Predictive Approach on Flexible Job Shop Scheduling Problem Considering Controllable Processing Times

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***Abstract*—As a result of rapid developments in production technologies in recent years, job shop scheduling problem becomes more complex with presence of routing alternatives. This problem is known as flexible job shop scheduling problem (FJSP). On the other hand, as cutting tool technology also developed, time process may vary by accelerating/decelerating cutting speed. Processing time could be increased or decreased by considering some specific variables. In practice, scheduling problem is usually subject to disturbances, such as machine breakdown. The most common method in coping with machine breakdown is by using predictive approach, which put in a certain amount of idle times within the schedule for machine repair. This paper deals with three main factors: FJSP, controllable processing time and machine breakdown. Mathematical models will be used to build an initial solution that determines job assignment and processing times of the jobs. Later, this initial solution will be used to reschedule jobs by considering expected downtime for each machine and downtime probability for each operation. A number of scenario will be described to show the merits of the proposed algorithm.**

***Index Terms*—Flexible job shop, controllable processing times, machine breakdown, predictive scheduling.**

I. Introduction

Generally, job shop scheduling problem could be defined as problem where a number of jobs having its processing times and routing has to be allocated to a set of resources. As processing technology developed, processing time of a process now could be treated as decision variable and an operation could be done in more than one machine i.e. it has routing alternatives. Flexible job shop scheduling problem (FJSP) extends classical job shop scheduling problem by assuming that each machine is flexible and able to offer more than one particular capability [1], resulting in needs of jobs assignment considering specific variables, such as cost. When the processing times of jobs are controllable, selected processing times affect both of manufacturing cost and scheduling performance [2].

In most machine scheduling problems with different objective functions, it is assumed that machines are available all the time [3]. In practice, schedule is prone to disruptions of machine breakdown. Such disruptions could result in tardiness and increase production cost. Rescheduling activities after disruptions occur may become inefficient since it will consumes more time and cost. Thus, it is critical to build an initial schedule that already considered expected downtime to solve scheduling problem subject to machine breakdowns.

Several related researches are found in the area of interest. Ozguven [4] proposed a mathematical model for FJSP that accommodates routing and process plan flexibility. Kayan [5] developed bounding mechanism for CNC machines considering controllable processing times. The determination of upper and lower bound is obtained by performing destructive experiment over the tools. Yulianty [6] proposed a job-shop scheduling model incorporating processing times as decision variable to minimize manufacturing and tardiness cost. Mehta [7] defined predictive scheduling approach by inserting idle times to schedule in order to absorb disruptions. Yang [8] consider predictive-reactive scheduling problem where there is uncertainty of the future jobs. Ben [9] studies the job shop scheduling problem under periodic unavailability periods and presents a multi-objective genetic algorithm-based method to solve it. Gurel [10] gave an anticipative scheduling approach to solve scheduling problem with machine breakdowns by considering downtime probability and controllable processing times.

This paper proposes a predictive scheduling algorithm that is able to solve FJSP by considering processing times as controllable variables and expected downtime. The algorithm is carried in two main steps: an initial schedule and rescheduling. Initial schedule determine optimal schedule considering machine job assignment and controllable processing times, whereas rescheduling carries the need of inserting expected downtime into the schedule. Objective function in initial schedule is to minimize machine operating cost, tooling cost and tardiness cost. Rescheduling problem minimizes the increasing cost that may occur if machine breakdown occurs.

II. Description of Problem

Flexible job shop scheduling problem consists of a set of jobs where $J = \{j_i\}^n_{i=1}$. Each job consists of O operations, where $O = \{O_i\}^n_{i=1}$ and and O_i is an operation routing set where $O_i = O_{if(i)}, \ldots, \ldots, O_{il(i)}$. Each operation must be assigned through a certain set of machine where the operation could be processed (L_{ij}).

As processing times considered as decision variable, then processing times for operation j of job i processed on machine k (p_{ijk}) is bounded by an upper limit ($p_{ijk}{}^u$) and could be compressed up to its maximum compressibility (u_{ijk}) where certain tolerance specification is maintained. Amount of compression of operation j of job i on machine k defined as ε_{ijk}. Each job has attributes such as due date (dd_i), released date (r_i), priority weight (w_i), and tardiness (T_i), if occur.

Total expected downtime for each machine defined

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through the end of period of each machine on initial schedule. Expected downtime for each machine will be allocated to operations that is processed on that machine by considering processing time's allowance (δ_k), downtime probability (Pd_{ijk}), and rescheduling cost.

Assumptions used on this research are: 1) Inspection policy is used to perform maintenance, 2) Single disruption, 3) Non-preemptive job, 4) Overtime cost is ignored.

III. Proposed Model and Algorithm

The proposed algorithm is a predictive approach to schedule jobs to resources. When a disruption occur, schedule will need to be repaired. By building a predictive initial schedule that already considered downtime probability, disturbance on a schedule could be minimized. The proposed algorithm is as follow:

Predictive Scheduling Algorithm
Step 1. Machine-job assignment (MJA)
Step 2. Sequencing algorithm
Step 3. Calculation of expected downtime and downtime probability
Step 4. Calculation of available compressibility
Step 5. Rescheduling
Step 6a. Calculation of tardiness cost
Step 6b. Calculation of saving cost

A. Machine-Job Assignment (MJA)

1) Mathematical model

In solving flexible job shop scheduling problem, machine-job assignment has to be defined first. Gurel [10] proposed a MJA (Machine-Job Assignment) model with controllable processing times. We modified this model by setting the objective function to minimization of total cost consists of two cost elements: machine operating cost and tooling cost. Machine operating cost defined as multiplication between processing times and machine operating cost (Co_{ijk}). Tooling cost is defined as non-linear relationship between operation exponent (e_{ij}), tooling multiplier (mu_{ij}) and tooling cost (B_{ij}). Assignment decision is given by a binary variable x_{ijk} which is 1 if operation j of job i processed on machine k, and 0 if otherwise. Mathematical model of MJA is defined as follow:

$$\min = \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{l}[(Co_{ijk} \times p_{ijk}) + (mu_{ij} \times B_{ijk} \times p_{ijk}{}^{e_{ij}})] \times x_{ijk}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m}(p_{ijk}^{u} \times x_{ijk}) - \varepsilon_{ijk} \le d_k \qquad \forall k \in L_{ij} \qquad (1)$$

$$\varepsilon_{ijk} \le x_{ijk} \times u_{ijk} \qquad \forall i, (j \in O_i), (k \in L_{ij}) \qquad (2)$$

$$\sum_{k=1}^{l} x_{ijk} = 1 \qquad \forall i; \forall j \qquad (3)$$

$$p_{ijk} = p_{ijk}^{u} - \varepsilon_{ijk} \qquad \forall i, (j \in O_i), (k \in L_{ij}) \qquad (4)$$

$$x_{ijk} \in \{0,1\} \qquad p_{ijk}, \varepsilon_{ijk} \ge 0$$

Constraint (1) is to ensure job allocation to each machine does not exceed the capacity. Constraint (2) guarantees amount of compression that applied to a job is less than its maximum compressibility. Constraint (3) ensures that one job is assigned to only one machine at a certain time. Constraint (4) determine that processing time is equal to its upper bound substract to amount of compressibility.

2) Controllable processing times

A scheduling problem in which the processing times of the jobs can be reduced at some expense is called a scheduling problem with controllable processing times [11]. Operations processed in CNC machine are a well-known example of controllable processing times. Processing times may be controllable by allocating resources (that may be continuous or discrete) [12], for example by adjusting cutting speed and feed rate. Machine operating cost will be increased if processing time is decelerated. Otherwise, if processing time is accelerated, tooling cost will be increased, since tool life is decreased. Therefore, there is an upper and lower bound of processing time to optimize trade-off that might be occurred. MJA model that already mentioned before will decide the optimal processing time with machine operating and tooling cost.

B. Sequencing Model

Sequencing is one of several key points in job shop scheduling problem [13]. MJA model decides machine-job assignment and optimal processing time. The decision then will be used for sequencing jobs to schedule in order to minimize tardiness cost. As in [14], tardiness cost is defined as linear relationship between priority weight (w_i) and tardiness occur (T_i).

In making a schedule, some decision variables is going to be determined, such as starting time (s_{ijk}), completion time (c_{ijk}), and sequencing binary variable y_{ijabk} which is 1 if O_{ij} precedes O_{ab} on machine k, and 0 if otherwise. In order to obtain optimal sequencing, mathematical model used is as follow:

$$\min = \sum_{i=1}^{n} w_i \times T_i$$

$$c_{ijk} \ge s_{ijk} + p_{ijk} \qquad \forall i, (j \in O_i), (k \in L_{ij}) \qquad (5)$$

$$s_{ijk} \ge c_{i,j-1,k'} \qquad \forall i, (j \in O_i - O_{if(i)}), (k, k' \in L_{ij}) \qquad (6)$$

$$s_{i1k} \ge r_i \qquad \forall i, (j \in O_i), (k \in L_{ij}) \qquad (7)$$

$$s_{ijk} \ge c_{abk} - (y_{ijabk} \times M)$$
$$\forall (i < a), (j \in O_i), (b \in O_a), (k \in L_{ij} \cap L_{ab}) \qquad (8)$$

$$s_{abk} \ge c_{ijk} - (1 - y_{ijabk}) \times M$$
$$\forall (i < a), (j \in O_i), (b \in O_a), (k \in L_{ij} \cap L_{ab}) \qquad (9)$$

$$y_{ijabk} + y_{abijk} = 1$$
$$\forall (i < a), (j \in O_i), (b \in O_a), (k \in L_{ij} \cap L_{ab}) \qquad (10)$$

$$f_i = c_{i,Oil(i),k} \qquad \forall i, (j \in O_i), (k \in L_{ij}) \qquad (11)$$

$$T_i = f_i - dd_i \qquad \forall i \qquad (12)$$

$$y_{ijabk} \in \{0,1\} \qquad T_i, s_{ijk}, c_{ijk} \ge 0$$

Constraint (5) calculates the completion time for a job. Constraint (6) makes sure that precedence relationship of a job is not violated. Constraint (7) ensures that a job start after its released date. Constraint (8) and (9) guarantee that two consecutive jobs do not overlap. Constraint (10) determine the precedence of operations within each machine Constraint (11) calculates the finish time of a job. Constraint (12) set the tardiness of a job.

MJA and sequencing model give an initial schedule subject to machine operating cost and tardiness cost, but have not considered machine breakdowns. The initial schedule will be used for building a new schedule considering machine breakdown, explained in the following section.

C. Downtime Factor

1) Expected downtime

On some cases, an item is not always monitored continuously. An inspection must be done in order to know whether an item is in working or failed state. In Jiang [15] it is stated that maintenance policy for cases where failure detected only at inspection and done at discrete points is inspection policy. Inspection policy calculated the expected downtime on a certain time cycle. In this research, it is assumed that inspection will be done every time a machine finish all jobs that is assigned to it. If failure time follow Weibull distribution, then expected downtime could be calculated using equation (13):

$$\tau_k = Tc \times F(Tc) - \alpha \times \Gamma(1+\frac{1}{\beta}) \times G[\Lambda(Tc), (1+\frac{1}{\beta}), 1] \quad (13)$$

where Tc is cycle time assumed as end of schedule for a machine. α is Weibull scale parameter, whereas β is shape parameter. $\Gamma(x)$ defined Gamma function and $G(a,b,c)$ determined Gamma distribution function with b is the shape parameter and c is scale parameter.

Expected downtime calculated by equation (13) is total of downtime that is possible to occur on a machine. The expectation then will be divided and allocated to schedule operation determined before. Processing time amount and allocation will be determined through rescheduling model which considered downtime probability.

2) Downtime probability

Given failure time and repair time distribution, then downtime probability of a machine on a certain time point could be determined. Given $Gy(T)$ and $fx(T)$ consecutively are repair time distribution function and failure time probability density function for a machine, then downtime probability of a machine on a certain time point t defined as follow:

$$Pd(t) = \int_{-\infty}^{t} [(1 - Gy(t-x)) \times fx(x)]dx \quad (14)$$

Downtime probability obtained from equation (14) will be used for determined flexibility of job. A certain time t is picked from midpoint of an operation in initial schedule ($t = (s_{ijk}+c_{ijk})/2$). As downtime probability of a midpoint of an operation is decreasing, then the operation become more flexible to be compressed in order to cope with additional amount of time.

D. Available Compressibility

New schedule has to catch up with initial schedule when expected downtime is considered. By treating processing time as decision variable, the range between upper and lower bound of processing time is the maximum compressibility could be applied (u_{ijk}). An optimal processing time will be decided by determining amount of compression (ε_{ijk}) that will be applied.

MJA and sequencing model explained in previous section has defined an optimal schedule and processing time by considering total cost consists of machine operating cost and tooling cost. When a disruption occur, schedule will be shifted and it could increase tardiness. Controllable processing time gives us allowance to be able to catch up the initial schedule by accelerating processing time. The acceleration performed by applying additional compression to the processing time. Since processing time has been compressed when we determined machine job assignment, it is necessary to calculate available amount of compressibility (ca_{ijk}). Available amount of compressibility could be calculated by equation (15)

$$ca_{ijk} = u_{ijk} - \varepsilon_{ijk} \quad (15)$$

An operation could only be compressed, therefore total allowance of processing time (δ_k) is calculated by summing maximum value of compressibility of an operation of a job. Equation (16) provide formulation for calculating δ_k.

$$\delta_k = \sum_i \sum_j ca_{ijk} \quad (16)$$

E. Rescheduling Model

Rescheduling needs to address various issues: 1) when and how to react to real-time events, and 2) the method combination used to revise existing schedule [16]. In this research, rescheduling is performed by determining allocation and amount of additional compressibility that could be applied for an operation of a job. Allocation of compression is determined by considering downtime probability. If an operation is placed on a time point where a disruption is more likely to happen, then the operation become less flexible to be compressed. Additional compression is stated through percentage of change of processing time (σ_{ijk}) where $\sigma_{ijk} < 1$ since the new processing time will always be less than optimal processing time.

On some cases where processing time has low compressibility, δ_k or processing time's allowance value may be less than value of expected downtime (τ_k). On this case, there will be downtime left that could not be allocated to processing time's allowance. The remainder time will be treated as tardiness. Mathematical model for rescheduling problem is defined as follow:

$$\min = \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{l}[(Co_{ijk} \times (p_{ijk} \times \sigma_{ijk})) + (mu_{ij} \times B_{ij} \times (p_{ijk} \times \sigma_{ijk})^{e_{ij}})] \times pd_{ijk}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m} p_{ijk} - (p_{ijk} \times \sigma_{ijk}) = tt_k \qquad \forall k \in L_{ij} \quad (17)$$

$$tt_k = \begin{cases} \tau_k & if\ \delta_k \geq \tau_k \\ \delta_k & if\ \delta_k < \tau_k \end{cases} \qquad \forall k \in L_{ij} \quad (18)$$

$$0 \leq p_{ijk} - (p_{ijk} \times \sigma_{ijk}) \leq ca_{ijk}$$
$$\forall i, (j \in O_i), (k \in L_{ij}) \quad (19)$$

Constraint (17) ensures that the additional amount of compressibility applied in rescheduling model is equal to transition variable (tt_k). Constraint (18) sets value of transition variable (tt_k) is equal to expected downtime if all expected downtime could be allocated using processing time's allowance, and otherwise, tt_k is equal to δ_k if not all expected downtime could be allocated. The remainder time will be considered as tardiness. Constraint (19) ensures the additional change in processing times is greater than or equal to 0 and does not exceed its available compressibility.

IV. Numerical Example

A numerical example is given for job shop scheduling problem for a case of 3 jobs and 2 machines, where each job consists of 2 operation. Machine 1 is able to process all operation, excluding operation 2 of job 1, whereas machine 2 is able to process only certain operation, which are operation 2 of job 1, operation 1 of job 1, and operation 1 of job 3. Capacity of each machine d_k is 50 hours.

Execution of algorithm is performed through steps mentioned in the previous section. Table I depict the process parameters for the numerical examples. The upper and lower bound of processing time is assumed ±20% of ideal processing time.

TABLE I: Process Parameters

i	j	k	p^u_{ijk}	u_{ijk}	B_{ijk}	Co_{ijk}	e_{ij}	mu_{ij}
1	1	1	6	2	3500	3000	-1.2	25
		2	-	-	-	-		
	2	1	-	-	-	-	-1.5	26
		2	3.6	1.2	5000	4000		
2	1	1	4.2	1.4	4000	3000	-1.7	28
		2	4.08	1.36	5000	4000		
	2	1	3.12	1.04	4000	3000	-1.1	27
		2	-	-	-	-		
3	1	1	6.72	2.24	5000	3000	-1.3	30
		2	5.88	1.96	5000	4000		
	2	1	7.2	2.4	4000	3000	-1.4	29
		2	-	-	-	-		

Table II shows the decision variable value obtained from Step 1. Table III depict the job parameters used in step 2. The result of Step 2 is the initial schedule of jobs as shown in Fig. 1.

TABLE II: Decision from Step 1

k	i	j	p_{ijk}
1	1	1	5.03
	2	1	4.2
		2	3.12
	3	1	6.14
		2	5.27
2	1	2	3.6

Step 3 is conducted based on the initial schedule from previous step. The expected downtime is calculated by setting the cycle time as the completion time of last operation processed in a machine. Failure time is assumed to follow 2-parameter Weibull distribution with α=30 and β=2. Expected downtime for both machine consecutively are τ_1 = 6.381 and τ_2 = 0.024.

TABLE III: Job Parameters

i	wi	dd_i	ri	Ti
1	5000	10	0	0
2	6000	15	0	0
3	4000	20	0	8

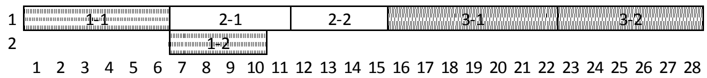

Fig. 1. Gantt chart for initial solution.

Besides expected downtime, downtime probability on midpoint of each operation of a job in a schedule is also considered ($t = (s_{ijk}+c_{ijk})/2$). Failure time assumed to follow Weibull distribution with same parameters as expected downtime calculation. Repair time follows an exponential distribution with λ=0.5. Table IV shows downtime probability for each operation.

TABLE IV: Downtime Probability

	Machine 1					Machine 2
i-j	1-1	2-1	2-2	3-1	3-2	1-2
t	3	8.5	13	18.5	25	8
Pd(t)	0.00445	0.027	0.042	0.054	0.056	0.025

Next, available compressibility value are calculated from amount of compression applied on the initial solution. Table V gives us value of available compressibility.

TABLE V: Available Compressibility

i-j-k	u_{ijk}	ε_{ijk}	ca_{ijk}
1-1-1	2	0.97	1.033
1-2-2	1.2	0	1.2
2-1-1	1.4	0	1.4
2-2-1	1.04	0	1.04
3-1-1	2.24	0.58	1.66
3-2-1	2.4	1.93	0.47
δ_1		5.603	
δ_2		1.2	

From Table V, it is shown that total allowance (compressibility) of processing time on machine 1 (δ_1) is less than expected downtime on the same machine (τ_1 = 6.381). This means that the maximum amount of expected downtime which could be allocated to machine 1 is equal to its allowance, resulting 0.778 (6.381-5.603) hours that will be considered as tardiness. Table VI shows the amount of processing time for each operation after additional compression. A gantt chart for rescheduling problem solution is depicted in Fig. 2.

Changing on optimal processing time obtained from initial solution may increase production cost. There are two cost elements considered in comparing initial solution and rescheduling solution: production cost, which consists of machine operating and tooling cost, and tardiness cost.

Based on the initial solution as shown in Fig. 1, job 3 is tardy for 8 days. On the other hand, rescheduling solution as shown in Fig. 2 job 3 is tardy for 1 days. The initial solution has not considered expected downtime, resulting in additional cost, where expected downtime is considered as tardiness. Therefore, cost comparison in performing initial and rescheduling solution is given on Table VII.

TABLE VI: ADDITIONAL AMOUNT OF COMPRESSION

i-j-k	σ_{ijk}	pa_{ijk}
1-1-1	0.7947651	4.0002571
1-2-2	1	3.6
2-1-1	0.6666667	2.8
2-2-1	0.6666667	2.08
3-1-1	0.7296758	4.4807752
3-2-1	0.9109117	4.8056623

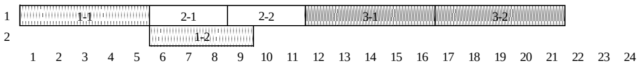

Fig. 2. Gantt chart after rescheduling.

Two other scenarios has been performed on this algorithm, where processing time's upper and lower bound is 10% and 0% of its ideal processing time. Those scenarios gives us that the algorithm is able to provide cost saving cost when tardiness cost is high.

Numerical tests on scale parameter (range 10-50) also shows that expected downtime tends to decrease if the scale parameter is high. Otherwise, it could be inefficient since expected downtime could be two times larger than the uptime. Shape parameter does not give much contribution as scale parameter does, but tests on shape parameter (range 1.5-2.5) shows that expected downtime tends to decrease when shape parameter is high. This shows us that characteristics of machine failure affects expected downtime, where indirectly will also affects the new schedule obtained from rescheduling steps.

TABLE VII: TOTAL COST

TOTAL COST				
Initial Cost				
Production Cost	Rp	183,458.50		
Tardiness Cost (from Gantt Chart)	Rp	32,000.00	Rp	243,458.50
Downtime Cost	Rp	28,000.00		
Rescheduling Cost				
Production Cost	Rp	206,450.07	Rp	218,450.07
Tardiness Cost	Rp	12,000.00		
Saving			Rp	25,008.43

V. CONCLUSION

This research proposes an algorithm for flexible job shop scheduling problem considering controllable processing time and expected downtime by using predictive approach. The proposed model is able to decrease number of tardiness and minimize the cost spent. Output of proposed algorithm is schedule to minimize rescheduling cost and tardiness.

The algorithm has been tested on some scenarios and this algorithm is able to give significant cost saving in cases that tardiness cost is high. Future research will be elaborated on simultaneous scheduling in minimizing cost and tardiness.

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