Batch Scheduling for a Single Deteriorating Machine to Minimize Total Actual Flow Time

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Abstract

This research addresses a problem of scheduling batches processed on a single deteriorating machine where the failure of machine is assumed as the so-called ROCOF (rate of occurance of failure) function of Weibull distribution with two parameters. The processing time of parts in a batch processed in a position is considered constant but will increase if the batch is processed in the previous position in a backward schedule. The objective is to minimize total actual flow time defined as total interval between respective arrival times of all parts in all batches and their common due date. Decision variables are the number of batches (*N*), batch sizes (*Q*) and the sequence of processing the resulting batches. The problem is formulated as a non-linear programming model for which a relaxation is applied by considering variable *N* to be a parameter. The solution method begins by detemining the maximum value of *N*, and the next step is to solve the model for several values of *N*, started from *N* = 1 and incresed one by one iteratively until a stopping rule is satisfied (the optimal *N* will be less than or equal to the maximum *N*). Numerical experiments shows the effectiveness of the proposed method are also provided.

Keywords
Deteriorating machine, batch scheduling, total actual flow time

1. Introduction

The literature research on maintenance problems, as discussed for example in Jiang and Murthy (2008) showing that an equipment deteriorates in line with its lifespan and usage until ultimately damaged and can not be used anymore. The impact of machine deterioration will decline machine's ability causing that the part processing time becomes longer. This problem on scheduling literature is known as the increase of processing time or aging effect or deterioration (Sukoyo et al. 2008).

The research on the deteriorating effect in scheduling problems has been discussed for example in Larijani et al. (2011), Hsu et al. (2011), Wu et al (2011), Moslehi and Jafari (2010), Zhao and Tang (2010), Yang et al. (2010), Wu, Xiau and Lee (2008), Kuo and Yang (2006) and Cheng et al. (2004). In general, their studies discuss deterioration in job scheduling problems. Meanwhile in the practical situations,, deterioration also occurs on batch scheduling problems (Haddad et al. 2012, Mor and Mosheiov 2012, Sukoyo et al. 2010, Sukoyo et al. 2009, Sukoyo et al. 2008, Barketau et al. 2007).

This research discusses batch scheduling problems on a single machine by considering the effect of machine deterioration. The objective used is the so-called total actual flow time, defined by Halim et al. (1994) as the total interval between the respective arrival times of all parts and their common due date. This criteria has been used on the research of batch scheduling problems for example in Sukoyo et al. (2010), Sukoyo et al. (2009), Halim and Yusriski (2009), Yuniartha and Halim (2008) and Sukoyo et al. (2008) and proven effectively to solve the problems. The decision variables of model are to determine the number of batches (*N*), batch sizes (*Q*) and the sequence of resulted batches.

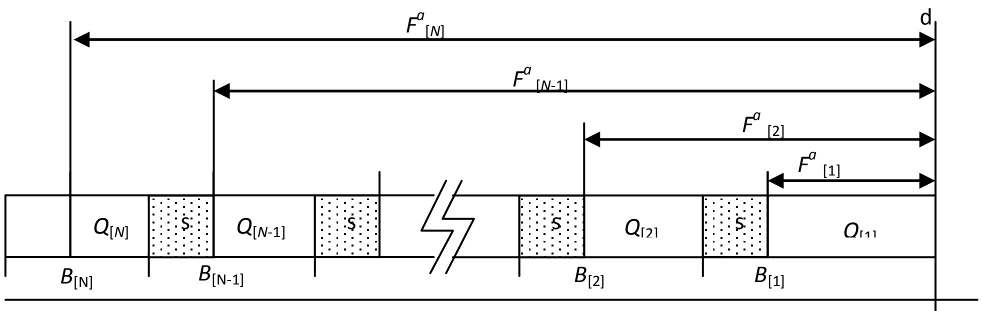
The motivation of this research is cases faced in practical situations i.e, batch scheduling problems in the material thinning process using a freis machine. A thinning process of jobs is usually divided into several batches. The lag time between two batches processed consecutively is used by operator to perform a maintenance actions, for example machine cleaning and lubrication. The maintenance actions are taken to avoid machine fatigue due to manufacturing products continuously. Even the maintenance actions have been done, the deterioration will still occur due to acuity degradation of cutting tool. As a result, part processing time depends on batch positions in the schedule. The parts in a batch processed latter will require a longer processing time than the previous processed batch. Since the arrival of parts is controlable and the delivery time should be at their common due date, the actual flow time criteria can be adopted as the objective function for this prolem.

The Discussion in this paper is divided into five sections. An Introduction of the research is discussed in the first section. A description of batch scheduling with actual flow time criteria and machine deterioration phenomenon is discussed in the second section. Problem formulation and solution method is discussed in the third section. Numerical experiment and sensitivity analysis are discussed in the fourth section, and then the last section consists of concluding remarks and the problems to be dealt in further research.

2. Batch Machine Scheduling with Deterioration

2.1 Batch scheduling with Actual Flow Time

The research on batch scheduling problems for example in Dobson et al. (1987) shows the trade-off between reducing the number of setups and increasing flow time by using the objective function to minimize flow time. Dobson et al. (1987) proposed a formula for calculating the optimal number of batches and batch sizes and proven the concept of SPT (Shortnest Processing Time) rule can minimize the flow time. Dobson model is appropriate for companies that have an ability to manipulate demand and due date. However in practical situations, there are some cases that the companies should submit their finished product right on due date, therefor the companies need to set the arrival of parts as required. The research in Halim et al. (1994) proposed the so-called actual flow time, defined as the interval between respective arrival times of the parts and their common due date. The objective adopted backward scheduling approach and have been proven effective to solve the problems of batch scheduling. An Illustration of actual flow time criteria is shown in Figure 1.



Legend:
s: setup time *B:* starting time of batch processing *d:* due date F^a*:* actual flow time *Q:* Batch Size

Figure 1: Total actual flow time of batches

Based on Figure 1, the actual flow time formula is as follows:

$$
\begin{aligned}
F^a &= \sum_{i=1}^{N}\left(d - B_{[i]}\right)Q_{[i]} \\
&= \sum_{i=1}^{N}\left(\sum_{j=1}^{i}\left(s + tQ_{[j]}\right) - s\right)Q_{[i]}
\end{aligned} \tag{1}
$$

The decision variables are the number of batches (N), batch sizes (Q) and the schedule of resulting batches. The constraints which should be considered are the number of parts of all batches must be equal to the demand, all of batches must be processed at available time, the completion time of the first batch must be finished at the common due date, the number of batches must be an integer value, and the batch sizes must not be negative. The Research of Halim et al. (1994) proposed a formula to calculate the optimal number of batches and batch sizes. In addition it was proven that LPT (Longest Processing Time) rule can minimize the total actual flow time using backward scheduling approach.

2.2 Machine deterioration phenomenon

Machine deterioration phenomenon in scheduling problems is shown by the increase of processing time when the job scheduled latter due to capability degradation of the machine (Cheng et al. 2004). According to Jiang and Murthy (2008), this phenomenon occurs on any equipment in line with lifespan and usage until ultimately damaged even the tool created with the best design, construction and operation. Maintenance actions are carried out as an effort to reduce the impact of deterioration or to eliminate the impact of deterioration and restore the machine to its original state. A Minimal repair action is one of preventive maintenance actions to slow down the effect of deterioration. Meanwhile, a replacement action is one of maintenance actions to eliminate the impact of deterioration and to restore the machine to its original state.

The deterioration (also called sad or unhappy) defined as the increase of rate of occurrence of failures (ROCOF) and can be used to estimate the behavior of the system as the amount of equipment failures on the time interval $[0,t]$ (Kaminskiy and Krivtsov 2008). The expectation amount of failures or expectations of machine deterioration at the interval $[0,t]$ with ROCOF concept can be formulated as follows:

$$E\{N(t)\} = \Lambda(t) = \int_0^t \lambda(x)dx \tag{2}$$

If we assume the rate of failures following the two-parameters Weibull distribution (α and β) then the expectation number of failures at the time interval $[0,t]$ can be rewritten into:

$$\Lambda(t) = \left(\frac{t}{\alpha}\right)^{\beta} \tag{3}$$

$\Lambda(t)$ is expected number of failures at the time t, α is the scale parameter and β is the shape parameter.

There are N batches to be processed on a single machine. Let us assume that the machine will be damaged at time T and machine deterioration will occur at interval $[0,T)$. The additional processing time occur due to machine deterioration effect. By adopting ROCOF concept, batch processing time can be formulated as follows:

$$t_{[i]} = p + \mu\left\{\Lambda\left(B_{[i]}\right)\right\} \tag{4}$$

p is the initial processing time, μ is the additional time due to machine deterioration, $B_{[i]}$ is starting time batch-i and $\{\Lambda(B_{[i]})\}$ is the expectation number of deterioration in the interval $[0,B_{[i]}]$. Based on equation (3) then the expectation number of deterioration can be formulated as:

$$\Lambda\left(t_{[i]}\right) = \left(\sum_{k=1}^{i} t_{[k-1]}Q_{[k-1]} \Big/ \alpha\right)^{\beta} < 1 \tag{5}$$

where t is the batch processing time and Q is the batch sizes.

Substitution of equation (4) to (5) yields the batch processing time formula adopting forward scheduling approach as follows:

$$\begin{gathered} t_{[i]} = p + \mu\left(\sum_{k=1}^{i} t_{[k-1]}Q_{[k-1]} \Big/ \alpha\right)^{\beta} \\ \text{where } \left(\sum_{k=1}^{i} t_{[k-1]}Q_{[k-1]} \Big/ \alpha\right)^{\beta} < 1, \\ t_{[0]} = 0,\ t_{[1]} = p \text{ and } Q_{[0]} = 0 \end{gathered} \tag{6}$$

For example, let there be three batches and the batch sizes are: $Q_{[1]}= 1$, $Q_{[2]}= 2$ and $Q_{[3]}= 3$. The initial processing time (p) is 2 minutes. Meanwhile, the additional time due to deterioration (μ) is 0.2 minutes. The scale parameter (α) is 4 minutes and the shape parameter (β) is 2. Then, by using equation (6) obtained $t_{[1]}= 0.5$ minutes, $t_{[2]}= 0.503$ minutes and $t_{[3]}= 0.528$ minutes. Based on the result, we can see that the trend of batch processing time increases. Assume that the first processed batch is a batch at N position in the schedule using backward scheduling approach then equation (6) can be written as:

$$\begin{gathered} t_{[i]} = p + \mu_f\left(\sum_{k=i}^{N} t_{[k+1]}Q_{[k+1]} \Big/ \alpha\right)^{\beta} \\ \text{where } \left(\sum_{k=1}^{i} t_{[k-1]}Q_{[k-1]} \Big/ \alpha\right)^{\beta} < 1, \\ t_{[N+1]} = 0,\ t_{[N]} = p \text{ and } Q_{[N+1]} = 0 \end{gathered}$$

(7)

For example, let there be three batches and the batch sizes are: $Q_{[1]}$= 3, $Q_{[2]}$= 2 and $Q_{[3]}$= 1. The initial processing time(p) is 2 minutes. Meanwhile, the additional time due to deterioration (μ) is 0.2 minutes. The scale parameter (α) is 4 minutes and the shape parameter (β) is 2. Then, by using equation (14) obtained $t_{[1]}$= 0528 minutes, $t_{[2]}$=0.503 minutes and $t_{[3]}$= 0.5 minutes. The calculation results using forward approach and backward approach show similar.

3. Problem Formulation and Solutions Methods

3.1 Problem Formulation

Let be n units parts to be processed on a single machine. The parts are divided into N batches and the set up time required before any batches processed. Let us assume that the machine will be damaged at time T and machine deterioration will occur at interval $[0,T)$. The additional processing time occur due to machine deterioration effect. Since batch processing time affected by machine deterioration, therefor the batches that processed latter require a longer processing time than the batch previous processed. The company has capability to control the arrival times for all of batches and they should be delivered at their common due date. The objective is to minimize the total actual flow time. The problem can be modeled as non-linier programs using the following notation:

Decision variables
- N : number of batches
- $Q_{[i]}$: batch size at position i, with i = 1,2, ..., N

Parameters
- d : due date
- n : demand
- s : Setup time, it is required before any batch processed on the machine
- p : batch processing time at position-N (initial processing time)
- μ : additional time due to machine deterioration
- α : scale parameter, we assume α is the first failure of machine
- β : shape parameter, we assume β is machine deterioration parameter (β>1)

Dependent variable
- $t_{[i]}$: batch processing time at position-i, the value affected by machine deterioration

Objective function
- F^a : Actual flow time

Mathematical model is:

Objective function

$$\min\ F^a = \sum_{i=1}^{N}\left(\sum_{j=1}^{i}\left[s+\left\{p+\mu\left(\sum_{k=i}^{N} t_{[k+1]}Q_{[k+1]} \Big/ \alpha\right)^{\beta}\right\}Q_{[j]}\right]-s\right)Q_{[i]} \tag{8}$$

subject to

$$\sum_{i=1}^{N} Q_{[i]} = n \tag{9}$$

$$\sum_{i=1}^{N}\left\{p+\mu\left(\sum_{k=i}^{N} t_{[k+1]}Q_{[k+1]} \Big/ \alpha\right)^{\beta}\right\}Q_{[i]} + (N-1)s \le d \tag{10}$$

$$B_{[1]} + \left\{p+\mu\left(\sum_{k=1}^{N} t_{[k+1]}Q_{[k+1]} \Big/ \alpha\right)^{\beta}\right\}Q_{[1]} = d \tag{11}$$

$$\left(\sum_{k=i}^{N} t_{[k+1]} Q_{[k+1]} \Big/ \alpha\right)^{\beta} < 1 \tag{12}$$

$$Q_{[N+1]} = 0,\ t_{[N+1]} = 0 \tag{13}$$

$$Q_{[i]} > 0,\ N > 1 \text{ and integer} \tag{14}$$

Equation (8) shows the objective function of the model is to minimize the total actual flow time by considering machine deterioration. Equation (9) is the constrant that shows a material balance i.e, the number of parts in all of batches is equal to the demand. While equation (10) shows that all of batches should be completed before or at their common due date. Equation (11) is the constraint to explain that the first scheduled batch should exactly coincides with the due date. Equation (12) states that the expectation number of deterioration must be less than one. Equation (13) declares that there is no batch will be processed before the last batch has been scheduled. Equation (14) is the constrant that shows the batch sizes must be greater than zero and the number of batches must be positif value and integer.

3.2 Solution Method

The steps of validating the maximum expectation number of deterioration and determining the maximum number of batches are taken to propose an algoritm. Based on the assumption that machine deterioration occurs in the interval of $[0,T)$ therefor the maximum number of deterioration must be smaller than one (see on equation (12)). In this study, we relax equation (12) to be

$$\Lambda_{\max} < \left[n - (n/N)/\alpha\right]^{\beta} - 1 \tag{15}$$

where α is scale parameter and β is shape parameter. This research assume α as the first failure of machine and β as machine deterioration parameter. The value of α must be positive and the value of β must be greather than one.

The Solution method on this research based on Sukoyo et all. (2008) that proposed an algorithm which is obtained by relaxing the decision variable N (or the number of batches) as a parameter and then proceed by searching an optimal solution. The solution method begins by detemining the maximum value of N, and the next step is to solve the model for several values of N, started from $N = 1$ and incresed one by one iteratively until a stopping rule is satisfied (the optimal N will be less than or equal to the maximum N). The maximal number of N obtained when all parts are processed by the initial value of batch processing time. The maximal number of N formula is as follows:

$$N_{\max} = \left[\left\{d - (np)\right\}/s\right] + 1 \tag{16}$$

The algorithm steps as follow:

Step 1: Validate the maximum expectation number of deterioration with using equation (14). If Λmax<1 then go to step 2 otherwise stop because there is no feasible solution.

Step 2: Calculate $N_{\max}$ based on equation (16). If $N_{\max} \geq 1$ then go to step 3 otherwise stop because there is no feasible solution.

Step 3: Calculate the actual flow time and batch sizes (Q) with N=1 using non-linear programing models (8) to (14) and set the value as the best total actual flow time (Z optimal) and obtained $Q_{[I]}$ values as $Q_{[I]}$ optimal values. Proceed to step 4

Step 4: Increase the number of batches, N=N+1 and go to step 5

Step 5: Find the optimal values of $Q'_{[I]}$ using non-linear programing models (8) to (14) for the given N value. Calculate the actual flow time that is obtained from $Q'_{[I]}$ optimal and set as Z'. Proceed to step 7.

Step 6: If $Z' < Z$ optimal then set Z optimal = Z', $Q_{[I]}$ optimal values = $Q'_{[I]}$ optimal values. N optimal =N and go to step 7

Step 7: Evaluate N. If N= $N_{\max}$ then go to step 8 otherwise go back to step 4

Step 8: Stop, set as optimal solution

4. Numerical Experiment and Analysis Model

The model testing is carried out by providing a data as follows: p= 0.5, n= 100, d= 100, s= 2, μ= 0.2, α= 50 and β= 2. The proposed solution algorithm is shown in Table 1.

Table 1: Model Testing Results

Number of batches (N)	Batch sizes ($Q_{[i]}$)	Batch processing time ($t_{[i]}$)	Total actual flow time (F^a)
1	$Q_{[1]}$=100	$t_{[1]}$=0.5	5000
2	$Q_{[1]}$=52.496, $Q_{[2]}$=47.504	$t_{[1]}$=0.3, $t_{[2]}$=0.5	3973
3	$Q_{[1]}$=36.050, $Q_{[2]}$=34.915, $Q_{[3]}$=29.035	$t_{[1]}$=0.585, $t_{[2]}$=0.517, $t_{[3]}$=0.5	3680
4	$Q_{[1]}$=29.054, $Q_{[2]}$=28.067, $Q_{[3]}$=24.029, $Q_{[4]}$=18.850	$t_{[1]}$=0.608, $t_{[2]}$=0.537 $t_{[3]}$=0.50, $t_{[4]}$=0.5	3574
5	$Q_{[1]}$=25.724, $Q_{[2]}$=24.622, $Q_{[3]}$=21.085, $Q_{[4]}$=16.582, $Q_{[5]}$=11.988	$t_{[1]}$=0.62, $t_{[2]}$=0.551, $t_{[3]}$=0.516, $t_{[4]}$=0.503, $t_{[5]}$=0.5	3540
6	$Q_{[1]}$=24.143, $Q_{[2]}$=23.017, $Q_{[3]}$=19.637, $Q_{[4]}$=15.359, $Q_{[5]}$=11.027, $Q_{[6]}$=6.817	$t_{[1]}$=0.627, $t_{[2]}$=0.558, $t_{[3]}$=0.522, $t_{[4]}$=0.506, $t_{[5]}$=0.501, $t_{[6]}$=0.5	3536
7	$Q_{[1]}$=23.515, $Q_{[2]}$=22.468, $Q_{[3]}$=19.141, $Q_{[4]}$=14.926, $Q_{[5]}$=10.684, $Q_{[6]}$=6.618, $Q_{[7]}$=2.648	$t_{[1]}$=0.629, $t_{[2]}$=0.561, $t_{[3]}$=0.525, $t_{[4]}$=0.508, $t_{[5]}$=0.502, $t_{[6]}$=0.5, $t_{[7]}$=0.5	3543

The calculation in equation (14) obtains the value of $N_{\max}$ = 26. Table 1 shows the optimal value of the total actual flow time is 3536 obtained by N= 6. The results show that the optimal schedule obtained by scheduling batches according to the LPT rule using backward scheduling approach. The largest batch size is scheduled to the closest due date and followed by other batches which have smaller sizes non-increasingly.

<u>Theorem 1</u>

Let there be N batches to be processed on a single machine which has constant setup time and the processing time influenced by machine deterioration effect. The sequence of batches which minimize the total actual flow time obtained by LPT rule using backward scheduling approach.

$$\left(t_{[1]}Q_{[1]}+s\right)/Q_{[1]} \le \left(t_{[2]}Q_{[2]}+s\right)/Q_{[2]} \le \ldots \le \left(t_{[N]}Q_{[N]}+s\right)/Q_{[N]} \tag{17}$$

Proof:

There are two feasible schedules for N batches. The first Schedule places batch (i) to (i) sequence and batch (i+1) to (i+1) sequence and both of them are sorted using backward scheduling. The defference between the first and the second is only in the batch position of (i) is in (i+1) sequence and the position of batch (i+1) is in (i) sequence. If F^{a1} and F^{a2} are each total actual flow time for both of the first and the second schedule, then obtained:

$$F^{a1}-F^{a2}=\left(t_{[i]}Q_{[i]}Q_{[i+1]}+s\ Q_{[i+1]}\right)-\left(t_{[i+1]}Q_{[i+1]}Q_{[i]}+s\ Q_{[i]}\right) \tag{18}$$

The first schedule will give smaller total actual flow time or equal to the second schedule ($F^{a1} \le F^{a2}$) if and only if:

$$\left(t_{[i]}Q_{[i]}+s\right)Q_{[i+1]} \le \left(t_{[i+1]}Q_{[i+1]}+s\right)Q_{[i]} \tag{19}$$

or

$$t_{[i]}+s/Q_{[i]} \le t_{[i+1]}+s/Q_{[i+1]} \tag{20}$$

Batch scheduling problems with machine deterioration effect assuming that the batch processing time of (i) sequence is longer than or equal to the processing time of (i+1) sequence. It means the processing time ($t_{[i]}$) is always sorted from largest to smallest in backward scheduling approach. The equation (20) will result the left side value is smaller than the right side if the batch size on the left side ($Q_{[I]}$) is greater than the right side ($Q_{[i+1]}$). Therfor, the optimal value of total actual flow time is obtained by scheduling batch non-increasingly in backward scheduling approach (proven) ■

Further tests are carried out by testing the sensitivity of the model by changing the scale parameter (α) and shape parameter (β). The first test is carried out by assuming a constant shape parameter (β= 2) but using varying of scale parameter i.e: 25, 50, 75, 100, 125, 150 and 175. In the second test, we assume a constant scale parameter (α= 50) and using varying of shape parameter i.e: 1, 1.5, 2, 2.5 and 3. Let there be an input data are n =100 units, d=100 minutes, p= 0.5 minutes, s= 2 minutes, μ= 0.2 minute. The results of sensitivity test are shown in Table 2 and Table 3.

Table 2: Tests using various values of α

scale parameter (α)	Shape parameter (β = 2)
	Optimal value of Total actual flow time (F^a)
25	No solution because the machine is failed
50	3536
75	3425
100	3389
125	3373
150	3364
175	3359

Table 3: Tests using various values of β

shape parameter (β)	Scale parameter (α = 50)
	Optimal Value of Total actual flow time (F^a)
1	3730
1.5	3612
2	3536
2.5	3487
3	3453
3.5	3429
4	3421

Table 2 shows the larger of α parameter, the minimum total actual flow time. This is logical because the larger α the longer time of machine failure, therefor the machine deterioration will be slow causing the actual flow time become smaller. Meanwhile, Table 3 shows the larger of β parameter, the smaller of actual flow time. The reason is the larger β the smaller effect of machine deterioration causing the actual flow time become smaller.

5. Concluding Remarks

This study addresses batch scheduling problems on a single machine where batch processing time is affected by machine deterioration to minimize the total actual flow time. The proposed algorithm is obtained by relaxing the decision variables N (number of batches) as the parameter. The concluding remarks are: (1) an optimal value of the total actual flow time obtained by scheduling batches in a non-increasing using backward scheduling approach; (2) the larger of scale parameter (α), the minimum of total actual time; (3) the larger of shape parameter (β), the minimum of total actual time. This study is able to generate solutions in batch scheduling problems with the increase of batch processing time, specially due to machine deterioration effect. However, the problems in practical situations show that the processing time affected by learning (the processing time will decrease) and deteriorating (the processing time will increase) simultaneously. Therefor, a further research is needed to discuss the batch scheduling problems by considering the increase and decrease of processing time simultaneously.

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