Order flow times in case of single stage production batches based on flexible batching rules : a preliminary simulation approach

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- a preliminary simulation approach

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Abstract
Work station dependent batching is a frequently observed phenomenon in industry. In many cases these production batches are created in a flexible way, i.e. depending on the situation at hand. In this paper we study the implications of the creation of production batches based on some simple batching rules concerning the number of jobs per batch taking into account the situation at hand. Preliminary simulation results show that such flexible batching rules have a major impact on job flow times.

1. Introduction

In this paper we consider component manufacturing shops where components are being produced in work orders requiring several operations on a number of work stations. A work order can be regarded as an order to produce a set of identical components that is treated as an entity during production. In other words, the entire set of components of a work orders is assumed to arrive at a work station at the same time, and the operation performed at the work station on the work order is regarded to be completed only after the operation is completed for all items. We will assume that it is not possible to have immediately subsequent operations on the same work station. The operation of a work order on a particular work station will be called a job.

In the component manufacturing shops considered we assume that at certain work stations it is required to produce in production batches. A production batch (sometimes also called a production run) can be regarded as a set of jobs produced on a work station one after the other (or sometimes together) using the same work station set-up. Production batches are created for several reasons. The most common reasons for batching are related to efficiency and/or capacity reasons: increasing the batch size often increases the efficiency and possible output of work stations. Some examples of these situations are:
- combining work orders reduces the total time spent per period on setting up a work station;
- combining work orders increases the output rate of the work station during production, e.g. in case of ovens;
- combining work orders reduces the fraction of items that are rejected due to set-up problems.

The main reason for creating these batching at the work station instead of at work order release is that the work orders considered do not follow the same routing.

In this paper we consider the flow time consequences of creating production batches according to flexible, viz. situation dependent batching rules. We will limit ourselves to the case where production batches are created according to the number of work orders at hand.

2. Batching based on flexible batching rules

By definition production batches are work station dependent. In case two or more work stations require production batches, usually the batches required at the different work stations are not identical (either because a different batch size is required, or because a different combination of work orders is required). Examples of such work station dependent batching are:

- a production department where some work stations are highly utilized and require longer set-up times than others;
- a production department where set-up times to a large extend are dependent on the production sequence of jobs, while the characteristics determining these sequence-dependent set-up times are different for distinct work stations;
- a production department where some work stations can process several jobs simultaneously (e.g. ovens), while others cannot.

Apart from being work station dependent, production batches can also be situation dependent. In such a case the contents of a production batch (and thus also the batch size of the production batch) is dependent on the situation at the time the batch is created at the work station. For instance, in case the number of jobs waiting at the work station is large, the batch size of the production batches may increase, while in case there are only a few jobs waiting at the work station, the batch size may be small. We distinguish two cases of situation dependent batching at work stations, viz.:

1 Batching based on sequencing considerations. In this case batches are created more or less spontaneously based on e.g. sequencing rules. In other words, no explicit batching rules are used. The sequencing rules may consider aspects like work order priority and pre-determined production programs based on set-up considerations (e.g. a cyclic production program).

2 Batching based on explicit (situation dependent) batching rules. In this case the scheduling problem at the work station is split up into two sub-problems, viz. the batching problem (i.e. the creation of batches according to predetermined batching rules) and the sequencing problem (i.e. sequencing of these batches). Each job joins a batch of the right class (which is determined by the set-up requirements of the job) immediately after arrival. As long as the set of available jobs of a particular class hasn't met a certain batching criterion yet (e.g. the number of jobs belonging to the batch is not large enough), this set is not considered for production.

In this paper the discussion is limited to the second case of situation dependent batching, i.e. we assume that explicit batching rules are used. We study the case where production batches are created according to the number of work orders required. We distinguish two flexible approaches, viz.:

- The standard batching rule is expressed in a fixed batch size (i.e. the number of jobs required). However, this standard criterion is overruled if this prevents the machine from getting idle. In other words, as long as the machine remains busy, batches are created according to the fixed batch size. However, if the machine is idle and no batches meeting the fixed batch size are available, batches containing less jobs may be selected for production. Which of these batches should be selected is based first of all on a so-called idleness batching criterion. The idleness batching criterion is a batching criterion which is used only in case a machine of the work station is idle, and is also expressed in the number of jobs required (batch size). Secondly, among the batches meeting the idleness batching criterion, a batch is chosen according to a particular priority rule. In this paper we will assume a FIFO-rule. Note that an idleness batching criterion is only useful if it is smaller than the standard batching criterion. In other words, the set of batches meeting the standard batching criterion is a subset of the set of batches meeting the idleness batching criterion.

- A different, but similar way of batching in a flexible way, is the case where both a minimum and a maximum batching criterion is used. In these cases, on the one hand for batches in order to be considered for production some minimum criterion (i.e. a minimum batch size) must be met, while on the other hand each batch size is limited by some maximum criterion (the maximum batch size) in order to prevent the machine from being occupied too long for one class of jobs.

In the next section we will formulate the problems to study in more details. For each of the flexible batching criteria we will study the job flow and discuss some of the flow time consequences.

3. Problem definition

Consider a component manufacturing shop with job shop characteristics where jobs are completed at certain work stations in production batches. We partition the set of jobs to be produced on a work station m into N classes such that a (production) batch for work station m can only be created from jobs belonging to the same class. Since we are only interested in the flow times of jobs at a work station, we will ommit the index m. We assume for each class k a Poisson arrival process with an average rate of λ_k. As has been indicated before, each job is considered to be an entity, i.e. the items belonging to the same job are not considered individually.
We assume that the jobs belonging to one batch are completed one after the other. We will refer to this way of production as *sequential production*. The opposite of sequential production is *simultaneous production*, where all jobs belonging to one batch are completed at the same time (e.g. in case of an oven). The case of sequential production is also known as *item flow* [Karmarkar et al., 1984] or item availability [Santos and Magazine, 1985], whereas the case of simultaneous production is sometime referred to as *batch flow* [Karmarkar et al., 1984] or batch availability [Santos and Magazine, 1985]. In case of sequential production, the total batch operation time depends on the operation times for each job. We will assume that within each batch jobs are completed in FIFO-sequence. For instance, assume that batch j consists of three jobs (resp. *1, 2, 3*). Assume further that job *1* has arrived prior to job *2*, while job *2* has arrived prior to job *3*. As soon as this batch j is taken into operation, we assume that first job 1 will be completed, then job *2* and finally job *3*.

We will denote the operation time of job i of class k as $p_{i,k}$, where $p_{i,k}$ can be regarded as a random draw from a negative exponential distribution with an average of p_k. Within a batch no set up time is required except for the time already specified by $p_{i,k}$. However, set up time is required between two batches of distinct classes. We assume that this set up time is only dependent on the next batch, not on the previous batch. The batch set up time for batch j of class k is denoted as $s_{j,k}$ and can be regarded as a random draw from a negative exponential distribution with an average of s_k.

We will consider batching based on three batching criteria used simultaneously, i.e.:

- a maximum batching criterion, defining the maximum number of jobs in each batch;
- a minimum batching criterion, defining the minimum number of jobs required for a batch to be considered for production, assuming that the machine is not idle;
- an idleness batching criterion, defining the minimum number of jobs required for a batch to be considered for production, assuming that the machine is idle.

Clearly, we assume that the idleness batching criterion is not larger than the minimum batching criterion, while the minimum batching criterion on its turn is not larger than the maximum

batching criterion.
A batch is producible if it meets the idleness batching criterion. If the batch meets the minimum batching criterion, it will be called a standard batch. Clearly, all standard batches are producible. If the batch also meets the maximum batching criterion, it is called a closed batch. Table 1 gives an overview of the different batches.

Table 1: Definitions of batches based on batching criteria.

Batch			idleness bat.crit.	minimum bat.crit.	maximum bat.crit.
producible	standard	closed			
non	non	open	–	–	–
producible	non	open	+	–	–
producible	standard	open	+	+	–
producible	standard	closed	+	+	+

+: batch meets criterion; –: batch doesn't meet criterion

We define a Q_k^-, a Q_k^+, and a Q_k^i as the number of jobs required by batches of class k to meet resp. the minimum batching criterion, the maximum batching criterion, and the idleness batching criterion. Also, we will only study the symmetric case of sequential production. A queueing model is called symmetric if from a statistical point of view all characteristics of all the job classes involved are identical [Takagi, 1988]. In other words, we assume that:

$\lambda_k = \lambda$ (for all k)
$p_k = p$ (for all k)
$s_k = s$ (for all k)
$Q_k^- = Q^-$ (for all k)
$Q_k^+ = Q^+$ (for all k)
$Q_k^i = Q^i$ (for all k)

Furthermore, in our study we assume for each job class a separate Poisson arrival process. Also, we assume that the work station considered consists of only one machine.

3. Analysis

3.1 Fixed batch size

Before studying the case of flexible batching, we will first have a look at the case where production batches are created according to a predetermined fixed batch size. In other words, we assume that $Q^i=Q^-=Q^+=Q$. At first sight, such a case resembles the case where the impact of work order lot sizes on (average) flow times is studied. It is a well known result that reducing the lot size of a work order usually has two or three effects, i.e. a reduction in average operation time and an increase in utilization rate (due to an increase in the number of set-ups required). Usually also the standard deviation of the operation times changes. This may result in a reduction in flow times, because the reduction in operation times has a larger impact than the increase in utilization rates. This will be the case for low utilization rates. On the other hand, if utilization rates are high, reducing lot sizes is likely to increase the flow times, because the increase in utilization rate has such a large impact (see e.g. [Karmarkar et al., 1984]). In other words, in case of large lot sizes and not too high utilization rates, reducing the lot size will result into a reduction in average flow time, because the reduction in operation time has a larger impact than the increase in utilization rate. However, in case lot sizes get very small, utilization rates already are high (due to the large number of set-ups). Reducing the lot size even further will result into a further increase in utilization rate, which will have a large impact on the average flow time. Therefore, in these cases the average flow time will grow. As a result, we may expect a convex bowl-shaped curve as shown in Fig.1.

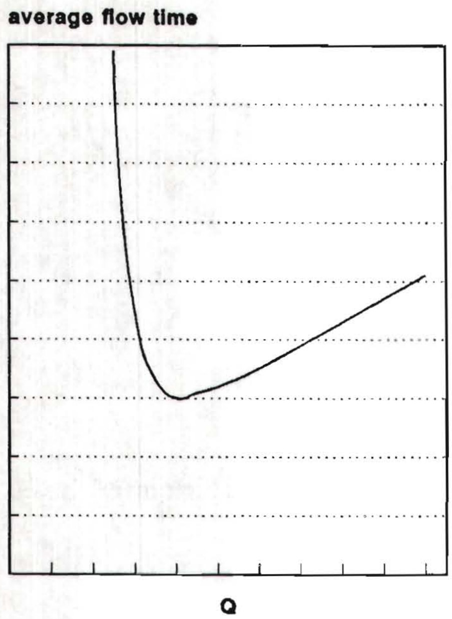


Figure 1: Expected flow time effect of change in lot size.

In our case we are not interested in the lot sizes of jobs, but in the batch sizes of batches created at a work station according to a fixed production batch size. The difference between this latter case and the lot sizing problem is that the average flow time of a job not only consists of a waiting time component and a operation time component, but also of a batch completion time component. In other words, in order to determine the job flow time, we have to consider three different time components:

- completion time: the time required after arrival of a job before a batch is created;
- waiting time: the time required after the creation of a batch before the batch is taken into operation;
- operation time: the time required after the batch has been taken into operation before the job is completed.

Clearly, the expected completion time of the n-th job of a batch will be:

$$\frac{(Q-n)}{\lambda}$$

Then the average completion time of a job will be:

$$\underline{\bar{c}} = \frac{\sum_{n=1}^{Q} \frac{(Q-n)}{\lambda}}{Q} = \frac{(Q-1)}{2\lambda}$$

Obviously, the larger the batch size, the longer the expected completion time will be. Since we assume that the interarrival time of jobs of the same class is a random draw from a negative exponential distribution function, we know that the interarrival time of batches of the same class in the waiting queue can be considered as a random draw from an Q-Erlang distribution with an average of:

$$\bar{\underline{a}} = \frac{Q}{\lambda}$$

and a standard deviation of:

$$\sigma_{\underline{a}} = \frac{\sqrt{Q}}{\lambda}$$

In other words, the variation coefficient will be:

$$y_{\underline{a}} = \frac{\sigma_{\underline{a}}}{\bar{\underline{a}}} = \frac{1}{\sqrt{Q}}$$

Thus, the larger the batch size, the lower the variation coefficient of the class dependent batch interarrival time will be.
For the overall batch arrival rate in the waiting queue, we obtain:

$$\Lambda_{overall} = \frac{\lambda N}{Q}$$

For a first rough estimate of the flow time, we will assume that the overall arrival process of batches will be a Poisson process, thus creating a M/G/1 queue. Clearly, for large batch sizes this assumption will give an overestimate of the waiting time.
From a similar analysis, assuming an exponential distributed job operation time ($\underline{p}$) and a constant setup time for each batch, we know that the batch operation time will have a Q-Erlang distribution with an average of:

$$\bar{\underline{P}} = s + Q\bar{\underline{p}}$$

and a standard deviation of:

$$\sigma_{\underline{P}} = \bar{\underline{p}}\sqrt{Q}$$

The variation coefficient of the batch operation time is:

$$y_{\underline{P}} = \frac{\bar{\underline{p}}\sqrt{Q}}{s + Q\bar{\underline{p}}}$$

Using the P/K-formula for the calculation of the average waiting time of a batch in the waiting queue, for a M/G/1-queue, we obtain:

$$\bar{\underline{w}} = \frac{\frac{\lambda N}{Q}\left((s+Q\bar{\underline{p}})^2+\bar{\underline{p}}^2 Q\right)}{2\left(1-\frac{\lambda N}{Q}(s+Q\bar{\underline{p}})\right)}$$

Finally, the average job operation time will be:

$$\bar{\underline{o}} = \frac{(\bar{\underline{s}}+\bar{\underline{p}})+(\bar{\underline{s}}+2\bar{\underline{p}})+\ldots+(\bar{\underline{s}}+Q\bar{\underline{p}})}{Q} = \bar{\underline{s}}+\bar{\underline{p}}\frac{(Q+1)}{2}$$

Then, the average job flow time will be:

$$\bar{\underline{t}} = \bar{\underline{c}}+\bar{\underline{w}}+\bar{\underline{o}}$$

In Fig.2 two examples are given of the relation between Q and the average job flow time, assuming two particular settings for the job arrival rate, the setup time and the job processing time.

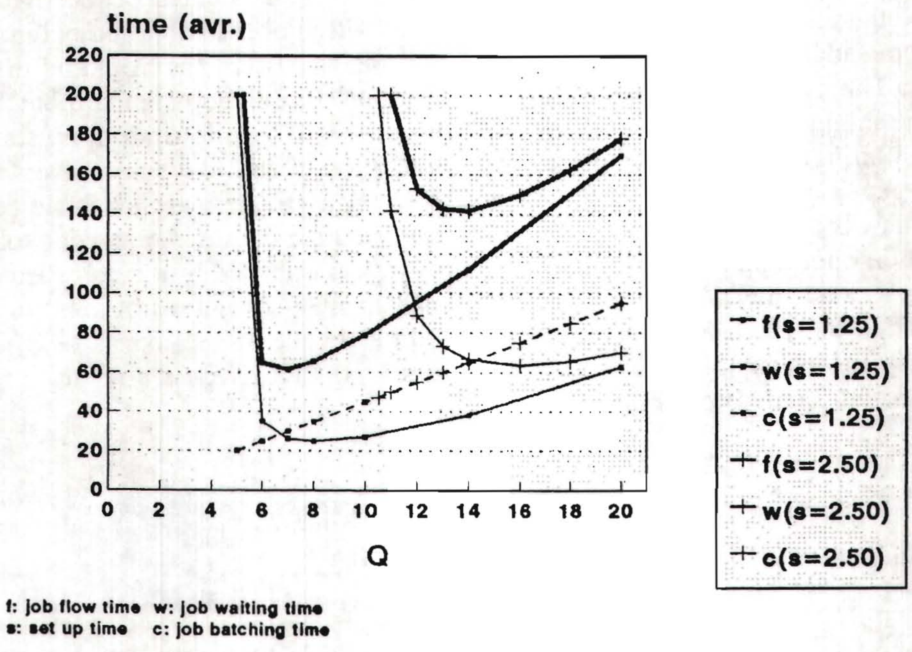


Figure 2: Average job flow time as function of a fixed Q.

As we can see, indeed for a fixed Q we obtain a convex bowl-shaped curve as shown in Fig.1.

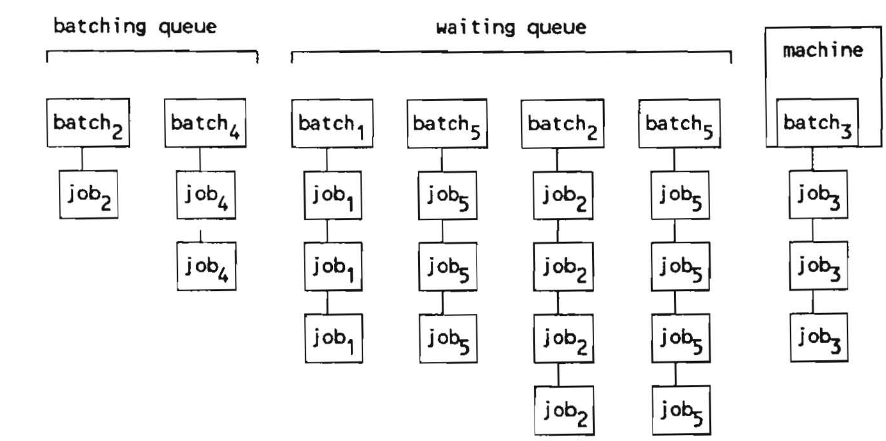
3.2 Flexible batch size

One of the major disadvantages of a fixed Q in this situation is the fact that it is possible that the machine is idle while at the same time jobs are available, viz. in case the number of jobs per class is smaller than the required number for a batch. On top of that, a fixed batch size makes it impossible to adapt to the situation at hand. In case of a large work load, limiting the set-up time makes it possible to decrease the work load rapidly. On the other hand, in case of a small work load, a small batch size will make sure that jobs are taken into operation rapidly. In other words, it might be worthwhile to increase batch sizes in case of a large work load, while in case of only a small work load small batch sizes seem to be advantageous (even though the average utilization rate may be high).

4. Simulation Model

In order to study the flexible batching rules mentioned in the previous section more closely a simulation model was used. We will illustrate the simulation model by using an example. In this example we distinguish six job classes (N=6). The idleness batching criterion is two jobs ($Q^i=2$), the minimum batching criterion is three jobs ($Q^-=3$), while the maximum batching criterion is four jobs ($Q^+=4$). Fig.3 gives a schematic view of a possible state for the example case. As we can see, we distinguish a batching queue and a waiting queue. In the batching queue all non standard batches (producible or non producible) are located. In the example this means that all batches in the batching queue have a batch size of one or two jobs. In the waiting queue all batches are located that meet the minimum batching criterion (i.e. both open standard batches and closed standard batches), but have not yet been taken into production. In other words, in the example the batches in the waiting queue have three or four jobs (see Fig.3).

New jobs arriving at the work station will either join one of batches already present at the work station, or will cause the creation of a new batch. As long as there is a batch of the right class available not meeting the maximum batching criterion, jobs will join this batch. Sometimes this means that an open standard batch will turn into a closed standard batch (as would be the case if e.g. a job of class 1 or 5 arrives). If the arriving job joins a producible non standard batch, this batch will meet the minimum batching criterion and therefore will turn into an open standard batch and join the waiting queue. Such would be the case if a job of class 4 would arrive. In case at job arrival no open standard or non standard batches of the right class are available (e.g. in case of class 6), a new batch will be created and put in the batching queue. An arriving job may even join the batch in operation if this batch is not closed yet (as opposed to the so-called gated case where as soon as a batch is taken into operation newly arriving jobs may not join the batch anymore, even though the batch is not a closed standard batch; see also [Takagi, 1988]). This would be the case if in the example of Fig.3 a job of class 3 would arrive. As a result, for each class at most one closed standard batch will be available.



batch$_k$: batch of class k
job$_k$: job of class k

Figure 3: A possible state in the example case.

Note that the idleness batching criterion is not relevant for the situation given in Fig.3. Only in case both the machine and the waiting queue are empty, batches in the batching queue may be considered for production.

In case the machine gets idle while the waiting queue is not empty, a new batch from the waiting queue will be taken into production according to the so-called waiting queue priority rule. If the waiting queue is empty at the time the machine gets idle, one of the producible batches in the batching will be choosen according to the so-called batching queue priority rule.

The model is programmed in Simula and runs on a IBM P70 386 with co-processor.

5. Simulation Experiments

We have studied the implications for job flow times of the flexible batching rules presented in section 1 using the simulation model described in the previous section. In all simulation experiments, batch set up times are random draws from a negative exponential distribution. We assume sequential production. The job operation times are drawn from a negative exponential distribution function (different from the distribution function used for batch set up times). Furthermore, both the waiting queue priority rule and the batching queue priority rule are FCFS. A batch in the batching queue is assumed to have arrived on the moment the first job of this batch is arrived. A batch in the waiting queue is assumed to have arrived on the moment the minimum batching criterion is met.

5.1 Fixed Q Experiment

In the first experiment we assume that all batching criteria are equal, thus:

$$Q^i = Q^- = Q^+$$

Table 2: Settings for the Fixed Q Experiment.

Number of Job Classes:	8
Number of jobs:	10,000
For each Job Class:	
job operation time density:	exponential
average job operation time:	1.0
job interarrival time density:	exponential
average job interarrival time:	10.0
batch set up time density:	exponential
average batch set up time:	1.25 resp. 2.50

Fig.4 presents the results of several simulation experiments assuming that $Q^i=Q^-=Q^+$. The settings of these experiments are given in Table 2. Fig.4 not only gives the average job flow time, but also the average job completion time and the average job waiting time (i.e. the time a job remains in the waiting queue). Since $Q^i=Q^-=Q^+$, the waiting time of a job equals the waiting time of the batch the job belongs to. In Table 3 the resulting utilization rates are given. As we can see, indeed the average flow time curve has the shape as expected.

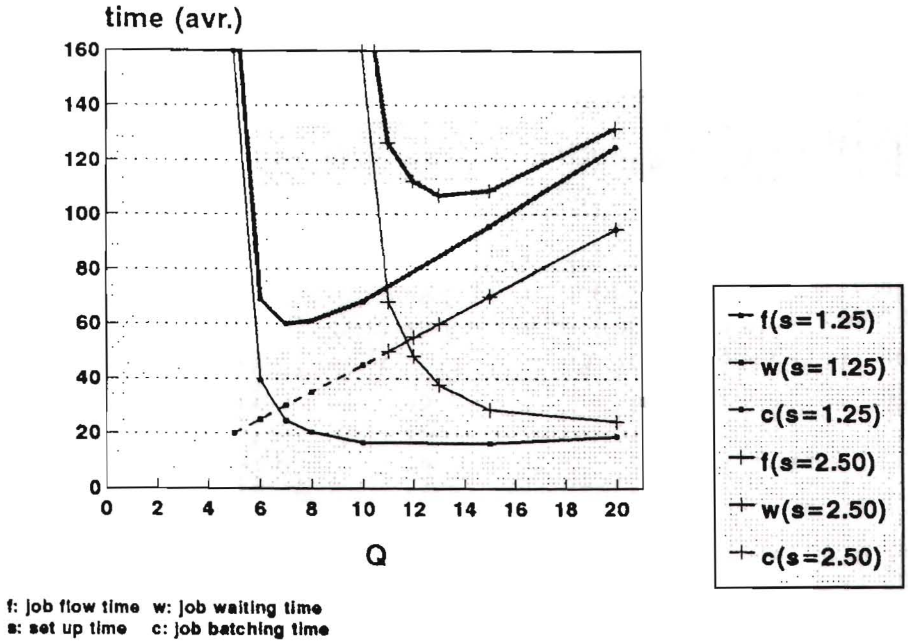


Figure 4: *Results in case of Fixed Q Experiment.*

Table 3: *Resulting utilization rates in Fixed Q Experiment*

ρ (%)	Q									
	5	6	7	8	10	11	12	13	15	20
s=1.25	99.2	96.1	93.8	92.1	89.5	-	-	-	86.2	84.6
s=2.50	-	-	-	-	-	97.6	96.2	94.8	92.7	89.5

5.2 Minimum Q Experiment

In the next experiment we study the influence of the minimum batching criterion. In other words, we will assume that:

$$Q^{-} \leq Q^{+}$$

Clearly, the average batchsize will be larger than Q^{-} and smaller than Q^{+}. Or more precisely:

$$Q^{-} \leq \overline{Q} \leq Q^{+}$$

In order to avoid any influence of the idleness batching criterion, we will assume that:

$$Q^{i} = Q^{-}$$

In the simulation experiments conducted in this experiment, we used the same settings as in the previous experiment (see Table 2). In all experiments Q^{+} was set at 20.
This case is more flexible than the previous case where $Q^{i}=Q^{-}=Q^{+}$. In this case the batch size will adapt to the situation at hand: in case of a high work load batch sizes will increase, while in case of a low work load batch sizes will decrease. On the other hand, the utilization rate will increase with a reduction in Q^{-}. However, we know from polling models (see e.g. [Takagi, 1988]) that in case of flexible batching the utilization rate may not have the same impact as it has in case of fixed batches.

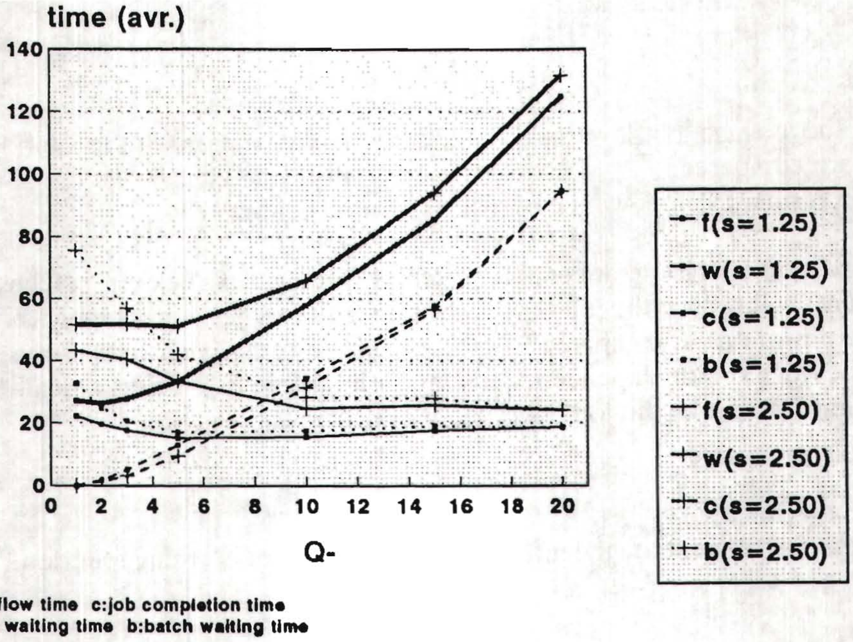


Figure 5: *Results in case of the Minimum Q Experiment.*

Fig.5 presents the results of the simulation experiments. The figure gives the average job flow time, the average job completion time and the average job waiting time. Since $Q^{-} \leq Q^{+}$, and thus some jobs still can be added to the batch while the batch is waiting for production (or even in production), the average waiting time of a job usually is shorter than the average waiting time of the batch. In Table 4 the resulting utilization rates are given. It is remarkable to notice that even though the utilization rates get very high, the average flow time does not really increase. Obviously the flexibility of the batch sizes compensates for these high utilization rates.

Table 4: *Resulting utilization rates in Minimum Q Experiment*

ρ (%)	Q^{-}						
	1	2	3	5	10	15	20
s=1.25	99.9	98.9	96.7	92.8	87.2	85.0	84.6
s=2.50	100.0	-	99.8	98.7	93.3	90.1	89.5

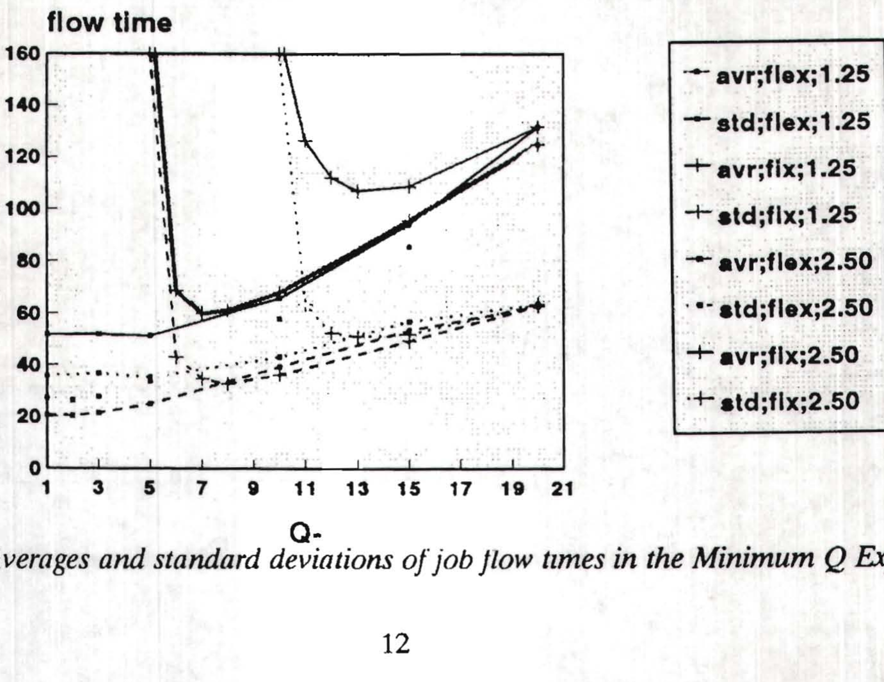


Figure 6: *Averages and standard deviations of job flow times in the Minimum Q Experiment.*

In Fig.6 both the average job flow times and the standard deviations of the job flow times of both experiments are compared.
Observing the results the following conclusions may be drawn:

1) In case of work station dependent batching the use of flexible batches (i.e. situation dependent) will reduce the job flow times for small batches considerably (both average and standard deviation) as compared to the case where fixed batch sizes are used.
2) In case of work station dependent batching with flexible batch sizes a small Q^- is preferable to a large Q^- as far as the job flow time is concerned.

5.3 Idle Q Experiment

In the next experiment we study the influence of the minimum batching criterion. We will assume that:

$$Q^i \leq Q^- \leq Q^+$$

In other words, we will study the situation where not only the batch size may vary between Q^- and Q^+ according to the situation at hand, but also in case the machine gets idle a batch size smaller than Q^- will be accepted.

Again, in the simulation experiments conducted in this experiment, we used the settings of Table 2. In all experiments Q^+ was set at 20, while s was set at 1.25.

Since this case is even more flexible than the case described in the Minimum Q Experiment, we expected a further reduction in the average flow time. However, the smaller the difference between Q^- and Q^i, the less the reduction was expected to be. Clearly, in case $Q^-=Q^i$ there will be no difference between the Minimum Q Experiment and the Idle Q Experiment.

Fig.7 presents the results of the simulation experiments. The figure gives the average job flow time in case $Q^i=10$, $Q^i=5$, $Q^i=3$, and $Q^i=1$. In order to be able to compare the results of the Minimum Q Experiment and this Idle Q Experiment, the average flow time in case $Q^i=Q^-$ is included. It is surprising to see that in the Idle Q Experiment the average job flow time seems to be insensible to Q^-. In other words, setting Q^i at a certain value gives the same results as setting Q^- at the same value (assuming an identical Q^+).

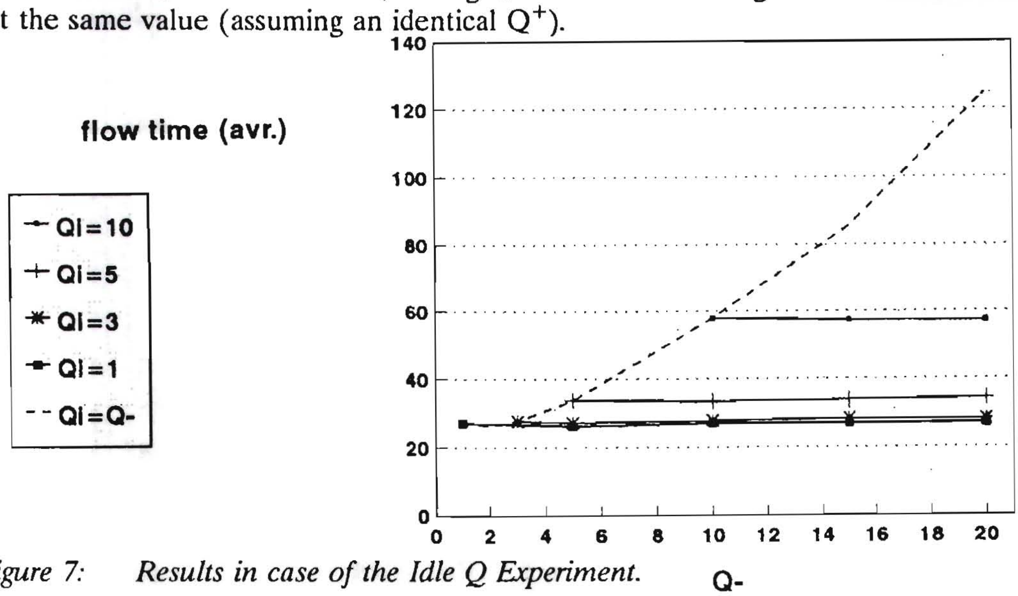


Figure 7: Results in case of the Idle Q Experiment.

6. Conclusions and further research

From the simulation experiments the following conclusions may be drawn:

1 In case of fixed batching rules the work station dependent production batch size will have an impact on the job flow time similar to the influence of work order lot size on the work order flow time, i.e. the average flow time will be a convex bowl-shaped function of Q.
2 In case of work station dependent batching the use of flexible batches rules will reduce the job flow times for small batches considerably (both average and standard deviation) as compared to the case where fixed batch sizes are used.
3 In case of work station dependent batching with flexible batch sizes a small Q^- is preferable to a large Q^- as far as the job flow time is concerned.
4 In case of work station dependent batching the impact of an idleness batching criterion on job flow times is identical to the impact of a minimum batching rule equal to the idleness batching criterion on job flow times.

Within the experiments presented in this paper we have not considered due dates. However, in most cases the batching problem not only involves flow times, but also delivery performance, e.g. measured by the job tardiness. Therefore, more experiments are required including job due dates. On top of that, we have not considered the case where batching is required at more than one work station. Including more work stations with possibly different batching criteria will be a further extention of this research. Finally, based on the results of these experiments, concepts should be formulated to be used in the control of situations with work station dependent batching. These concepts should be tested in real life settings.

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