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# Dispatching rule-based algorithms for a dynamic flexible flow shop scheduling problem with time-dependent process defect rate and quality feedback

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**Abstract**

We consider a three-stage dynamic flexible flow shop scheduling problem in which jobs of multiple types arrive dynamically over time, a quality feedback mechanism is present, and the setup timing and the process defect rate are closely related. At each machine in the second stage, a sequence-independent setup operation is necessary to changeover job types. Once a setup is done for a job type at a machine, the defect rate for the job type at the machine is reset to a low and stable phase which will be maintained for a predetermined time periods. However, after the phase, it turns to a relatively high and unstable phase. At the final inspection stage, jobs are inspected and the quality feedback will be given to the previous stage when the accumulative defect rate of each job type exceeds a certain tolerance level. To cope with the dynamic nature of the flexible flow shop scheduling problem, we propose two dispatching rule-based scheduling algorithms which consider the quality feedback as well as the real time shop information for the objectives of maximizing the quality rate and the mean tardiness of the finished jobs. The results of a series of simulation experiments will be given to evaluate the performance of the suggested algorithms. Since there have been few research on the shop floor scheduling problems with quality feedback, we expect that this research will make a contribution to the development of a practical real time scheduling methodology in multi-stage production systems with the consideration of the imperfect process quality.



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*Keywords:* Scheduling; Dynamic flexible flow shop; Time-dependent defect rate; Setup; Quality feedback; Dispatching rule

## 1. Introduction

Scheduling, one of the most important decision making process in the operation of manufacturing systems, is a series of activities to allocate available resources to jobs by determining the exact production schedules for achieving a set of objectives. The real life scheduling environment is extremely complicated due to the dynamic nature of manufacturing systems, such as dynamic arrival of customer orders, random defect rate, unexpected occurrence of disruptions, changing priorities of jobs, and so on. To ensure the sustainability in this environment, generating effective production schedules in real time is the key in the operational aspect.

In this paper, we focus on a scheduling problem in the dynamic flexible flow shop (DFFS) which is one of the major manufacturing system configurations. The DFFS under consideration is composed of three sequential production stages, and there are multiple parallel machines in one of the stages. Jobs arrive continuously over time, and a setup operation is required to changeover job types at each one of the parallel machines.

The most interesting point in the DFFS scheduling problem is that the defect rate depends on the setup timing, that is, the random defect rate of each job follows a normal distribution with the mean and standard deviation depending on the setup timing. If the elapsed time after a setup becomes longer, the defect rate becomes higher and unstable because the mean and standard deviation become larger according to the elapsed time. This kind of quality problem usually occurs in manufacturing processes with process parameters sensitively fluctuating by the uncontrollable or hard-to-control factors, such as mechanical stress, vibrations, variations in thermal conditions and impurities accumulated. We assume a two-phased setup time-dependent defect rate, one with a low and stable defect rate and the other with a high and unstable defect rate, in this research.

For the solution approach, a general dispatching rule-based scheduling algorithm is proposed in this paper because dispatching rules are very effective techniques for dynamic and flexible manufacturing systems. We consider two distinct objectives, maximizing the quality rate and minimizing the mean tardiness of jobs, because each of them is one of the most important performance measures in terms of production efficiency, cost and the customer satisfaction.

This paper is organized as follows. A literature review is given in the next section, and the DFFS scheduling problem considered in this research is introduced in detail in section 3. Then, two dispatching rule-based scheduling algorithms are proposed in section 4, and the result of the computational experiments is presented in section 5. The final section is devoted to conclusions with the future research directions.

## 2. Literature Review

As surveyed by Ruiz and Vázquez-Rodríquez [1] and Ribas *et al.* [2], a number of research papers have focused on the flexible flow shop (FFS) scheduling problems. However, there have been a few studies on the dynamic version of the FFS, i.e., DFFS, with the mean tardiness objective. Kianfar *et al.* [3] develop four dispatching rules for a DFFS with the decision problem for accepting or rejecting new jobs for the objective of minimizing the sum of tardiness and rejection costs. Kia *et al.* [4] propose several hybrid heuristic algorithms in which dispatching rules and construction heuristics are combined for a DFFS with sequence-dependent setup times for the objectives of minimizing the mean tardiness and flowtime. Choi *et al.* [5] develop a real time scheduling algorithm with a decision tree selecting one of multiple dispatching rules for a flexible flow shop with reentrant flows for the objectives of the throughput, the mean flow and tardiness, and the number of tardy jobs. Kianfar *et al.* [6] propose a neighborhood search-based dispatching rule and a hybrid genetic algorithm for a DFFS with sequence-dependent setup times for the objective of minimizing the mean tardiness.

There are many dispatching rules focusing on setups, as surveyed by Pickardt and Branke [7]. Among those, the apparent tardiness cost with setups (ATCS) rule developed by Lee *et al.* [8] for single machine scheduling problems, which is an extended version of the apparent tardiness cost (ATC) rule developed by Vepsalainen and Morton [9], showed the best performance in terms of the mean tardiness. Lee and Pinedo [10] and Yang *et al.* [11] propose the modified versions of ATCS for identical parallel machines and for flexible flow shop scheduling problems, respectively. For identical parallel machines scheduling problems with setup times and ready times, Pfund *et al.* [12] propose an extended version of ATCS with the consideration of the ready times of jobs.

A number of research papers consider the scheduling problems with the process quality or yield. Lee and Yano [13], Akella *et al.* [14], Sloan and Shanthikumar [15], Kazaz and Sloan [16], and Raviv [17] consider the deteriorating process yields in single or multi-stage manufacturing systems. However, the scope of these papers does not include the shop floor scheduling problems. Meanwhile, there has been one research paper of Ko *et al.* [18] for shop floor scheduling problems with the consideration on the process quality or yield. For a dynamic non-identical parallel machines scheduling problem with sequence-dependent setups, they developed ATCSQ rule, an extended version of ATCS of Lee and Pinedo [10], in which a quality-related priority function is additionally considered. In this rule, the real time quality measurement data is used to calculate the process capability index for each job and machine pair, and this index is used to compute the normalized quality priority value for each pair. In terms of minimizing the mean tardiness of jobs, ATCSQ shows the best performance while ensuring the predetermined quality rate of jobs.

## 3. Problem Definition

The flexible flow shop under consideration is composed of three serial stages with a single machine, $M$ identical parallel machines and a single inspection machine at stage-1, 2 and 3, respectively. The notation being used throughout this paper is given as follows.

Jobs arrive dynamically at the first stage over time, and their inter-arrival times are exponentially distributed with the mean $\mu = \left(\alpha \cdot \bar{s} + \bar{p}_2\right)/M$ . When each job $j$ arrives at time $a_j$, its job type $f$ and due date $d_j$ is determined randomly by the equal ratio and by a uniform distribution with a range of $[a_j + p_f, a_j + \beta \cdot p_f]$, respectively. Note that $\alpha$, $\beta$ and $p_f$ are the inter-arrival time and due date ranging parameters and the total processing time of type-$f$ jobs. Each job should be processed sequentially from stage-1 to stage-3 at the single machine or one of the multiple machines in each stage. The processing or inspection time of stage-$i$ of type-$f$ jobs is defined as $p_{f,i}$ and assumed to be deterministic. Note that the inspection time of stage-3 of all jobs of all types is assumed to be identical.

Jobs are processed first at the single machine of stage-1. When each job is completed at stage-1, it is transferred to the common queue of stage-2 to be processed next at one of the machines in stage-2. Then, at each time when a machine becomes available, the job with the highest priority value is selected among all jobs in the queue and processed at the machine. Unlike the stage-1, a deterministic sequence-independent setup time $s_f$ should be inserted to process a type-*f* job directly after jobs of different type at any machine of stage-2. Once a setup is completed for type-*f* jobs at time $t_{f,k}$ at machine *k*, the defect rate for type-*f* jobs at the machine is reset to the *phase-I* with a low and stable defect rate, and this phase will be maintained for a predetermined $\Delta_f$ time periods of job type-*f* from $t_{f,k}$, where $\Delta_f = \gamma_f\left(\bar{s}+\bar{p}_2\right)$ in which $\bar{p}_2$ is the average processing time at stage-2 for all job types and $\gamma_f$ is the phase-I duration ranging parameter with a positive integer value. Note that $\Delta_f$ is assumed to be unknown in advance and only depends on the job type because the machines in stage-2 are identical. And then, the phase-I is turned to the *phase-II* with a relatively high and unstable defect rate, and this phase will be maintained until the next setup is done for any job type at the machine.

Once a job is completed at stage-2, it is transferred to the queue of stage-3 to be inspected at the single inspection machine. As mentioned before, the defect rate of each job to be processed on a machine in stage-2 is time dependent, i.e., dependent on the completion time of the latest setup for the job type on that machine as well as the completion time of the job on that machine. In this research, the defect rate for job *j*, $R_j$, is determined as the following rule. If $C_{j,2} - t_{f,k} \le \Delta_f$ is satisfied, i.e., the time duration between the latest completion time of the setup for type-*f* at machine *k* of stage-2 and the completion time of job *j* at stage-2 ($C_{j,2}$) is not larger than $\Delta_f$ (when job *j* had been processed at machine *k*), $R_j$ is obtained from a normal distribution with the mean $\mu^{P1}{}_f$ and standard deviation $\sigma^{P1}{}_f$ for phase-I. Otherwise, $R_j$ is obtained from a normal distribution with the mean $\mu^{P2}{}_f$ and standard deviation $\sigma^{P2}{}_f$ for phase-II. After each job is inspected, one can decide that the job will be successfully completed if its defect rate is not larger than the predetermined tolerance level $\tau$. On the other hand, each job will be scrapped if its defect rate is larger than $\tau$. Note that the inspection time $p_3$ is identical for all jobs of all types and set to relatively shorter than the processing times of jobs at the previous stages.

At stage-3, in order to give quality feedback to stage-2, the defect rate of each job is also utilized to calculate the accumulative defect rate (ADR) for each job type at each machine of stage-2. The ADR for job type-*f* at machine *k*, $R_{f,k}$, is the average defect rate of type-*f* jobs that had been processed at machine *k* of stage-2 only after the latest setup for type-*f* at machine *k*. Note that the ADR for each type at each machine is reset to zero and calculated again whenever a setup operation is performed at that machine. When the ADR for type-*f* at machine *k* exceeds $\tau^A$, i.e., the tolerance level for ADR, a quality feedback for job type-*f* will be sent to machine *k* at stage-2 if its setup status has not been changed. Once each machine receives a quality feedback, a setup operation should be done at the machine to process any job even if its type is identical to the currently setup type. This is because the status of machine with a quality feedback is thought to be unstable in terms of process quality.

There are some additional assumptions in this research. Each machine can process at most one job at a time, and preemptions are not allowed. The transfer time of jobs between stages is not considered, and the capacity of each queue is assumed to be unlimited. No time delay exists to send the quality feedback from stage-3 to stage-2.

We consider the average quality rate as well as the mean tardiness of the finished jobs as the objectives of this research. These two objectives are very important performance measures in practice in terms of the quality-related production cost, the customer satisfaction, and the operation efficiency. In this paper, the quality rate of the finished jobs and the mean tardiness are defined as the ratio of the successfully finished jobs to the total number of finished jobs and the sum of tardiness values of the finished jobs divided by the total number of finished job, respectively. To find effective production schedules in real time, we propose two dispatching rule-based scheduling algorithms with the consideration of the defect rate as well as the due date of jobs.

## 4. Dispatching Rules

In this section, we give the details of the scheduling algorithms suggested in this research which is based on the general dispatching rule-based scheduling procedure. When a machine becomes available at a certain stage, jobs waiting in the queue of the stage are prioritized by using a dispatching rule. Then, the job with the highest priority is selected and scheduled at the machine. In case that when a new job arrives at each stage, the same scheduling procedure will be performed if there is any available machine in the stage.

As mentioned before, ATCSQ uses the real time quality measurement data to compute the quality-related priority values of jobs. For the effective use of ATCSQ, it is strongly required to use the reliable real time quality rate of jobs. However, in case that the time duration of phase-I defect rate is not long enough to obtain the reliable quality measurement results, any dispatching rule using this measurement data may not be work effectively as expected. Also, it should be considered that the real time quality feedback system is not usually being used in practice. Moreover, it may not be possible to obtain the quality information as soon as each process step is completed since the inspection function for each process step is not integrated into the process itself in many practical situations, especially in the machining shops. In this situation, there exists a time gap between the completion time of each process step and the completion time of the corresponding inspection step, and the quality information is not up-to-date although it is transferred in real time.

To cope with the characteristics of the DFFS under consideration, we develop an independent prioritizing module, named the *time-dependent quality module* (*TQ1*), which uses the real time information on the elapsed time after the latest setups instead of the quality measurement data. At stage-2, when machine $k$ becomes available at time $t$, the TQ1 value for each job of type-$f$ at machine $k$ is calculated by the following equation,

$$TQ^{1}_{k,f,t} = \left( e^{\frac{-D_{k,f}}{\rho \cdot D_{\max}}} + \sum_{l=1, l\neq k}^{M} e^{\frac{-(D_{\max} - D_{l,f})}{\rho \cdot D_{\max}}} \right) / M \tag{1}$$

In above equation, the elapsed time after the latest setup at machine $k$, $D_{k,f}$, is set to $(t - t_{f,k})$ if machine $k$ is currently set for job type-$f$ or 0 otherwise. Also, $D_{l,f}$ is set to $(t - t_{f,l})$ if machine $l$ is set for job type-$f$ or $D_{\max}$ otherwise, where $D_{\max} = \max[\varepsilon, \max_{l=1,\ldots,M}\{D_{l,f} \mid l \neq k\}]$ and $\varepsilon$ is a small positive value for preventing the denominator in the equation from being zero. Note that $\rho$ is a scaling parameter which should not be smaller than 1. If there are several machines set for a job type with different elapsed times, the difference in the values of the exponential terms becomes smaller if $\rho$ is close to 1 and larger otherwise. From equation (1), the TQ1 value or priority for jobs of a certain type will become higher if machine $k$ is set for that type, the elapsed time after the setup of machine $k$ is short, the other machines are rarely setup for that type, and the average elapsed time of the other machines is long.

As another independent prioritizing module, the *time dependent quality module II* (*TQ2*) which also uses the real time information on the elapsed time after the latest setups is developed in this research. The main difference between TQ1 and TQ2 is that we focus only on the machines with the elapsed time after the latest setups are not longer than a predetermined time periods, i.e., the phase-I defect rate duration estimating parameter $\pi$. This is intended to preserve the setup status for those machines as much as possible for ensuring the quality rate of jobs. The information on the real time queue status is also used in TQ2 unlike TQ1. At stage-2, when machine $k$ becomes available at time $t$, the TQ2 value for each job type-$f$ is calculated by the following equation,

$$TQ^{2}_{f,t} = A_{f,t} \cdot \frac{|n_{f,t}|}{|n_t|} - \omega \cdot \frac{|G_{f,t}|}{M} \tag{2}$$

In equation (2), $n_t$, $n_{f,t}$, $G_{f,t}$, and $G$ denote the set of all jobs and type-$f$ jobs waiting in the queue of stage-2, the set of stable machines that are setup for job type-$f$ and the elapsed times after setup are not longer than $\pi$ at time $t$, and the set of all stable machines in $G_{f,t}$ for all job types, respectively. Also, $A_{f,t}$ denotes the mean of ATCS values for all type-$f$ jobs waiting in the queue at time $t$ as shown in equation (3) where $\bar{s}$, $k_1$ and $k_2$ are the average setup time at stage-2 for all job types and the scaling parameters being used in ATCS, respectively. In addition, $\omega$ is a scaling parameter with a value from 0 to 1, and $|x|$ denotes the cardinality of set $x$. Note that for a certain job type without any waiting job, TQ2 value for the job type is set to a big negative value.

$$A_{f,t} = \left( \sum_{j \in n_{f,t}} \frac{1}{p_{f,2}} \cdot e^{\frac{-\max\{d_j - t - p_{f,2}, 0\}}{k_1 \cdot \bar{p}_2}} \cdot e^{\frac{-s_f}{k_2 \cdot \bar{s}}} \right) / |n_{f,t}| \tag{3}$$

The scheduling procedure of TQ2 is presented in Procedure 1. In the procedure, the job type-$f^*$ with the maximum TQ1 value is selected because for the type-$f^*$ jobs, the number of stable machines setup for type-$f^*$ is supposed to be not enough when considering the priority based on ATCS and the number of waiting jobs of type-$f^*$. If the status of machine $k$ is unstable or if it is stable but already setup for job type-$f^*$, one among the waiting job of type-$f^*$ is selected and processed. In case that the status of machine $k$ is stable but not setup for job type-$f^*$, it selects a job of type-$f^*$ if all machines are stable or a job of type-$f_k$ is selected based on the assumption that jobs of type-$f^*$ may have another chance to be selected later by other unstable machines. Note that $f_k$ denotes the index of job type which is currently setup at machine $k$.

**Procedure 1**. *Time dependent quality module II* (*TQ2*)

*Step* 1. Select the job type-$f^*$ with the maximum TQ2 value among all job types. If machine $k$ belongs to $G$, go to step 2. Otherwise, go to step 5.

*Step* 2. If machine $k$ is setup for job type-$f^*$, go to step 5. Otherwise, go to step 3.

*Step* 3. If $|G| < M$, go to step 4. Otherwise, go to step 5.

*Step* 4. If any type-$f_k$ job exists in the queue, select one with the highest ATCS value among the type-$f_k$ jobs. Otherwise, go to step 5.

*Step* 5. Select the job with the highest ATCS value among the waiting jobs of type-$f^*$. Schedule the selected job at machine $k$.

For stage-1, we use a common dispatching rule, named slack per remaining work with the setup ratio

(S/RW-SR), which is based on the well-known slack per remaining work (S/RW) rule as well as the setup ratio for each job type. The setup ratio for job type-$f$ is calculated as $(M – M_f / 2) / M$, where $M_f$ is the number of machines setup for job type-$f$ in stage-2 at time point of scheduling decision. It is clear that S/RW-SR is intended to support the real time scheduling decisions of stage-2 which is set to be a bottleneck stage, by making scheduling decisions based on the real time setup status of stage-2 as well as the urgency of each job. In addition, for stage-3, jobs are selected and inspected by first come first served (FCFS) rule since the inspection time for jobs of any type is set to be relatively short.

## 5. Experimental Results

In the test, four dispatching rules for stage-2, S/RW-TQ1, ATCSQ, ATCS-TQ1 and ATCS-TQ2, are included based on three existing dispatching rules, slack per remaining work (S/RW), ATCSQ, and ATCS. For S/RW, TQ1 is applied since no quality factor is considered in them, and both TQ1 and TQ2 are applied for ATCS due to the same reason. In the dispatching rules, the setup time for a job is set to 0 only when the available machine under consideration is already setup for the same job type and do not have a quality feedback for the job type. In ATCSQ, the mean and standard deviation of the real time defect rate are used while the upper and lower specification limits are set to 0 and $\tau$, respectively. In both ATCS and ATCSQ, the parameters $k_1$ and $k_2$ are set by using the rules suggested in Lee and Pinedo [10]. From a series of preliminary tests, we set the values for the parameters being used in TQ1 and TQ2. The scaling parameter $\rho$ for TQ1 is set to 1, and for TQ2 two sets of the scaling and ranging parameters ($\omega$, $\pi$), (0.03, 70) when $M$ = 3 and (0.015, 130) when $M$ = 5 in set-I and (0.09, 70) when $M$ = 3 and (0.09, 150) when $M$ = 5 in set-II, are used.

Table 1. Summary of test parameter settings

| Parameter | Value (Range) |
|---|---|
| $M$, $\alpha$, $\beta$ | 3 or 5, 0.5 or 0.7, 2 or 4 |
| $p_{f,i}$ | Uniform distribution [10, 20] for $i$=1, [35, 55] when $M$=3 and [65, 85] when $M$=5 for $i$=2, [5,5] for $i$=3 |
| $s_f$ | Uniform distribution [10, 20] |
| ($\mu_f^{Ph}$, $\sigma_f^{Ph}$) | (3, 1) for $h$=1 and (5, 2) for $h$=2 |
| $\tau$, $\tau^A$, $\gamma_f$ | 5, 3.5, random selection among 5, 7 and 9 |

Table 1 shows the summary of test parameter settings, and 8 test scenarios are generated according to the variations in three factors, $M$, $\alpha$, and $\beta$. For each scenario, 20 random problem instances were generated and tested to evaluate the performance of the four dispatching rules. For each problem instance, the test runtime is set to 10,000, and the number of job types $F$ is fixed to 3. For the reliable performance evaluation, the results within the steady state (95% utilization for machines in stage-2) are only considered.

Table 2 shows the average quality rate (upper) in % and the mean tardiness (lower) of the four dispatching rules for all test scenarios.

Table 2. Performance of the dispatching rules

| Scenario ($M/\alpha/\beta$) | S/RW-TQ1 | ATCSQ | ACTS-TQ1 | ACTS-TQ2 with set-I | set-II |
|---|---|---|---|---|---|
| (3/0.5/2) | 97.8 | 93.6 | 93.8 | 94.1 | 95.1 |
| | 621.72 | 141.85 | 138.65 | 122.72 | 142.33 |
| (3/0.5/4) | 97.9 | 93.7 | 93.5 | 94.2 | 94.8 |
| | 571.46 | 82.55 | 82.47 | 73.87 | 86.08 |
| (3/0.7/2) | 97.9 | 95.7 | 95.5 | 96.2 | 96.4 |
| | 368.19 | 66.31 | 65.29 | 60.42 | 63.10 |
| (3/0.7/4) | 97.8 | 96.1 | 96.3 | 95.9 | 96.3 |
| | 330.38 | 30.32 | 30.64 | 29.06 | 32.70 |
| (5/0.5/2) | 97.7 | 92.6 | 92.3 | 92.9 | 97.1 |
| | 525.52 | 207.40 | 201.78 | 193.25 | 265.63 |
| (5/0.5/4) | 97.7 | 92.1 | 91.8 | 93.8 | 96.9 |
| | 440.93 | 129.73 | 125.05 | 123.88 | 174.55 |
| (5/0.7/2) | 97.8 | 93.6 | 93.6 | 94.8 | 97.3 |
| | 357.55 | 130.24 | 120.43 | 113.90 | 152.03 |
| (5/0.7/4) | 97.8 | 94.0 | 93.7 | 95.2 | 97.3 |
| | 285.02 | 66.15 | 62.11 | 60.26 | 83.83 |
| Average | 97.8 | 93.9 | 93.8 | 94.6 | 96.4 |
| | 437.60 | 106.82 | 103.30 | 97.17 | 125.03 |

As shown in Table 2, S/RW-TQ1 and ATCS-TQ2 with parameter set-I showed the best performance in terms of the average quality rate and the mean tardiness, respectively. In fact, there exists a trade-off between the two performance measures. Due to the setup timing-dependent defect rate, the average quality rate will be increased if the number of setup operations increases while it will be decreased if the number of setups is minimized. In S/RW-TQ1, a lot of setups are made because the influence of the due date-related factors is set to be much stronger than that of the quality-related factors. Meanwhile, ATCS-TQ1 and ATCSQ showed similar performance for the objective of the average quality rate while ATCS-TQ1 showed better performance in terms of the mean tardiness.

As expected, when the due date range becomes shorter, the mean tardiness becomes larger because the average due date of jobs becomes tighter. Also, when the mean inter-arrival time becomes shorter, the mean tardiness becomes larger because the expected average waiting time of jobs becomes longer and the average slack time of jobs becomes shorter. For the test scenarios with the tight due date and the short inter-arrival time, the influence of the due date-related factors on the priority values becomes stronger than that of the quality-related factors so that the average quality rate of jobs becomes smaller in the dispatching rules except S/RW-TQ1. When the number of machines becomes larger, the machines in stage-2 may have less chance to changeover job types because the number of machines is larger than the number of job types, and the test result for the scenarios with 5 machines shows worse average quality rate of jobs than that for the scenarios with 3 machines.

Meanwhile, ATCS-TQ2 with parameter set-II showed better performance than ATCSQ, ATCS-TQ1 and ATCS-TQ2 with set-I in terms of the quality rate due to the effect of using the scaling parameter for adjusting the weight for each term in its equation, although it showed slightly worse performance in terms of the mean tardiness. Note that in all dispatching rules except S/RW-TQ1, some amount of quality loss is somewhat inevitable due to the time gap resulting by the independent inspection stage as mentioned earlier. For example, when a quality feedback for a job type is sent to a machine of stage-2, it may be already processing another job of that type due to the time gap. As a conclusion, ATCS-TQ2 is suggested for the manufacturing industry for which both the quality rate and the mean tardiness are important performance measures.

## 6. Concluding Remark

In this research, we consider a dynamic flexible flow shop scheduling problem with time-dependent process quality and a quality feedback mechanism, and two prioritizing modules focusing on the latest setup timings of the machines are developed. From the computational experiments, TQ2 showed the best performance in terms of the mean tardiness of jobs when it is used with ATCS rule. For the shop floor scheduling problems with time-dependent process quality, we expect that TQ2 can be easily applied with most of existing dispatching rules if its weight is appropriately adjusted. For the future research issues, the two proposed prioritizing modules can be extended to the dynamic flexible job shop or flow shop scheduling problems with more complicated process flows, such as rework or reentrant flows, under the presence of the time-dependent process quality.

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