# Order release in a workload controlled flow-shop with sequence-dependent set-up times

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*Abstract*

In this paper, we report a simulation study of the role of sequence-dependent set-up times in decision making at the higher planning levels of a workload controlled make-to-order flow-shop. The study evaluates the potential for set-ups savings, dependent on the level of workload in the shop, for two alternatives, namely considering set-up times centrally, within the release decision or locally, within the dispatching decision. These strategies are compared and assessed on the basis of two performance measures namely time in system and standard deviation of lateness. Results indicate that the local strategy, which has been traditionally adopted in practice and in most of the studies dealing with sequence-dependent set-up times, does not always give the best results. The release frequency and the shop workload appear critical to the selection of the strategy to adopt, strongly influencing system performance.

Keywords: order release, set-up time, simulation

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## 1. Introduction

Workload Control (WLC) is a production, planning and control (PPC) concept that has received much attention in recent years (Thuerer et al. 2009). It is particularly appropriate for jobbing and flow-shops in the make-to-order (MTO) sector of industry (Haskose et al. 2004). WLC applies the basic principles of input/output control (Plossl and Wight 1973) to keep the length of queues on the shop floor at appropriate levels. The aim is to achieve short, stable and predictable shop flow times towards meeting the promised delivery dates. This requires limiting and balancing workload on the shop floor to avoid temporary overloading or underloading of machines. When workloads are balanced the queues on the shop tend to be stable. Stable queues lead to predictable shop flow times, which can be used to determine the planned release times of orders.

Order release is described as an essential decision function and a core parte of WLC (Missbauer 2009). It determines the type, amount and time point of release of new orders into the shop (Qi et al. 2009). For this propose, an order release mechanism is used, in combination with a pre-shop pool. Orders that arrive to the production system are gathered in this pool and are only released if they fit the workload norms, or limits, of the required machines or capacity groups. This means that the decision to release an order is based on its influence on the current shop floor workload. The pre-shop pool acts buffering the shop floor against the dynamics of the incoming flow of orders, reduce perturbations due to order cancelation and allows later ordering of raw materials, between other benefices, as pointed out by Land and Gaalman (1998).

WLC conceptualises a shop floor as a queuing system. Any released order (job) enters the shop and goes to the first machine of its routing. It waits in the queue if the machine is busy. Once processed in a machine, the job is moved to the next machine of its routing where it again waits until processing starts. WLC acts to ensure that workload at each machine do not exceed its norm. This workload norm is established with basis on the maximum acceptable flow time at each machine. Limiting in this way the workload on a machine means that, a limit on the number of jobs which can join the queue of a machine is imposed. Therefore, at times, jobs are not released because the workload norms of the required machines would bee exceeded. Thus, Haskose et al. (2004) considered the existence of finite buffers at machines.

The shop flow time of a job is the sum of the set-up time, the processing time and the queuing time at each machine on the job's routing. Set-up time refers to the time required to prepare a machine to perform a job operation. Set-up times are dependent on both, the job to be processed and the one that had been processed immediately before. Most WLC literature assume that set-up time is either nonexistent or consider it as part of the processing time of the operation. While this may be acceptable for scheduling in some production environments, in many others sequence-dependent set-up times need to be taken into consideration separately. In this situation, shop performance cannot be effectively improved without the aid of appropriate scheduling procedures which take set-up times into account (Kim and Bobrowski, 1994).

From the perspective of the WLC concept, essentially two alternatives can be considered to deal with sequence-dependent set-up times: considering them centrally, i.e. within the release decision, or locally, i.e. within the dispatching decision.

The first strategy is concerned with the role of set-ups in scheduling jobs on one or more machines to optimize certain objectives. Although a vast literature has investigated different scheduling problems in terms of set-up times (e.g. Allahverdi et al. 1999, 2008, Cheng et al., 2000, Liu and Chang 2000 and Norman 1999) few studies have been reported on dynamic jobbing and flow-shops with sequence dependent set-up times. Examples are the works by Kim and Bobrowski (1994) and recently Vinod and Sridharan (2009). Both studied dynamic job shops with sequence-dependent set-ups using computer simulation. Kia et al. (2009) have also recently investigated dispatching rules for sequence-dependent set-up times in a dynamic flexible flow line. These studies showed that set-up-oriented dispatching rules were very effective on improving shop performance, when compared with ordinary rules such as *shortest processing time* (SPT) or *first-in-first-out* (FIFO). The difference in performance between these two groups of rules, ordinary and set-up-oriented rules, was emphasised as shop load and set-up to processing time ratio increased.

The second strategy is concerned with the role of set-ups in decision making at the higher planning levels of the WLC system. Until now, this topic has hardly received attention in the literature. A remarkable exception is the work of Missbauer (1997), which examined the functional relationship between *work-in-process* (WIP) and total set-up time, in order to establish the suitable level of WIP on the shop floor.

This paper reports an investigation into the implications of sequence-dependent set-up times in decision making at the order release level of a workload controlled make-to-order flow-shop. In particular, it attempts to show if orders should be sequenced in the pre-shop pool or on the shop floor in order to reduce the number of set-ups and improve system performance. Apparently, as long as the avoided set-up time is greater than the time the orders wait in the pre-shop pool, due to set-up based order release, time in system of jobs is likely to be reduced. However, the objective of workload balancing within the release decision, required by the WLC approach, may conflict with the strategy of reducing set-ups. The impact of this on the shop performance is here evaluated through a simulation study. The results of the study will contribute for better decision in choosing between the two above referred control strategies, to deal with sequence-dependent set-up times in practice.

The remainder of this paper is organized as follows. Section 2 presents and discusses the experimental design of the simulation study referred. Section 3 is focused on the analysis of the results from simulation experiments and in Section 4 some concluding remarks and directions for future research work are put forward.

## 2. Simulation Study

### *2.1 Simulation model and production system configuration*

To investigate the effects of the two alternatives control strategies discussed in the previous section, a simulation study using Arena® software (Kelton et al. 2004), was set-up. A dynamic flow-shop is considered under the following assumptions:

1. The shop has six machines, M1 to M6, all equal in terms of capacity.
2. Each job has six operations each of one processed on each of the six machines in the same order, starting on machine M1 and ending on machine M6.
3. A machine can only perform one operation at a time on any job and an operation of a job can be performed by only one machine at a time.
4. Each machine is continuously available and there are no breakdowns.
5. Operations are processed without pre-emption.
6. Job processing cannot be started at a machine before it is finished at the previous one.
7. The transportation time between machines is assumed to be zero.
8. Set-up time of each job on each machine is sequence-dependent.

9. Each machine has a limited buffer capacity, i.e. a limit to the workload allowed to be released to the machine; nevertheless, no restriction is imposed to the movement of released jobs from a machine to the next, after processing.
10. Orders arrive continuously to the production system.

Due dates of orders are set externally and known upon arrival. Four types of jobs are considered, each of which with an equal probability of being assigned to an arriving order. Orders inter-arrival time follows a negative exponential distribution, with a meant that results in a machine utilisation rate of 90% at unrestricted workload norms and when ordinary rules are used at both, order release and dispatching (section 2.2). The mean inter-arrival time (ν) of orders, is given by the following equation (Yu and Ram 2006, Vinod and Sridharan 2009):

$$\nu = \frac{\mu_p . \mu_g}{U . m} \qquad (1)$$

Where $\mu_p$ is the mean processing time per operation (including set-up), $\mu_g$ the mean number of operations per order, U is the shop utilization and *m* is the number of machines in the shop.

Orders arrive at the production system (see figure 1) over time and flow directly into the pre-shop pool. At release time *t,* orders in the pool are selected for eventual release according to a *priority rule* i.e. the selection rule for release. An order is released only if as a consequence of such, the accounted workload of each machine in its routing does not exceed its workload norm. If one or more workload norms are exceeded the order must wait in the pool until, at least, the next releasing period. Once an order is released the workload of each machine in the order routing is updated with the workload contribution of the selected order. This procedure is repeated until all orders in the pool, at release time *t,* have been considered for release. Therefore, only a subset of orders currently waiting in the pool is released each time order release is activated, i.e. at release time *t*.

Different methods to update workload at machines (or capacity groups) upon order release are presented in literature. Breithaupt et al. (2002) make a review of these methods. The *adjusted aggregated load method*, which has been shown to perform well in flow-shops (Oosterman et al. 2000), is adopted in this work. The underlying idea of this method is that the accounted workload of an operation to a machine is a function of the sequencing position of the operation on the orders' routing. In this study, the workload contribution is obtained by dividing the order operation time in a machine by the operation position number in the orders' routing and added up to the machine accounted workload.

After release, priority dispatching rules are used to control the progress of the jobs through the shop floor. Operations times are stochastic following a 2-Erlang distribution with a mean of 0.75 hours per job. Setup times are deterministic and equal to 0.15 hours (i.e. 20% of the mean operation time). For simplicity, we assume the same set-up time for each job type. In the literature, set-up times have been typically set between 20% and 40% of mean processing time (e.g. kia et al. 2009, Vinod and Sridharan 2009, Kurz and Askin 2003). Kim and Bobrowski (1994) consider that 20% represents a realistic set-up time and provides an environment that will differentiate the performance of sequencing rules without giving undue advantage to set-up-oriented rules. Jobs of the same type can be processed with the same machine setting, i.e. no set-ups are required for the same type of job.

### *2.2 Experimental Design*

Table 1 summarises the four experimental factors and associated levels studied: (1) dispatching rule; (2) selection rule for releasing; (3) releasing period length; and (4) workload norm levels.

[Insert table 1]

Two types of *dispatching rules* were tested on the shop floor: the ordinary FIFO and the set-up-oriented *SIMilar Set-up* (SIMSET). Since WLC reduces the length of queues on the shop floor, it has been suggested in the literature (Bechte, 1988) that WLC allows for the use of a simple dispatching rule such as FIFO. With this rule jobs are processed in the order they arrive at a machine, i.e. the highest priority is given to the job which is waiting most in queue. No consideration is given to set-up time savings. SIMSET, on the other hand, gives the highest priority to the job with the smallest set-up time, i.e. selects a job of the type of the one that just finished to be processed on the same machine. When there is no such a job another is selected using the FIFO rule.

Two *selection rules* for releasing are considered: the ordinary *Latest Release Date* (LRD) rule and the set-up oriented *Similar set-up and Latest Release Date* (SLRD) rule. According to the LRD the highest releasing priority is given to the more urgent order i.e. that which has the lowest latest release date. The latest release date (or time) of an order is determined by backward scheduling from the due date using the planned lead times in all machines of the orders' routing. These were established through some pilot simulation runs. SLRD, on the other hand, selects an order for release which is of same type of the order that had just been released. When there is no such an order another is selected using LRD rule.

The *releasing period length (T)* determines the time interval between order release activations, i.e. between releasing times and therefore determines the releasing frequency. The value of *T* influences the amount and of work that is released into the shop each time order release is activated. For *T* equal to zero the continuous timing convention is in place and for *T* greater than zero we say that a discrete time convention is applied (Bergamaschi et al 1997). Using the former, order release may occur at any time during the system operation; Using the latter order releases may occur only at periodic intervals of length *T.* Land (2006) explains that the choice of an appropriate period between releases is a delicate decision. A long release period results in increased opportunities to find orders in pool that fit workload norms, and therefore may lead to a better load balancing. However, it also delays orders in the pool - on average an order has to wait *T/2* before being released into the shop floor – which may increase the time jobs spend in the system.

The *releasing period T* was tested at seven levels, namely: 0, 2, 4, 6, 8, 10 and 20 hours. These different levels allow us to understand the influence of the release period and were chosen after a previous preliminary study for obtaining enough points to represent the pattern of change of performance curves.

*Workload norms levels (*WLN*)* are deterministic parameters setting the maximum workload that can be released from the pool to each machine and, therefore, setting the maximum shop workload. To determine the best performing workload norm levels it is common practice in simulation studies (e.g. Thuerer et al. 2009, Henrich 2007, Land 2006, Oosterman et al. 2000, Land and Gaalman, 1998) to define it as an experimental variable. Ten WNL were tested. We started with WNL=∞ such as the release of orders to the shop floor is not constrained by any norm. This means immediate release under the continuous timing convention and unrestricted periodic release under the discrete timing convention. For propose of simulation we used an approximation by replacing ∞ by 10,000 hours. Then the WNL is varied stepwise down from infinity, i.e. workload norms are decreased gradually from unrestricted to highly restrictive values. Since machines show identical characteristics, i.e. utilization, operation processing times, stream of arriving orders and average flow times, workload norms were set identical for all machines. According to Oosterman et al. (2000) the *adjusted aggregated load method,* which is used in this study, allows for identical workload norm levels, independently of the machines' position within the order's routing.

### *2.3 Performance measures*

The primary measure of the system performance is *time in system*. Time in system is the time an order or job spends waiting in the pre-shop pool plus the *shop flow time*. It provides a measure of the speed of the jobs through the whole system and is directly related to the percentage of late jobs. Reducing time in system has a beneficial impact on reducing the overall response time to customers.

*Shop flow time* is also recorded. This refers to the time that elapses between job release and job completion and helps evaluating the performance of the shop floor operation. Reducing the shop flow time has also intrinsic benefits. In particular, reduces WIP and, therefore, tied-up capital.

As an indicator of timing performance, the *standard deviation of the job lateness* is used. It indicates how close the completion times of jobs are to their planned due dates. The mean job lateness was also recorded, but only for some situations. It was observed, through some pilot simulation runs, that the system performance is very similar in terms of time in system and mean job lateness, i.e. good results in terms of time system meant good results in terms of mean lateness.

## 3. Experimental Results

During simulation runs, data were collected under system steady-state. The length of each run was for 125,000 simulated hours including a warm-up period of 25,000 hours. The average values of 100 independent replications are presented as results. The statistical analysis was performed using the paired Student *t*-test with a 95% confidence level.

Table 2 shows control strategies A1 to A3 that result from combining selection rules for releasing with dispatching rules. One of such combinations is not relevant for this study. The strategies have different implications for shop floor control and performance. While control strategy A1 gives no importance to savings in set-up time, control strategy A2 considers set-up times within the order release decision, and control strategy A3 considers them within the dispatching decision.

[Insert Table 2]

Figure 2 shows time in system performance for each control strategy under continuous timing convention, i.e. the releasing period length is set to zero ($T = 0$). This means that an order release may occur at any time during system operation. A point on a curve is the result of simulating a control strategy, i.e. A1, A2 or A3, at a specific workload norm level. Series of simulations experiments with decreasing workload norms levels, from unrestricted to highly restricted levels, were performed. Thus, time in system performance is indicated for different levels of workload norm tightness. Note that the shop flow time is used as an instrumental variable that indicates the level of tightness of the WLN: the lower the values, the higher the tightness. In this figure, time in system is plotted against shop flow time, showing the relative performance of the control strategies.

[Insert figure 2]

Performance curve A1 is based on the use of ordinary rules at both release (LRD rule) and dispatching decisions (FIFO rule). The curve has its right end point at a shop flow time of 27.9 hours. This is the result of releasing jobs immediately to the shop floor, i.e. jobs do not wait in the pre-shop pool. Tighter WLN, first leads to slightly lower values of time in system and after a certain point (i.e. the point of minimum time is system), represented by a square mark on the curve, time in system increases markedly. The minimum value of time in system is achieved for a shop flow time of 26.8 hours. Since time in system is the sum of the pool time and the shop flow time, this means that waiting times in the pool are increasing more than waiting times on the shop floor are decreasing. Thus, to avoid deterioration of time in system, WLN cannot be set excessively tight. Table 3 shows the simulation results with the 95% confidence intervals on the mean, for the two following "points":

1. the *right end point* of each strategy, representing an uncontrolled situation that results from unrestricting WLN level and
2. the *point of minimum time in system* of each strategy, representing the minimum time in system that results from an appropriate WLN level (found empirically).

In the case of performance curve A3, the *right end point* and the *point of minimum time in system* are coincident and refer to the unrestricted WLN level.

[Insert Table 3]

Performance curve A2 and A3 are based on the use of set-up-oriented rules, within order release and order dispatching, respectively. Figure 2 shows that the right end points of A1 and of A2 are coincident. This happens because under immediately release differences in strategies are expressed only at dispatching. Once A1 and A2 use the same dispatching discipline, i.e. FIFO, the same behaviour is expected. In the same circumstances, A3 is placed rather differently in the figure, as expected, because it uses a different dispatching rule, i.e. SIMSET. This explains the behaviour of the three strategies at these extreme points.

Tightening of WLN, under A3, results in time in systems deterioration due to fewer opportunities for set-up savings. Nevertheless, for time in system, at each level of norm tightness, control strategy A3, based on set-up-oriented dispatching, clearly outperforms control strategy A1, based on FIFO dispatching. In line with previous findings, e.g. from Kim and Bobrowski (1994), results show that set-up-oriented rules are very effective on improving system performance, namely time in system.

Figure 2 also shows that performance curves A2 and A3 cross each other as WLN becomes tighter. This means that the level of norms' tightness influences the decision for considering set-up time centrally or locally. Loose WLN, lead to a high level of shop floor WIP, i.e. longer queues of jobs, which, in turn, result in increased opportunities for set-up-oriented dispatching towards optimization of job sequencing with respect to set-ups. Thus, when set-up-oriented rules are used within the dispatching decision, curve A3, the lowest total set-up time and the lowest time in system are obtained under immediate release (right end point of the curve). However, tighter norms restrict WIP on shop floor and the set-up-oriented dispatching rules partially lose their effectiveness. In this situation the use of set-up-oriented selection rules within the release decision becomes a suitable option, as shown by the crossing of curve A2 with A3.

In Figure 3 the standard deviation of the job lateness (StDev lateness) is plotted against the shop flow time, indicating the timing performance of the control strategies A1 to A3. We observe that under unrestricted WLN, the StDev of lateness of control strategy A3 is much higher than that of the other strategies. This may be explained by the disruption of the 'natural', i.e. based on FIFO, processing sequence of jobs, introduced by set-up oriented dispatching. The large values of the StDev of lateness at unrestricted workload norms denote the high fluctuation of the queue lengths and therefore of the shop flow times. Since shop flow times are used for determining the planned release times of orders this may hinder the right timing of order's release. Tighter WLN first improve the StDev of lateness of strategies and, after a certain point, represented by a square mark on the curve, it worsens it. This happens because the order release procedure tends to retain longer the jobs (orders) at the pre-shop pool, resulting in both:

1. fewer jobs on the shop floor and fewer opportunities for strategy A3 to explore the SIMSET rule. As a consequence the StDev of lateness of A3 initially markedly decreases, up to a minimum.
2. increased choice of jobs in the pool and increased opportunities to find orders that fit workload norms. This also favours strategy A2 in its set-up-oriented order releasing process. As a consequence, the planned release sequence is disturbed by holding back the release of some urgent jobs and thus increasing the variability of the job lateness distribution.

It is also noteworthy that strategies A1 and A2 have a somewhat similar behavior in terms of the StDev of lateness. Contrary to set-up-oriented dispatching, set-up-oriented release does not seem to worse the timing performance of the release procedure across the whole range of norm tightness.

[Insert figure 3]

Next, based on figures 4 and 5, we compare control strategies A1 to A3 under the influence of the release period length, for the two "points" above referred. Thus, figure 4 shows time in system for different releasing periods under unrestricted WLN and figure 5 shows the time in system for different releasing periods for the WLN level that results in the minimum time in system. In both figures we can observe that performance curves A2 and A3 cross each other, meaning that the releasing period length, i.e. the releasing frequency, influences the relative performance of the control strategies A1 to A3. For short releasing period lengths (T < 4 hours) A3 outperforms A2, while for long releasing period lengths (T > 4 hours) it is the other way round. It is shown that strategies A2 and A3 always perform better than strategy A1. It is worth pointing out here that it has been observed in previous studies (e.g. Land, 2006), that under unrestricted WLN an increase in the releasing period leads to an increase in the average time in system. This is in fact shown in figure 5 for control strategies A1 and A3. However, for control strategy A2, this is verified only for long releasing period lengths. Apparently set-up-oriented releasing, used in A2, seems to offer alternatives to shop floor control that avoid the believed expected increase in the average time in system. Such, is most probably due to savings in total set-up times.

[Insert figures 4 and 5]

Results, also lead us to conclude that the answer to our research question is not independent from the level of workload in the shop, the release period length and performance measure considered.

## 4. Conclusions

Sequence-dependent set-up times may lead to major set-up savings if appropriate scheduling procedures are used. This can have a major influence on manufacturing system performance. This paper reports a simulation study of such influence in the context of the Workload Control concept.

Results show that the release frequency, as function of the release period length, and the shop workload are critical for the balancing and timing performance of the control strategies studied. Therefore, they need to be conveniently tuned in the order release procedure to be adopted. The traditional approach to deal with sequence-dependent set-up times, i.e. considering them locally within the dispatching decision, does not always result in the best performance. Particularly, for large release period lengths or for situations with limited workload on the shop floor, set-up oriented dispatching seems not to be as effective as set-up oriented releasing, in terms of time in system performance. In situations of uncontrolled workload, set-up oriented dispatching becomes attractive in terms of the time in system performance, but performs comparatively worse in terms of the timing performance, measured by the standard deviation of lateness.

Thus, the findings show that adjustments to the traditional release methods and thinking are required in order to account for sequence-dependent set-up times in a more effective manner. A deeper study on this, in the context of workload control theory will be carried out in the near future by the authors.

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# Tables

| Factor | Levels | |
|---|---|---|
| Dispatching rule | FIFO | SIMSET |
| Selection rule for releasing | LRD | SLRD |
| Release period length | TЄ{0, 2, 4, 6, 8, 10} | |
| Workload norm levels (WLN) | stepwise down from infinity | |

*Table 1. Experimental factors and levels.*

| Dispatching rule | Selection rule for releasing | |
|---|---|---|
| | *Ordinary*<br>(LRD) | *Set-up-oriented*<br>(SLRD) |
| *Ordinary*<br>(FIFO) | A1 | A2 |
| *Set-up-oriented*<br>(SIMSET) | A3 | Not relevant |

*Table 2. Control strategies by combining dispatching and selection rules for releasing.*

| Control strategy | Shop flow time | Time in system | Mean lateness | StDev of lateness |
|---|---|---|---|---|
| A1<br>*(unrestricted WLN)* | 27.899 (±0.10) | 27.899 (±0.10) | 3.402 (±0.10) | 15.469 (±0.10) |
| A1<br>*(WLN=10 hours)* | 26.857 (±0.09) | 27.853 (±0.12) | 3.354 (±0.12) | 15.204 (±0.10) |
| A2<br>*(unrestricted WLN)* | 27.899 (±0.10) | 27.899 (±0.10) | 3.402 (±0.10) | 15.469 (±0.10) |
| A2<br>(*WLN=5 hours)* | 22.007 (±0.04) | 25.037 (±0.07) | 0.538 (±0.07) | 16.335 (±0.14) |
| A3<br>*(unrestricted WLN)* | 22.581 (±0.07) | 22.581 (±0.07) | -1.920 (±0.07) | 27.305 (±0.15) |

*Table 3. Control strategies performance results.*

Figures

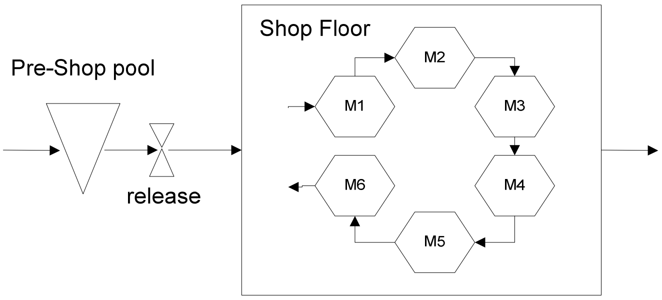

Figure 1: Simulated shop floor model.

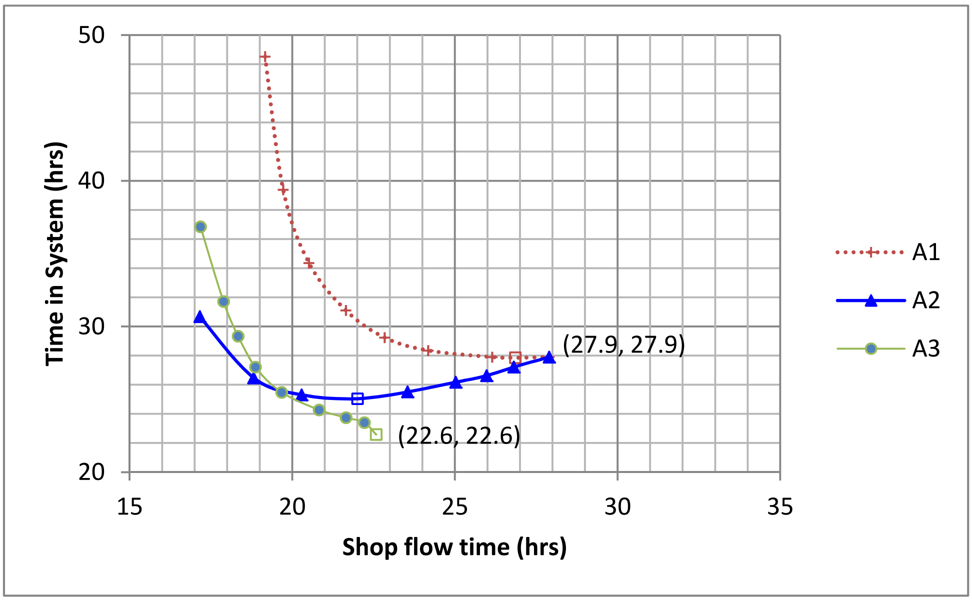

Figure 2: Time in system performance for different control strategies.

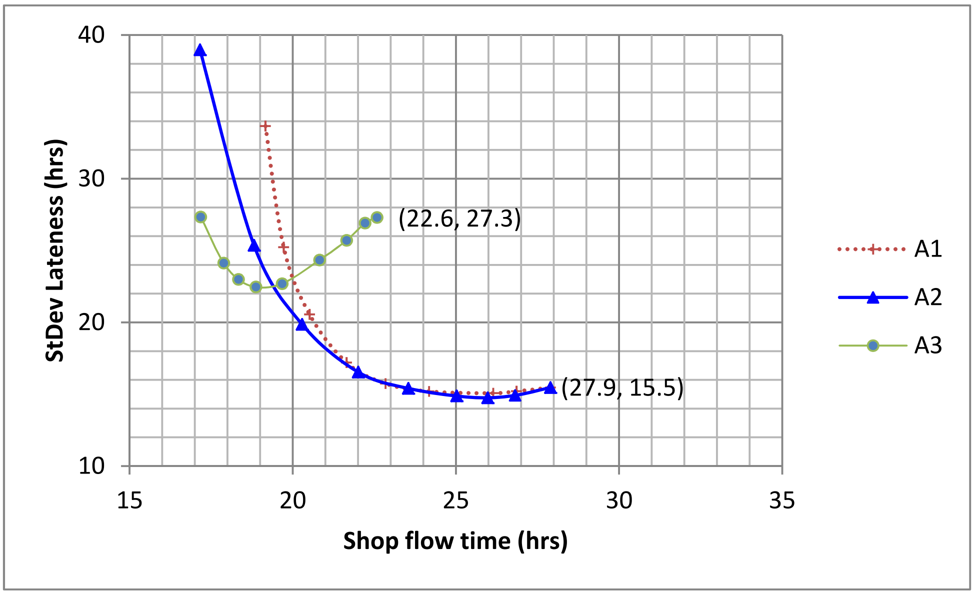

Figure 3: Timing performance for different control strategies.

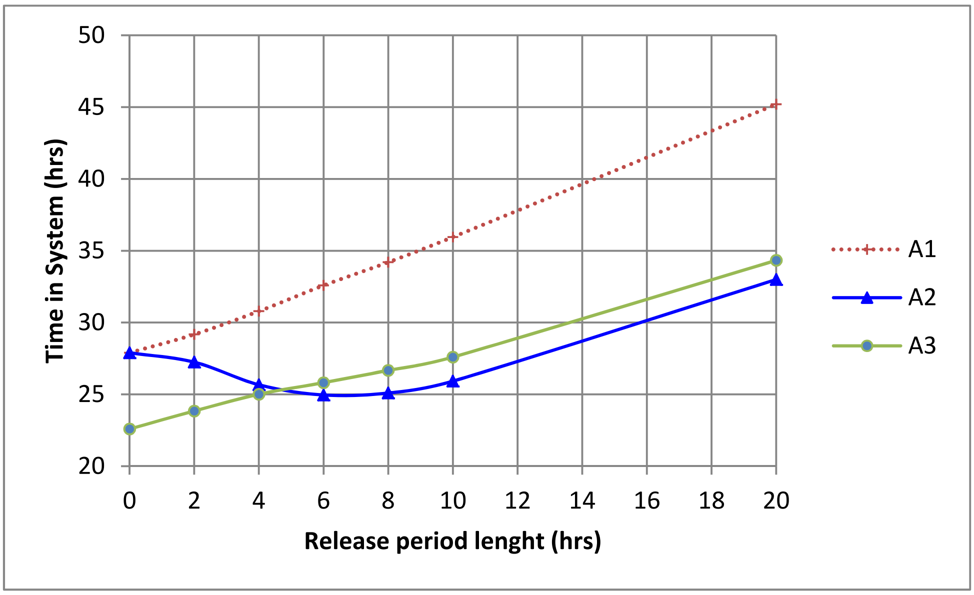

Figure 4: Time in system at unrestricted workload norms at different release period lengths.

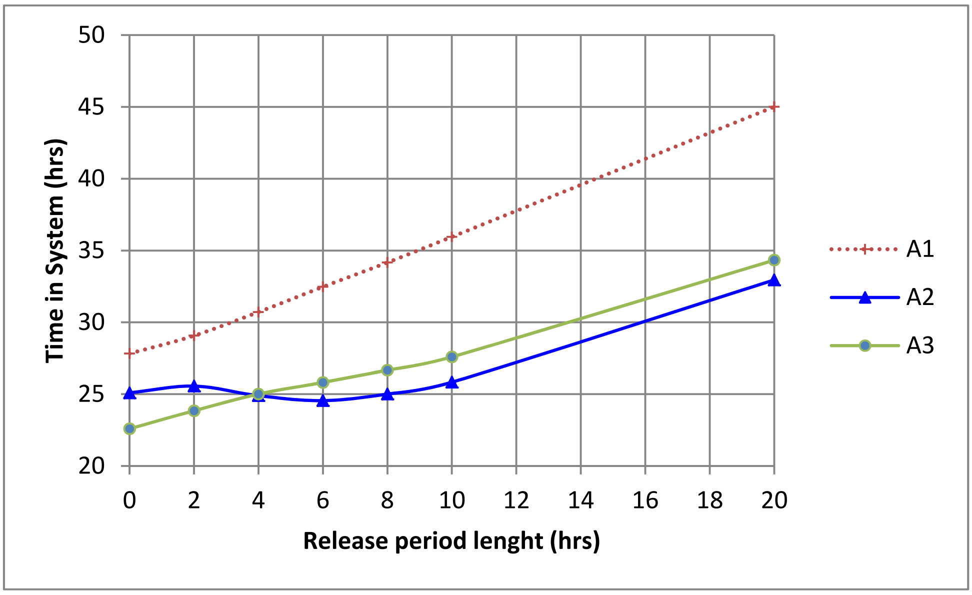

Figure 5: Minimum time in system at different release period lengths.