloads among machines has been the basis for few routing rules. Tunali [24] conducted a simulation study to investigate the benefit of employing flexible alternative routing plans as opposed to the traditional JSP fixed routes in flexible manufacturing systems (FMSs). The results demonstrated that in general, flexible routing plans reduce mean flow time and help in mitigating negative side effects caused by machine breakdowns. A heuristic, based on the concept of balancing the loads on machines and minimizing the AGV travel time from one machine to another, is used for routing decisions. Byrne and Chutima [25] studied a FJSP with full process planning flexibility. They presented several policies for selecting the next operation to be performed for a given part along with selecting its machine. They conducted simulation experiments on an eight-machine FMS, and concluded that the system performance is at its best using a policy which seeks to balance the workload between machines while also minimizing the distance travelled by the parts.

More recent routing rules have been developed. Chan [26] conducted a simulation study on a limited-buffer FMS to study the effect of three different routing policies combined with four different sequencing rules on the makespan, the average utilization, the average flow time and average delay at local input buffers. The studied routing policies are no alternative routings (NARs) which selects the route that gives the minimum total processing time for every part, alternative routings dynamic (ARDs) which selects the machine with the lowest workload, and alternative routings planned (ARPs) which optimizes the overall machine selection subproblem *a priori*. The simulation results suggest that the ARDs rule results in the best performance for all measures except the average delay at local buffers. Ozmutlu and Harmonosky [27] developed a threshold-based routing rule (TAR) which dynamically evaluates the benefit obtained in terms of waiting time until processing is greater than a certain threshold value for the system. The threshold value is empirically evaluated as a quadratic function of different system parameters. Although, TAR proved to generate better results in terms of the mean flow time when compared with WINQ and other routing rules from the literature, the determination of the threshold value is system-dependent and may not be generalized. Bilge et al. [28] studied a full flexibility situation for a hypothetical FMS. They proposed an adaptable fuzzy logic approach for part routing and compared it by simulation experiments with several routing rules from the literature. The results showed that the proposed fuzzy approach remains robust across different system configurations and flexibility levels, and performs favorably compared to the other algorithms.

As shown in the above literature review, several rules have been provided for both sequencing and routing of parts. For sequencing rules, Kim and Bowbrowski [13] reported that SIMSET provides the best performance for mean flow time when the setup times of jobs are sequence dependent. Nevertheless, Vinod and Sridharan [18] later showed that SSPT is better than SIMSET for mean flow time. They also showed that SSPT is performing better for the mean flow time and mean tardiness measures against many of setup-oriented rules and ordinary rules. Since the current study focuses on developing new routing rules, we opt to use the SSPT rule in the developed simulation experiments to conduct sequencing decisions on machines. For the routing decisions, the literature review showed that WINQ is one of the most commonly reported rules for alternative machine selection [27, 28]. Furthermore, there exist some routing rules that are built on the idea of balancing the loads on machines. In the current study both WINQ and a machine load-balancing rules are used to compare the new proposed routing rules.

3. Routing Rules

In the current study, five routing rules are investigated. The first routing rule is the least work in next queue (Winq), which was initially proposed in [21]. In Winq rule, from among the alternative machines, the machine with the least number of parts waiting in queue is selected, and tie-breaking is arbitrary. This routing decision is applied here regardless of the status of the machine-down or running. The second rule is referred to here as balanced loads (BL). This rule is based on the idea proposed in [24] which routes parts such that the loads among machines is maintained at equal levels. In BL rule, the total working and downtime hours of each machine are recorded, and the machine with the least total is selected from among the alternative machines.

Three new routing rules are proposed; two of them are modifications of Winq and the last is designed to account for both expected setup and waiting times in queues. These rules are:

- **Winq+BD**: This rule is an extension to Winq which takes into consideration the machine status. In this rule, both the queue length and the machine status (down or running) are monitored to decide which machine among the alternatives will process the next operation. If a machine has the shortest queue but is currently down, the job neglects this machine and search for another one having a shortest queue among the working machines. In case all the alternative machines are failed or all the alternative machines are not failed, the one with the shortest queue length will be selected.
- **MWinq**: This is the modified work in next queue (MWinq) rule. This rule can be considered as an extension to Winq in which the machine breakdown time is translated into an equivalent number of jobs waiting in queue. This is done by dividing the average remaining time expected to finish the repair by the average processing and setup times per part of the operations that will be conducted on that machine. Then, the machine with the least value of the summation of both the current number in queue and the equivalent number of jobs waiting in queue is selected, while tie-breaking is arbitrary.
- **SWST**: This rule is the shortest waiting and setup time (SWST) rule which combines waiting, setup and remaining repair times for the alternative machines. It evaluates the total estimated waiting time at each machine as multiplying the queue length by the average time required for setups and processing per job, this term is then added to the expected mean setup time at this machine. Then, the machine with the lowest total is selected.

4. System configuration and simulation model

The flexible job shop model considered in this research is comprised of ten machines and 20 part types. The processing sequence of each part type is fixed. Alternative machines are defined for a subset of operations in the sequence. The full definition of each part's processing sequence and the mean processing times of operations are selected from the benchmark problems provided in [29] which were developed for the static case of the FJSP. The following is a list of the assumptions considered in the simulation model.

- (1) Each machine can perform only one operation at a time.
- (2) Whenever an operation starts, it cannot be preempted.
- (3) The machines are not technologically similar and there is only one machine of each type.
- (4) Arrival times and due dates are only known in time and not *a priori*.
- (5) Machine setup for a given job is dependent on the preceding job on the same machine.
- (6) Machine breakdowns are allowed. Time between failures is a random variable.
- (7) If an operation is interrupted due to machine breakdown, it presumes its remaining processing time after repair.
- (8) There is sufficiently large storage space at each machine to accommodate all arriving jobs.

The output of the simulation model is designed to present results for three performance measures, namely mean flow time (F), mean tardiness (T), and average utilization (U). There are four main factors considered in the designed simulation experiments, and two levels (low and high) for each factor are defined. Thus, a 2^4 full factorial design is applied. The factors are:

- (1) *Traffic intensity* (TI) or *shop load*: This factor reflects the loading level of the shop.
- (2) *Flexibility ratio* (FR): This factor is well-known in the literature of static FJSP [29]. It represents the average number of alternative machines per operation. It is calculated as the total number of alternative machines for all operations divided by the total number of operations.
- (3) *Setup time ratio* (SR): This factor represents the relative magnitude of average setup time as compared to the average processing time.

- (4) *Breakdown level (BL)*: This factor is the ratio between the downtime (MTTR) to the uptime (the sum of MTTR and MTBF) of the machines.

Table 1 provides details about the two levels used for each factor and how these levels are realized in the simulation model.

Table 1: Factors and values for each factor level

Factor	Levels		Realization method
	Low	High	
TI : Traffic Intensity (%)	50	90	By controlling the mean inter-arrival time of the parts to the shop as related to the mean processing time of all operations.
FR : Flexibility Ratio	1.15	4.5	Two problem sets from [29] are selected. The first is problem la26 from the <i>edata</i> set with the low level, and the second is problem la26 from the <i>vdata</i> set with the high level.
SR : Setup time Ratio (%)	30	130	The percentage value at each level is used to generate separate sequence-dependent mean setup time matrix for each machine.
BD : Breakdown level (%)	0	20	By controlling the values of mean time to failure and mean time to repair for all machines in the shop.

The processing time of operations on the various machines is generated as follows. A processing time matrix is used for the mean processing time for all operations. The mean processing time in the matrix is obtained from the data sets provided in [29]. Using the mean processing times, the processing time random values are generated in simulation runs from a normal distribution, where the mean is given by the matrix and variance is selected to be 10% of the mean value. It has been observed in the literature that in job shops, the distribution of the job arrival process closely follows the Poisson distribution [30]. Hence, the time between arrivals of jobs is exponentially distributed. The mean of this exponential distribution is determined for a specified traffic intensity percentage and the processing requirements of the jobs. Thus, the mean inter-arrival time of jobs is obtained using the following relationship.

$$a = \frac{\mu_p \mu_g}{Um} \quad (1)$$

where a is the mean inter-arrival time, μ_p the mean processing and setup time per operation, μ_g the mean number of operations per job, U the traffic intensity (in %) value and m the number of machines in the shop.

The setup times for parts on machines are generated as follows. A separate setup time matrix is generated for each machine. The mean setup times in the matrix are generated by normal distribution with a mean, which related to the setup time ratio (SR) and a variance considered as 10% of the mean value. Using the mean setup times, the actual values of the setup times are generated. A normal distribution is used to represent the setup-time variation that reflects the variation in skills of setup crews and other 'noise' in the system. This approach of generating sequence-dependent setup values in the simulation model is similar to Kim and Bobrowski [14].

Due-date assignment is based on the number of operations, the average setup time, and the average processing time when a job arrives at the shop. Flow-time allowance is calculated by assuming that each operation requires a setup change. The total work content (TWK) method has been used widely for due date assignment [18]. Using TWK method, the due date of each job is set equal to the sum of the job arrival time and a multiple of the total job processing time. Thus, the due date of a job is determined using the following equation.

$$d_i = a_i + k(n_i(p + \mu_s)) \quad (2)$$

where d_i is the due date of job i , a_i the arrival time of job i , k the due date tightness factor, n_i the number of operations of job i , p the overall mean processing time, and μ_s the overall mean setup time.

Downtime is expressed by three terms; percentage downtime (PDT) or the breakdown level, mean time to repair (MTTR), and mean time between failures (MTBF). PDT is the ratio of MTTR to the sum of MTTR and MTBF. As shown in table 1, two values of breakdown levels 0% and 20% were considered in the present study. MTTR is the average time to repair a machine and bring it back to acceptable operating condition. It includes the actual time spent on arranging spares and resources and then restoring the machine to make it operation worthy. MTTR is considered as $5 \times \bar{p}$, where $\bar{p}$ is the average processing time of all parts. For MTBF, it is pertinent to note that the frequency of breakdown is inversely proportional to the mean time between failures. Hence, for a given PDT, it will be inversely proportional to the MTTR. The actual time between failures is expressed by exponential distribution with mean of MTBF = (MTTR – (PDT * MTTR)) / PDT.

5. Results and Analysis

The experimental design consists of $2^4 = 16$ different settings and five replications are performed for each setting. The simulation for each replication is run for 1200 simulated 8-hour days. Different random number seeds were used to prevent correlation between the cells of the factorial experiment. The system became stable after 200 simulated days. The first 200 days observations were discarded to remove the effect of the start-up condition, which was an idle and empty state. The outputs for the remaining 1000 days are used for the computation of the performance measures.

To investigate the performance of the proposed rules against WINQ rule, the relative percentage deviation (RPD) is evaluated for each performance measure. The value of $RPD(\pi)$ is defined as the difference between the performance measure π obtained by a routing rule and the performance measure obtained by WINQ for the same problem setting divided by the latter and multiplied by 100. For both the mean flow time and the mean tardiness, a negative RPD indicates a better performance obtained by a routing rule as compared with WINQ. For the average utilization performance measure, this condition is reversed.

Table 2 presents a comparison between the results obtained by the proposed routing rules and the results of WINQ for the mean flow time. A result that is better than, or at least equal to, the WINQ result is emphasized by a bold font. The three proposed rules WINQ+BD, MWINQ and SWST produced better results, or at least equal to, the WINQ results for all combinations. The proposed SWST rule produced better results for 14 out of the 16 combinations, and the overall average is better than the average of WINQ results by 12%.

Table 2: Routing rules comparison table for mean flow time (F)

Comb. #	TI	FR	SR	BD	WINQ	BL		WINQ+BD		MWINQ		SWST	
					F	F	RPD(F)	F	RPD(F)	F	RPD(F)	F	RPD(F)
1	H	H	H	H	25180	22391	-11.1	24510	-2.7	24742	-1.7	17611	-30.1
2	H	H	H	L	5351	7011	31	5351	0	5351	0	3169	-40.8
3	H	H	L	H	1582	8494	436.9	1475	-6.8	1474	-6.8	1353	-14.5
4	H	H	L	L	1017	1612	58.5	1017	0	1017	0	870	-14.5
5	H	L	H	H	14589	15636	7.2	15257	4.6	14546	-0.3	14415	-1.2
6	H	L	H	L	4322	4567	5.7	4322	0	4322	0	4326	0.1
7	H	L	L	H	3366	3980	18.2	3345	-0.6	3313	-1.6	3326	-1.2
8	H	L	L	L	1115	1146	2.8	1115	0	1115	0	1114	-0.1
9	L	H	H	H	2563	7493	192.4	2408	-6.1	2407	-6.1	2028	-20.9
10	L	H	H	L	1737	2569	47.9	1737	0	1737	0	1316	-24.2
11	L	H	L	H	1308	3418	161.3	1152	-11.9	1152	-11.9	1005	-23.1
12	L	H	L	L	876	1033	17.9	876	0	876	0	726	-17.2
13	L	L	H	H	3908	4324	10.6	3860	-1.2	3858	-1.3	3849	-1.5
14	L	L	H	L	1863	1906	2.3	1863	0	1863	0	1843	-1.1
15	L	L	L	H	1887	2106	11.6	1862	-1.3	1860	-1.4	1858	-1.5
16	L	L	L	L	846	852	0.7	846	0	846	0	841	-0.6
Average					4469.4	5533.6	62.1	4437.3	-1.6	4404.9	-1.9	3728.1	-12.0

Table 3: Routing rules comparison table for mean tardiness (T)

Comb. #	TI	FR	SR	BD	WINQ	BL		WINQ+BD		MWINQ		SWST	
					T	T	RPD(T)	T	RPD(T)	T	RPD(T)	T	RPD(T)
1	H	H	H	H	23725	20936	-11.8	23055	-2.8	23287	-1.8	16447	-30.7
2	H	H	H	L	3896	5556	42.6	3896	0	3896	0	2006	-48.5
3	H	H	L	H	290	7040	2327.6	220	-24.1	220	-24.1	173	-40.3
4	H	H	L	L	1.85	303	16278.4	1.85	0	1.85	0	1	-45.9
5	H	L	H	H	13134	14181	8	13802	5.1	13091	-0.3	12960	-1.3
6	H	L	H	L	2867	3112	8.5	2867	0	2867	0	2871	0.1
7	H	L	L	H	1934	2538	31.2	1915	-1	1882	-2.7	1896	-2
8	H	L	L	L	39	53	35.9	39	0	39	0	40	2.6
9	L	H	H	H	1111	6038	443.5	957	-13.9	956	-14	619	-44.3
10	L	H	H	L	299	1121	274.9	299	0	299	0	59	-80.3
11	L	H	L	H	142	1986	1298.6	74	-47.9	74	-47.9	48	-66.2
12	L	H	L	L	0	17	---	0	---	0	---	0	---
13	L	L	H	H	2453	2869	17	2405	-2	2404	-2	2395	-2.4
14	L	L	H	L	430	472	9.8	430	0	430	0	413	-4
15	L	L	L	H	555	736	32.6	537	-3.2	534	-3.8	535	-3.6
16	L	L	L	L	0.5	0.9	80	0.5	0	0.5	0	1	100
Average					3179.8	4184.9	1391.8	3156.1	-6.0	3123.8	-6.4	2529.0	-17.8

Table 4: Routing rules comparison table for average utilization (U)

Comb. #	TI	FR	SR	BD	WINQ	BL		WINQ+BD		MWINQ		SWST	
					U	U	RPD(U)	U	RPD(U)	U	RPD(U)	U	RPD(U)
1	H	H	H	H	80.4	71	-11.7	80.1	-0.4	80.1	-0.4	80.1	-0.4
2	H	H	H	L	99.6	88.6	-11	99.6	0	99.6	0	98.5	-1.1
3	H	H	L	H	61.7	58.4	-5.3	61.7	0	61.7	0	60	-2.8
4	H	H	L	L	61.6	61.1	-0.8	61.6	0	61.6	0	58.6	-4.9
5	H	L	H	H	77.4	75.7	-2.2	77.2	-0.3	77.4	0	77.4	0
6	H	L	H	L	93.6	92.1	-1.6	93.6	0	93.6	0	93.5	-0.1
7	H	L	L	H	60.6	60.1	-0.8	60.6	0	60.6	0	60.5	-0.2
8	H	L	L	L	61.9	61.9	0	61.9	0	61.9	0	61.8	-0.2
9	L	H	H	H	59.7	51.1	-14.4	59.7	0	59.7	0	54.9	-8
10	L	H	H	L	59.7	57	-4.5	59.7	0	59.7	0	51.3	-14.1
11	L	H	L	H	34.1	33.7	-1.2	34.1	0	34.1	0	32.3	-5.3
12	L	H	L	L	34	34	0	34	0	34	0	31.6	-7.1
13	L	L	H	H	55.8	54.7	-2	55.9	0.2	55.9	0.2	55.6	-0.4
14	L	L	H	L	59.2	58.9	-0.5	59.2	0	59.2	0	58.8	-0.7
15	L	L	L	H	34.3	34.2	-0.3	34.3	0	34.3	0	34.2	-0.3
16	L	L	L	L	34.6	34.5	-0.3	34.6	0	34.6	0	34.4	-0.6
Average					60.5	57.9	-3.5	60.5	0.0	60.5	0.0	59.0	-2.9

Table 3 presents a comparison between the results obtained by the proposed routing rules and the results of WINQ rule for the mean tardiness. The three proposed rules WINQ+BD, MWINQ and SWST mostly produced better or at least equal to the WINQ results. The SWST rule produced better results for 11 out of the 16 combinations, and the overall average is better than the average of WINQ results by 17.8%. Table 4 presents a comparison between the results obtained by the proposed routing rules and the results of WINQ rule for the average utilization. The performance of WINQ+BD and MWINQ rules is comparable to WINQ. The performance of the SWST rule is slightly worse than WINQ by 2.9% on average. For all performance measures, the BL rule is always the worst.

In order to study the effect of the four design factors on the performance of the shop, and to compare the relative performance of the routing rules, the main effects plots are drawn in figures 1 to 3. In these figures, the two routing rules, WINQ and SWST are included in the list of factors in order to illustrate the significance of using the SWST

rule as compared with the WINQ, since the SWST has shown the best performance in tables 2 and 3. As shown in figures 1 to 3, and the ANOVA results at 95% confidence level, the performance of the SWST rule is significant as compared to the WINQ rule for both the mean flow time and the mean tardiness. While for the average utilization, the difference between the two rules is not significant. It is also worth noting that the flexibility ratio does not have a significant effect on the performance measures as compared to the other factors.

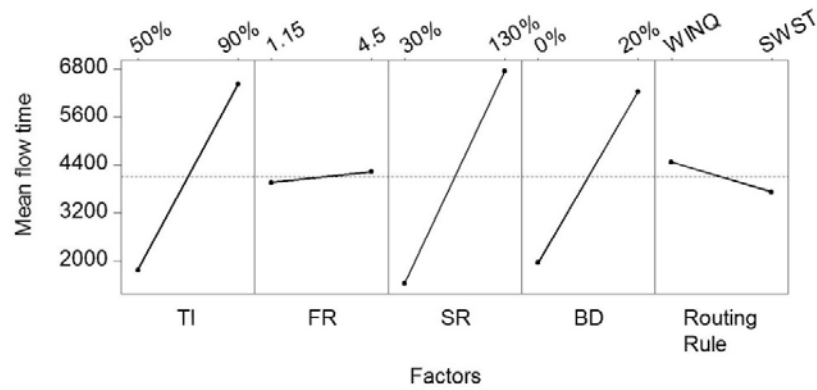


Figure 1: Main effect plots for the mean flow time

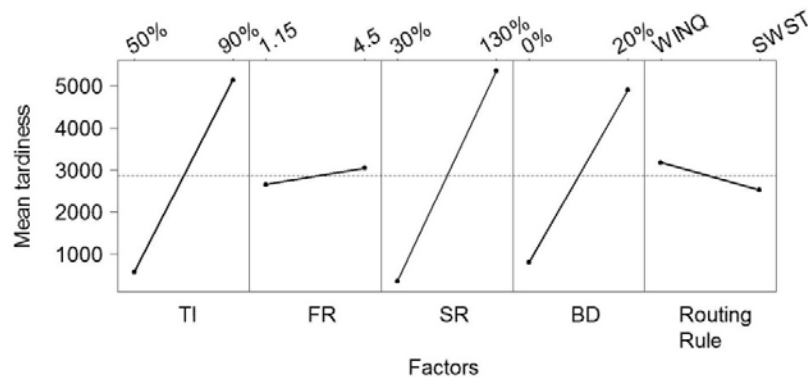


Figure 2: Main effect plots for the mean tardiness

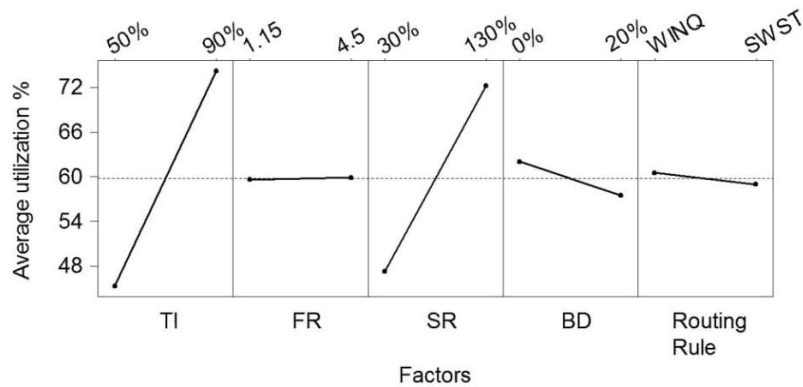


Figure 3: Main effect plots for the average utilization

6. Conclusions and Future Research

In this paper, the dynamic flexible job shop scheduling problem with sequence-dependent setup times and machine breakdowns is addressed. Five different routing rules are compared experimentally. These rules include two routing rules from the literature of dynamic FJSP (WINQ and BL), two new routing rules that are modifications to the WINQ rule (WINQ+BD and MWINQ) and inherently consider setup times and the machine downtime, and one new routing rule (SWST) that also counts for setup times and machine downtimes. Simulation experiments were conducted to compare the routing rules in terms of three performance measures, namely mean flow time, mean tardiness and average utilization. Four main factors are taken into consideration in the design of simulation experiments which reflects the major characteristics of flexible job shops that can be encountered in reality. These factors are traffic intensity or shop load, flexibility ratio, setup time to processing time ratio and machine breakdown level.

The simulation results show that the SWST rule outperforms the other rules for the mean flow time and mean tardiness performance measures. While, for the average utilization, the WINQ, WINQ+BD and MWINQ rules result in the best performance and the differences between them and the SWST rule are minor. These results emphasize the importance of designing suitable routing rules that take into consideration the effect of setup times for dynamic flexible job shops.

As part of future extensions to this research, other components in the flexible job shop system that may affect the job routing decisions such as the material handling equipment (MHE) can be considered. Hybrid job routing and MHE scheduling rules can be developed to address the simultaneous job sequencing/routing and MHE scheduling decisions. Another consideration related to system configuration is the study of the case in which there are limited storage spaces or buffer sizes at the machines. Such a situation can largely affect the job routing and sequencing decisions.

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