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# The influence of shop characteristics on workload control

*Bas Oosterman<sup>#</sup>, Martin Land<sup>&</sup>, Gerard Gaalman<sup>\*</sup>*

SOM Theme A: Primary Processes

## Abstract

Several order release methods have been developed for workload control in job shop production. The release methods of the traditional workload control concepts differ in how they deal with the flow of work to each station. Previous research has pointed at strengths and weaknesses of each method. Till now the choice of the appropriate method for a particular situation has hardly received attention. This research shows that shop characteristics are an important factor to this choice. A simulation study indicates that the relative performance of the release methods changes completely with for instance the presence or absence of a dominant flow direction in the shop. Adjustments to the traditional release methods are suggested which prove to make these methods more robust.

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## 1. Introduction

An important category of production control approaches for job shop production is based on workload control (WLC) principles. The WLC concepts buffer the shop floor against the dynamics of arriving orders by means of input/output control. The order release decision is the main instrument for the input control. Once released, a job remains on the shop floor until all its operations have been completed. WLC concepts set norms for the workload allowed on the floor. If a job does not fit in these norms, the release decision will hold it back. This results in a pool of unreleased jobs.

WLC has received a lot of attention from both practitioners and researchers. Practitioners appreciate the concepts, because they correspond with their intuitive ways of controlling shops. Moreover, they expect practical support in taking decisions. Researchers developed several concepts and workload controlling release methods. Pure job shop models have been used for evaluation, as the concepts were mainly developed for job shop environments. Few researchers have stressed the importance to test the concepts in more realistic situations that deviate from the pure job shop [Enns, 1995; Roderick et al. 1992].

In a pure job shop model the flows of jobs are undirected, and routings are completely symmetric. However, in most real life shops we distinguish asymmetric routings where workstations have different positions in the flow of jobs. As each of the WLC concepts deals differently with the flow of work to these stations, one may expect these deviating characteristics to have influence on the performance of WLC concepts. In this paper we analyse this influence. By means of a simulation study, different shop configurations are examined. The tested WLC concepts are three traditional concepts and two recently developed alternatives [Land & Gaalman, 1996a]. Preliminary simulation results have been discussed in [Oosterman, 1995].

The results of this study should contribute to the choice of an appropriate workload control in a practical situation. As there still is a lot of confusion on the gap between theoretical and practical results of WLC concepts, the simulation of more realistic shops may also contribute to our understanding of this gap.

The paper is organised as follows. First, we describe the basic principles of

workload control and give a detailed analysis of differences between the release methods of WLC concepts. Next, we formulate our expectations with respect to the influence of shop characteristics on each of these methods. Section 5 discusses the experimental design of the simulation study to verify these expectations. Sections 6 and 7 deal with the results and the implications of the study.

## **2. The workload control (WLC) concept and job release**

An important decision within WLC concepts is job release. See [Bergamaschi et al., 1997; van Ooijen, 1996] for thorough reviews of job release research. Job release determines when each job should enter the shop floor. Once released, a job remains on the floor until all its operations have been completed. The progress of jobs on the shop floor is controlled by priority dispatching in the queues at work stations. The principle of WLC concepts is to control these queues. Norms are set for the workload allowed on the shop floor. If a job does not fit in these norms, the release decision will hold it back. It results in a *pool* of unreleased jobs. This pool may absorb fluctuations of the incoming flow of orders. Besides a reduction of work-in-process costs, holding back jobs has numerous additional advantages. It creates a transparent shop floor situation with faster feedback opportunities, which is of great importance in the turbulent job shop situation. JIT literature extensively presents the benefits of a lean shop floor. In addition to these benefits, the time jobs spend in the pool enables the delay of decisions. It reduces the waste due to cancelled orders, facilitates later ordering of raw materials, takes away the need of expediting rush orders on the shop floor, etc. As illustrated by Figure 1, we refer to the waiting time in the pool as the *pool time* of a job and to the time that passes between release and completion of the job as its *shop floor throughput time* or shortly *shop floor time*. The shop floor throughput time of the job can be subdivided into *station throughput times*. Control of the queues on the shop floor should result in stable and predictable station throughput times. Thus, an accurate release moment for each job can be determined to guarantee a good due date performance. However, it can be argued that a good timing of job release may conflict with realising the norms for the workload on the shop floor [Land & Gaalman, 1996b].

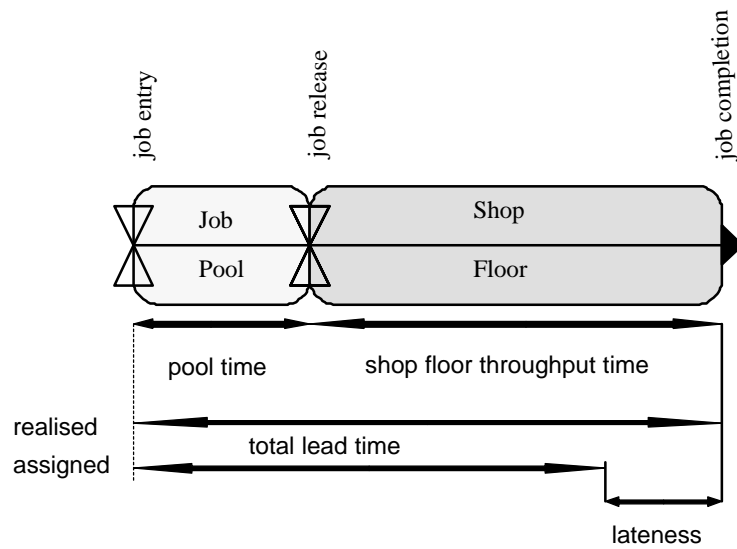


Figure 1: lead time components with controlled release

### 3. Three approaches of workload control

The workload released for a station can be subdivided into a *direct* part (work from jobs queuing at the considered station) and an *indirect* or *upstream* part (from jobs queuing at a station upstream). The aim of WLC concepts is to keep the direct load at a low and stable level. Job release cannot completely control the direct load of a work station. Only a part of the jobs in the pool are released directly to the work station. Other jobs arrive from the other work stations after their *upstream operations* have been completed.

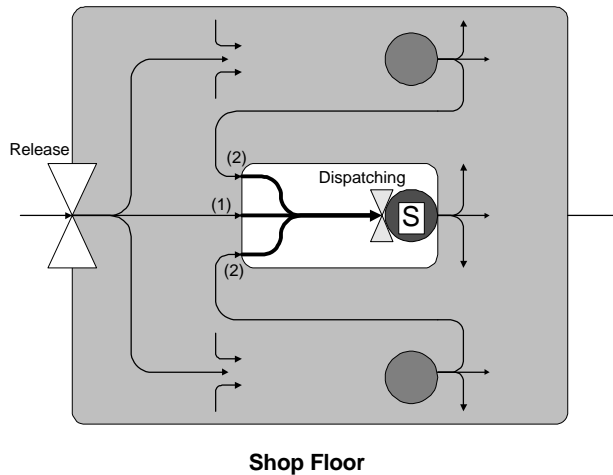


Figure 2: inputs to the direct load of a workstation  $s$ .

Figure 2 shows the flows on the shop floor of a job shop. The simplified context of three stations illustrates how job release influences part of the inputs of workstation  $s$  directly (1), while other inputs to the direct load of  $s$  (2) arrive from other workstations. Different approaches have been proposed, which all aim at keeping the direct load at a low and stable level.

(A) The WLC concept developed at the IFA in *Hannover* [Bechte, 1980, 1988, 1994; Wiendahl, 1995] estimates the input from jobs upstream to the direct load of a station. The estimated direct loads are subjected to norms.

(B) The WLC concepts developed in *Eindhoven* [Bertrand & Wortmann, 1981] and *Lancaster* [Tatsiopoulos, 1983; Hendry, 1989; Kingsman et al. 1989] avoid estimating the input to the direct loads. They aggregate the direct and the indirect workload of a station by simply adding them and subject this *aggregate workload* to a norm.

(C) Some implementations of the Lancaster concept use an alternative approach

[Tatsiopoulos, 1983] that extends the aggregate workload to what we will define as the *shop load*. The shop load of a station additionally includes work already completed at the station, but still downstream on the shop floor. The shop load of

each station is subjected to a norm. This approach has been developed to restrict the required feedback from the shop floor to completed jobs, instead of completed operations.

All approaches make the release decision periodically, and focus control on the remaining workload at the end of the imminent release period. The remaining workload of a station at the end of the release period together with the output during this period is subjected to a norm value. At the beginning of the period, a set of jobs is released such that the workload situation at the end of the release period will satisfy the norms. Balance equations may further clarify the difference between the three approaches.

Equation (1) gives the direct load balance of a station  $s$ .

$$D_s^E + O_s = D_s^B + I_s \quad (1)$$

with  $D_s^E$ : The remaining direct load of a station  $s$  at the end of a release period

$O_s$ : The output of station  $s$  during the release period

$D_s^B$ : The direct load of station  $s$  at the beginning of the release period

$I_s$ : The input to the direct load from jobs arriving during the release period

In equation (1)  $D_s^B$  is known at the moment of release. The station output  $O_s$  depends on the capacity of  $s$  and its utilisation during the release period. The input  $I_s$  comes from jobs already upstream at the moment of release and from jobs newly released. Since both  $O_s$  and  $I_s$  encompass uncertainties,  $D_s^E$  cannot be determined exactly at the moment of release.

The aggregate load satisfies balance equation (2):

$$(D_s^E + U_s^E) + O_s = (D_s^B + U_s^B) + R_s \quad (2)$$

with  $U_s^E$ : The load upstream of station  $s$  at the end of the release period

$U_s^B$ : The load upstream of station  $s$  at the beginning of the release period

$R_s$ : The input to the aggregate load from newly released jobs

Other variables defined as before

In equation (2) all right-hand side quantities are completely known upon the moment of release. Thus, the sum of the left-hand quantities can be determined exactly.

The shop load satisfies equation (3):

$$(D_s^E + U_s^E + V_s^E) + Z_s = (D_s^B + U_s^B + V_s^B) + R_s \quad (3)$$

with  $V_s^E$ : The load completed by station  $s$ , but still downstream at the end of the release period

$V_s^B$ : The load completed by station  $s$ , but still downstream at the beginning of the release period

$Z_s$ : The output of station  $s$  which leaves the shop floor during the release period

As in equation (2), all right-hand side quantities of equation (3) are completely known upon the moment of release, and thus the sum of the left-hand quantities can be determined exactly.

Notice that the equation (1) differs from equation (2) and (3) regarding the input, and that equation (3) differs from equation (1) and (2) regarding the output. In the system of equation (1) a job is part of the input as it arrives at the queue of station  $s$ , where in equation (2) and (3) the job becomes part of the input directly upon its release. In the systems of both equation (1) and (2) the jobs become part of the considered output as soon as they leave the station, in equation (3) a job does not become part of the output until it has left the floor.

Approach A, B, and C can be related to respectively equation (1) (2), and (3).

Approach A controls the direct load  $D_s^E$  by bringing an estimation of the right-hand side of equation (1) to a norm level. The input is roughly estimated by a method called *load conversion* [Bechte, 1988; Wiendahl, 1995]. As soon as a job is released, its processing time partly contributes to the input estimation, the contribution increases as the job progresses on its routing upstream. The whole of the direct load and the estimated input is indicated as the *converted load*. The norm for the converted load should be set at the desired level ( $N_s^D$ ) for the direct load  $D_s^E$  plus an allowance ( $N_s^0$ ) for the estimated output during the release period.



Approach B focuses on the aggregate load ( $D_s^E + U_s^E$ ). The right-hand side of equation (2), which does not require any estimation, is brought to a norm level. In this case, the norm value should be set at the desired level ( $N_s^A$ ) for the aggregate load ( $D_s^E + U_s^E$ ) plus an allowance ( $N_s^0$ ) for the estimated output during the release period. The aggregate load at the end of the release period ( $D_s^E + U_s^E$ ) can be determined upon release, except for fluctuations in the station output  $O_s$ .

Approach C is comparable to B. Here, a norm ( $N_s^F$ ) is specified for the shop load

( $D_s^E + U_s^E + V_s^E$ ). The output of  $s$  leaving the shop floor is treated analogously to the direct output of the station. Notice that a job contributes to the shop loads of all stations in its routing until it leaves the shop floor. Upon the completion of a full job, its operation processing times are removed from the shop load records for all stations in its routing. This avoids the need to record the completion of each operation.

In the above equations we distinguished the direct load, the aggregate load and the shop load of a station. Each load can be defined as the joint operation processing times of a certain set of jobs. Each of the balance equations relates to a different set of jobs. Alternatively, we can illustrate the difference between the three workload control approaches by following a single job on its routing. Consider a job  $j$  with an operation processing time  $p_{js}$  on station  $s$ . Say that the job is released at time  $t_j^R$ , enters the queue of station  $s$  at  $t_{js}^Q$ , is completed at station  $s$  at  $t_{js}^C$  and leaves the floor at  $t_j^Z$ . Then, the operation processing time of the job will be part of the direct load during the interval  $[t_{js}^Q, t_{js}^C]$ , it will be part of the aggregate load during the interval  $[t_j^R, t_{js}^C]$  and part of the shop load during  $[t_j^R, t_j^Z]$ . Figure 3 depicts the contribution of the job to respectively the converted load, the aggregate load and the shop load of station  $s$  in the course of time. Notice that the converted load of approach A includes an estimation of the direct load input, in addition to the direct load itself. Upon release, the job starts contributing to the input estimation. Figure 3 shows how the contribution increases after each completed operation upstream.

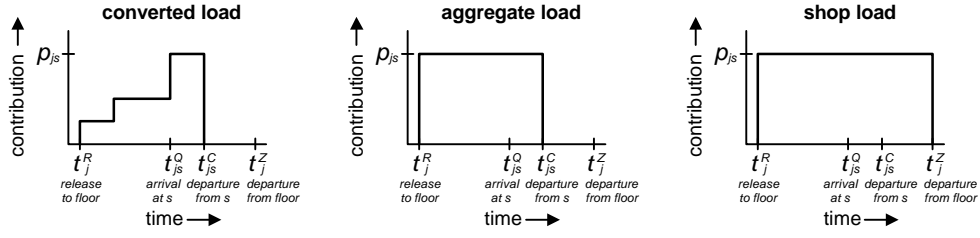


Figure 3: The contribution of job  $j$  across time to the workload (method A, B, C).

Figure 3 clearly illustrates the difference between the timing of input and output, which we observed in our discussion of the balance equations. We observe that method C differs from the others with respect timing of output: the full processing time of the job is included in the shop load of station  $s$  until the job leaves the shop floor. Method A differs from the others with respect to the timing of input. The processing time of a job is included in the aggregate load and the shop load as soon as the job is released to the shop floor ( $t_j^R$ ), and it becomes part of the direct load after arrival at the queue of station  $s$  ( $t_{js}^Q$ ). The direct load is fully included in the converted load. Between release and arrival at station  $s$  the processing time of job  $j$  is partly included in the converted load, as an element of the estimated input.

#### 4. Expected influences of shop characteristics

This research started from the perspective that pure job shops do not exist. In every real life job shop there will be more or less dominant flow direction. The operations performed by some stations have a preparative character (gateways or upstream stations), other stations perform typical finishing operations (downstream or finishing stations). Finishing stations will have most of their load upstream, while typical gateways have a lot of completed work downstream on the floor. As we observed that the three workload control approaches differ with respect to inclusion of upstream and downstream workload, we do expect that the flow characteristics will have a different influence on each of the approaches.

Method A tries to determine the influence of release on the direct loads of all

stations. In the theoretical pure job shop this is well possible, because part of the jobs reaches the station rather directly after release. But in shops with a more directed flow, the release of new work influences the direct load of a downstream station only after a time lag. Here, we question the usefulness of focussing on the direct load.

Also a second point indicates that method A is particularly developed for the strong routing variety of a pure job shop. The estimation of inputs uses information on the distance of the jobs upstream to the station. As routings vary strongly this information is important to enable a smooth flow of jobs to each station. When routing variety is small, this information loses its weight, as we already use workload norms for each station. The fact that also the more upstream stations reach their norm level might ensure a smooth inflow of work for downstream stations, so input estimation becomes less advantageous.

In method B work upstream of a station is included in its aggregate workload, and the aggregate workloads are subjected to workload norms. For a typical downstream station, it seems reasonable to keep this aggregate workload on a constant level. Its direct load will follow. For a pure job shop, the implications of a constant aggregate load for the direct load are less trivial.

More particularly, the position of a station in the routings of the job is an important factor. When the position of a station is more downstream in the flow of the jobs, there will be more load upstream of this station. In a pure job shop the position of each station varies strongly within the mix of routings, which may not allow for the use of fixed norm levels for the aggregate load. Previous research [*Land & Gaalman, 1998*] already indicates that method B performs worse than method A in a pure job shop. It is interesting to find out whether the relative performance of method B improves when the position of each station in the mix of routings is quite stable, which is the case with more flow shop like routing characteristics.

Method C is largely comparable to method B. The shop load is also an aggregation, now additionally including work downstream of the station. However, the information whether jobs have passed a specific station gets lost with this inclusion, while jobs that passed a station are no longer of interest for control of its

direct load. Especially for a typical gateway station this loss of information may be undesirable. So in shops with a dominant flow direction we expect that the detailed recording of completed operations in method B gives an important advantage over method C.

A more specific consideration with respect to method C relates to the number of operations per job. The direct load of a station, which should be controlled, may be only a small part of the shop load. The share of the direct load depends on the number of other operations that have to be performed on each job. The higher the number of operations, the larger the shop load should be to get the same share of the direct load. The number of operations per job generally varies strongly in pure job shops. This may have a negative influence on approach C that applies a constant norm level to the shop loads. Previous research of the authors [*Land & Gaalman, 1996a*] studies an alternative approach that corrects the shop load for the number of operations. This approach completely outperforms approach C in a pure job shop. This raises the question whether the relative performance of approach C improves in shops with a rather constant number of operations.

## **5. Experimental Design**

The previous section stated our expectations with respect to the influence of the shop configuration on each of the workload control approaches. We will analyse these influences by means of a simulation study. This section details the release methods and the shop configurations to be simulated.

### *Release methods*

In addition to the release methods A, B, and C, two alternative methods are included in the experimental design. The previous section suggested some particular influences of the station position and the number of operations in respectively method B and C. Previous research of the authors [*Land & Gaalman 1996a*] studies an alternative approach which corrects aggregated loads for the suggested influences. Two variants of this approach will be included in the experimental design to verify the expected influences, as alternatives for respectively method B and C. The alternatives will be indicated as B' and C'.

Method B' uses the same timing of input and output as method B. A job is included in the recorded load of station  $s$  directly upon release, and excluded as soon as the operation at station  $s$  is completed. The difference between method B and B' relates to the contribution of the job to the recorded load. Instead of a contribution  $p_{js}$  (the processing time of a job  $j$  at station  $s$ ), the job contributes  $p_{js} / n_{js}$  (during the same interval  $[t_j^R, t_{js}^C]$ ). Here  $n_{js}$  is defined as the position of station  $s$  in routing of job  $j$ , in other words: station  $s$  is the  $n_{js}$ th station that job  $j$  will visit. The left part of figure 4 depicts the workload recordings of method B and B'. We suggested that the aggregate load should increase when station  $s$  is more downstream in the momentary flow of jobs. Notice that the workload calculation of method B' automatically corrects for this factor. The expected influences of the station position can now be verified by performance differences between B and B'.

Method C' is comparable to method C with respect to the timing of input and output. A job  $j$  contributes to the recorded workload of station  $s$  during the interval  $[t_j^R, t_{js}^C]$ . Here the contribution of job  $j$  is decreased to  $p_{js} / N_j$ , where  $N_j$  is defined as the number of operations to be performed for job  $j$ , or the routing length. Where the shop load should increase when the momentary mix of jobs has a larger number of operations to be performed, method C' corrects for this factor. The difference between method C and method C' is illustrated in the right part of figure 4. Including C' helps in verifying the expected influences of the routing length.

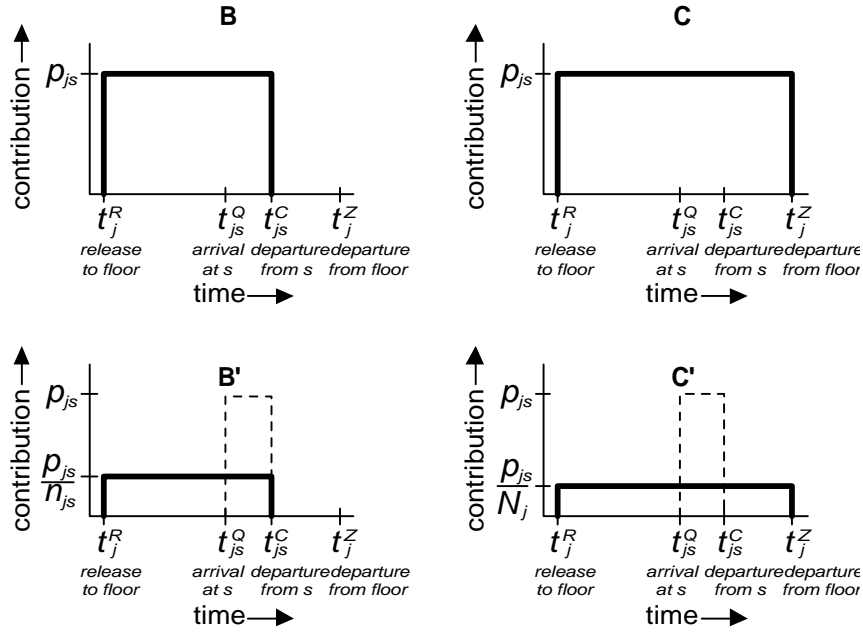


Figure 4: method B' and C': adjusting job contributions to the workloads

In [Land and Gaalman, 1996a] it is argued that the workload calculation of method C' can be seen as an estimation of the average direct load resulting from the actual mix of jobs on the floor. More precisely, it estimates the average direct load that would result if the actual job mix on the floor remained equally composed. The same holds for method B', now with respect to the mix of jobs upstream and at station considered. The estimation is based on the assumption that the station throughput times are equal for all stations in the routing of a job. In that case  $1/n_{js} = (t_{js}^C - t_j^R) / (t_{js}^C - t_{js}^Q)$  and  $1/N_j = (t_j^Z - t_j^R) / (t_{js}^C - t_{js}^Q)$ . In figure 4 the contribution of a job to the direct load across time is given by a dashed curve. We can see that, given the above assumption, the average contribution of a job in the workload calculation of method B' and C' during an interval including at least  $[t_j^R, t_j^Z]$  will be equal to its average contribution to the direct load during that interval. A norm for the workload calculated in method B' and C' can be seen as a norm for the average direct load.

The five methods included in the experimental design differ with respect to the quantities that are subjected to workload norms. The release procedure is

implemented equally for all methods. Upon arrival the jobs are sequenced in the pool according to planned release times. This planned release time is determined by subtracting  $N_j$  times a standard station throughput time from the due date of the job. Periodically (once a week), the release decision is made. In order of planned release times, the jobs are considered for release. A job is only selected for release, if its release does not cause the workload norm of any station to be exceeded. After selection, the job is included in the workloads. All jobs in the pool are considered, but according to the pool sequence, jobs with an earlier planned release time have a higher probability to be selected. Jobs that are not selected have to wait in the pool until the next release time. The load conversion procedure of method A is implemented as described in [Bechte, 1988].

After release to the floor, the jobs are sequenced 'first-come-first-served' in the queue of each station.

### *Shop configurations*

The *pure job shops* used in most simulation research show the most extreme type of routing variety. The same station might perform the first operation in the routing of one job, while it performs the final operation in the routing of another job. In other words, the routing sequence is completely random and the flows through the shop are undirected. Beside the routing sequence, the routing length varies strongly in most simulated job shops. Some jobs may have only one operation to be performed, while other jobs visit all stations in the shop.

Enns [1995] argues that real life job shops have most in common with the theoretical *general flow shop*. In the theoretical *pure flow shop*, each job has exactly the same routing. However in a general flow shop, a movement between any combination of two stations may occur, but the flow will always have the same direction. Compared to the pure flow shop routing, any set of stations might be excluded from the routing. Thus, the general flow shop may still show routing variety with respect to routing lengths, though there is one flow direction.

Including a *restricted job shop* with variable routing sequences and constant routing lengths completes the spectrum between a pure job shop and a pure flow shop. This results in a matrix of four shop configurations (table 1). These

configurations bound the spectrum, within which most real life job shops will fall.

	<b>Routing length:</b>	
	<b>variable</b>	<b>constant</b>
<b>undirected</b>	Pure Job Shop (JS)	Restricted Job Shop (RJS)
<b>Flow:</b>		
<b>directed</b>	General Flow Shop (FS)	Pure Flow Shop (FS)

*Table 1: simulated shop configurations*

The four shop configurations have been modelled for simulation as follows.

The pure job shop model (JS) of [Melnyk et al., 1989] has been the starting point of our study. This shop consists of 6 stations. No station performs more than one operation of a job. This means that return visits do not occur, and that the maximum number of operations per job is limited to 6. More precisely, the lengths of the job routings are determined by drawing from a discrete uniform distribution on [1, 6]. The routing sequence is completely random.

The routings in the general flow shop (GFS) are determined equally, only will the stations be visited in order of increasing station number. Thus, the number of stations to be visited by a job ( $N_j$ ) is drawn first (from the discrete uniform distribution on [1, 6]). Next, a random set of  $N_j$  stations is selected and sequenced in order of increasing station number. Thus, if station 1 is part of the selected set it will always be the first station in the job routing, and if station 6 is selected it will always be last.

In the restricted job shop (RJS) each job visits all stations. But, the sequence of the visits is completely random.

In the pure flow shop (FS) each job visits all 6 stations in order of increasing station number.

The routing of a job is determined directly upon its arrival in each of the simulated configurations. we can now derive routing matrices for the



configurations from the closed form expressions for the n-station case. Figure 5 shows these matrices, which improve our insights in the flows through each of the modelled shop configurations.

<b>JS</b>		To:						
		0	1	2	3	4	5	6
From	0	0	1/6	1/6	1/6	1/6	1/6	1/6
	1	2/7	0	1/7	1/7	1/7	1/7	1/7
	2	2/7	1/7	0	1/7	1/7	1/7	1/7
	3	2/7	1/7	1/7	0	1/7	1/7	1/7
	4	2/7	1/7	1/7	1/7	0	1/7	1/7
	5	2/7	1/7	1/7	1/7	1/7	0	1/7
	6	2/7	1/7	1/7	1/7	1/7	1/7	0

<b>RJS</b>		To:						
		0	1	2	3	4	5	6
From	0	0	1/6	1/6	1/6	1/6	1/6	1/6
	1	1/6	0	1/6	1/6	1/6	1/6	1/6
	2	1/6	1/6	0	1/6	1/6	1/6	1/6
	3	1/6	1/6	1/6	0	1/6	1/6	1/6
	4	1/6	1/6	1/6	1/6	0	1/6	1/6
	5	1/6	1/6	1/6	1/6	1/6	0	1/6
	6	1/6	1/6	1/6	1/6	1/6	1/6	0

<b>GFS</b>		To:						
		0	1	2	3	4	5	6
From	0	0	7/12	7/36	7/72	7/120	7/180	7/252
	1	1/21	0	2/3	1/6	1/15	1/30	2/105
	2	1/15	0	0	2/3	1/6	1/15	1/30
	3	1/10	0	0	0	2/3	1/6	1/15
	4	1/6	0	0	0	0	2/3	1/6
	5	1/3	0	0	0	0	0	2/3
	6	1	0	0	0	0	0	0

<b>FS</b>		To:						
		0	1	2	3	4	5	6
From	0	0	1	0	0	0	0	0
	1	0	0	1	0	0	0	0
	2	0	0	0	1	0	0	0
	3	0	0	0	0	1	0	0
	4	0	0	0	0	0	1	0
	5	0	0	0	0	0	0	1
	6	1	0	0	0	0	0	0

Figure 5: routing matrices for each of the shop configurations.

The element (m, n) of each matrix gives the probability that the job will move from station m to station n, given that station m is part of its routing. The element (0, n) gives the probability that the job enters the shop at station n. The element (m, 0) gives the probability that the job leaves the shop from station m, given that station m is part of its routing.

Notice that in the general flow shop the largest flow of jobs will occur between stations with consecutive station numbers. The probability that an arbitrary job at station s will move to station s+1 is equal to 2/3. We clearly observe the dominant flow in the routing matrix.

In all shop configurations the average operation processing time is the same (1 day). The job shop configuration of [Melnyk et al. 1989] uses exponentially distributed processing times. Instead, we use a 2-erlang distribution, which better approaches our observations in real life job shops. The same average utilisation level of 90 percent is created in each shop by setting the appropriate arrival rate. Jobs arrive according to a Poisson process.

### *Workload norms and performance measurement*

For each of the release methods, appropriate values for the workload norms have to be determined. In particular, we want to compare the methods at different levels of norm tightness. In each shop configuration we simulated 9 norm levels (including infinity) for each release method. Since each method uses different workload aggregations, it is difficult to set comparable norm levels. To compare the release methods at different levels of norm tightness, we use the average shop floor time as an intermediate variable.

More specifically, we suppose the norms of two methods to be equally tight when they result in the same average shop floor time. Therefore, the simulation results will be presented graphically, with the performance measure set against the shop floor time. Notice that the average shop floor time of the jobs will decrease when the workload norms for release to the floor are set tighter.

## **6. Simulation results**

Figure 6 shows the lead time performance for each of the four simulated shop configurations. The average total lead time (see figure 1) is plotted against the average shop floor time. For each release method a curve is constructed. A mark on the curves is the result of simulating a release method with a specific norm level. As we simulated 9 norm levels per method, each curve contains 9 marks. A mark is the result of 50 simulation runs of 6000 days, including a start-up period of 2000 days. The common random numbers technique has been used to reduce variance between experiments.

When the curve of one method remains below the curve of another, we may say that the former one shows the better lead time performance. Measures of due date performance have been recorded as well. However, we will not present the exact results here, as the relative due date performance of the simulated release methods did hardly differ from the presented lead time results. Obviously, due date performance is largely determined by the lead times.

Notice that the curves converge at the most right mark. This is the result of the infinite norm level. As might be expected, all release methods give the same result

if release is not restricted by the workload norms. By lowering the norm levels, the average floor time decreases. Thus moving from right to left, we see that also the total lead time tends to decrease first in most situations. As norms tend to get tighter (to the left end of the curves) total lead times tend to increase. Based on the analogy with semi-open queueing networks (Buzacott & Shanthikumar, 1993) several approaches will show asymptotic behaviour at low norms. To which extent the asymptotic behaviour differs between release approaches is difficult to foresee.

The observed lead time increase has been an important point of discussion in workload control literature [*e.g. Melnyk, 1991; Land & Gaalman 1998*]. As the total lead time is the sum of the pool time and the shop floor time, the increasing lead time implies that waiting time in the pool increases stronger than waiting time on the floor decreases for tighter norms. In the pure job shop we observe that lead times tend to increase rather fast as norms get tighter for method B and C, methods using norms for aggregated workloads. We observe that most simulations presented in job shop literature deal with strongly aggregating workload control methods. Our findings might partly explain the negative results reported from these studies. We also see that method A strongly outperforms method B and C as norms get tighter. Contrary to the other two, method A has quite a large region where the lead time does not increase. As was expected, method C shows worse performance than method B. Method B' and C' result in a strong improvement relative to method B and C.

In the restricted job shop the difference between the methods is rather small. All methods result in increasing lead times as norms get tighter. Method B' outperforms all other methods, including method A. Method C' gives exactly the same results as method C. Since the number of stations ( $N_j$ ) is 6 for each job  $j$ , the relative contribution of each job to the workload will be equal for method C and C'.

The general flow shop sketches a completely different picture. Method B outperforms the others. The correction in method B' no longer improves method B, and also the difference between method C and C' is small. Method A shows the worst results at higher shop floor times. Only at tight norms it improves over method C.

The pure flow shop shows quite spectacular results. Here method A is not able

to reduce the shop floor time. As soon as norms get tighter, a steady state cannot be reached during the simulation. This feature will be investigated thoroughly in the discussion of results. It may improve our understanding of the influence of a directed flow, and thus give insights in the worse behaviour of method A in the general flow shop as well. Method B strongly outperforms of method C, and method B' only slightly improves over method B at a small range of shop floor times. As the routing length is the same for all jobs, method C and C' give exactly the same results.

## **7. Discussion of results**

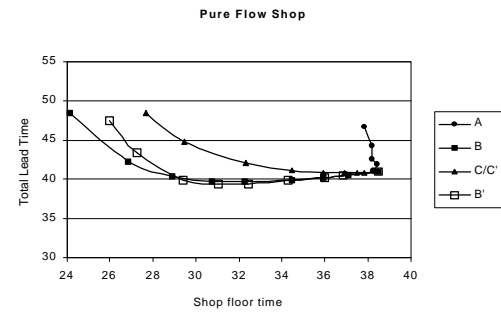
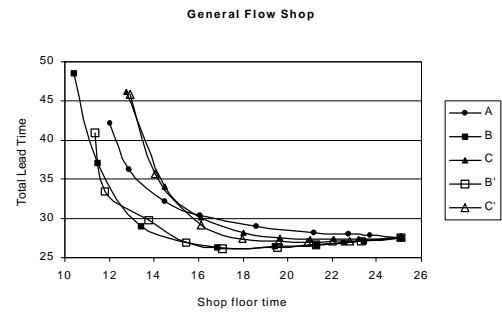
The different results found in each of the shop configurations give rise to further analysis. We will subdivide our discussion into two parts. First, we discuss the influence of variable station positions and routing lengths. Next, we assess the influence of a directed flow.

### *The influence of variable station positions and routing lengths*

In the pure job shop method A performs rather well. Method B and C are not able to realise the same reduction of shop floor time. In our earlier discussion we suggested that the position of each station varies strongly within the routing mix of a job shop. This might not allow for the use of a constant norm for the aggregate load, as in method B. Since the aggregate load includes the load upstream of a station, a momentarily increased station position will require an increased aggregate load. In the pure job shop, the station position continuously changes within the mix of jobs on the floor. Our expectation regarding the influence of the variable station position is confirmed by the strong improvement that results from using method B' instead of method B. The station position shows less variation in the job routings of the general flow shop. In the pure flow shop the position becomes even invariable. This might explain the strongly improved relative performance of method B in the flow shop configurations.

Regarding method C we expected the variable routing length to conflict with unchanging shop load norms. As method C' corrects for routing length differences among jobs, the improved performance of method C' in the shops with variable

routing lengths confirms our expectations. In the restricted job shop, the performance of method C is closer to that of method B. This also strengthens our argument on the influence of the number of operations.



*Figure 6: Lead time performance in each of the shop configuration*

The fixed routing length in the restricted job shop seems to affect all methods negatively, particularly method A. For a possible explanation of this feature, we look at the average position of a station in the job routings. The constant routing length is 6 stations and the average station position is 3.5 in the restricted job shop. In the pure job shop, the average routing length is 3.5 and the average station position in a routing is only 2.25. In the latter case it will be much easier to influence the direct load of a station by the release of jobs. As method A estimates the direct influence of job release on the direct loads, the difference of the average routing length might explain the deteriorated performance of method A. Further research is needed to explain the influence of this factor in more detail.

#### *The influence of a directed flow*

Method C is always outperformed by method B. This was expected, because information on completed operations is not used in the shop load of method C. Particularly in shops with a directed flow, the shop load of an upstream station hardly gives any information on its direct load situation. The simulation also shows more improvement of method B relative to method C in the flow shop configurations.

Method A displays curious behaviour in the pure flow shop. It becomes completely impossible to reduce the shop floor time by applying method A. In order to understand this behaviour, we gathered detailed input/output data of the pure flow shop during one simulation run. Figure 7 displays the exact course of the direct load for station 1 (the upper part of figure 7) and for station 6 (the lower part) during a certain interval. In addition, the value of the converted load is depicted for station 6. Remember that the converted load includes an estimation of the input (from jobs upstream) to the direct load during the next week. As station 1 is the gateway, the converted load of station 1 is exactly equal to its direct load.

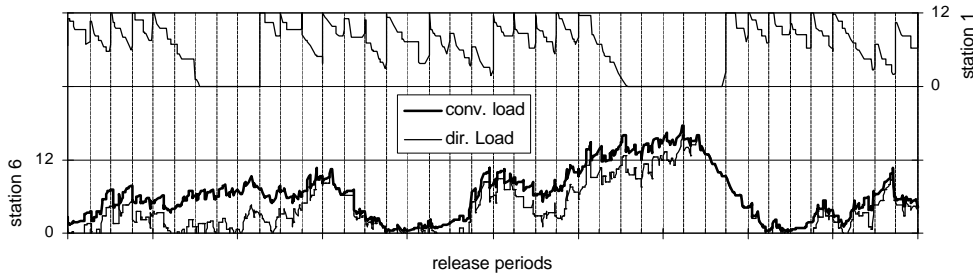


Figure 7: the course of the workloads for method A in a pure flow shop

In figure 7, the workload (in working days) is plotted vertically, and time is plotted horizontally. The release times (release takes place once every 5 days) are indicated by dashed vertical gridlines.

The release of new jobs will not be allowed, if it causes the converted load of any station to exceed the norm level. The workload norms are set tightly at 12 days of work in the presented situation. We see in figure that at most release times the norm level is exactly reached at station 1. At a certain time, it can be observed that the converted load of station 6 exceeds the norm level. At that time it is not allowed to release any job that contributes to the converted load of station 6. Since in the pure flow shop every job will visit station 6, the release of any job will contribute to the converted load of station 6 (see also figure 3). Thus, release is completely blocked. We see that the direct load of station 1 starts to decrease. However, station 6 still receives work from upstream. It takes at least 6 release periods until the workload of station 6 starts to decrease. In the mean time, we see that station 1 has starved. Since no job has been released for 6 periods, the flow upstream of station 6 has run dry. As a consequence the direct load of station decreases rather rapidly, and station 6 itself tends to starve. This cyclic pattern explains the disastrous behaviour of method A in a pure flow shop. Since stations starve too often the utilisation level of 90%, which is required by the arrival rate of the jobs, will not be realised. The pool of jobs waiting for release continues to grow and lead times continue to increase. Thus, the simulation becomes unstable.

This illustrates the danger of reacting on workload levels of downstream station in situations with more directed flow. The cyclic behaviour, which we could



show explicitly in the pure flow shop, might occur latently in other shop configurations. The strong performance of method B suggest that it is better to keep aggregate loads (including all work upstream) on a constant level. Perhaps it might be even better to exclude the direct load from the aggregate load and to focus on the quantities upstream in the case of a downstream station. However, verifying this suggestion requires further research.

## **8. Conclusions**

This research started from the perspective that pure job shops do not exist. In every real life job shop there will be a more or less dominant flow direction. The operations performed by some stations will have a preparative character, other stations will perform typical finishing operations. Finishing stations have most of their load upstream, while typical gateways have a lot of completed work downstream on the floor.

Three workload control approaches have been analysed and it has been observed that the concepts particularly differ with respect to the inclusion of upstream and downstream workload. Therefore, we expected that the flow characteristics of real life shops might have different influences on each of the approaches. A simulation study has confirmed this expectation. The approach that performs best in the theoretical pure job shop, shows the worst performance when the shop is characterised by a more dominant flow. As flows are completely undirected it appears to be important to estimate the influence of job release on the direct load of each station. Alternatively, it proved to be useful to adjust the aggregate load of stations (which include work upstream) for variations of the station position in the job routings or to adjust the shop load (also including work downstream) for the routing length variations. Obviously, the aggregate workload and the shop load do not appropriately indicate the future flow of work to a station in the case of job shops.

As the flow becomes increasingly directed, focussing on the direct load might create undesirable (cyclic) effects. In that case aggregate workloads seem to be a more appropriate variable to control. Aggregate workloads do no longer require adjustments.

The findings may explain part of the poor performance of controlled release methods reported in many simulation studies. These studies often apply release methods that strongly aggregate workloads in a pure job shop model.

This study investigated four shop configurations. Reality will be somewhere between these extremes. Knowledge on the performance of each WLC concept in these extremes may contribute to the choice of a WLC concept that fits well to a particular situation. Further research should detail intermediate shop configurations and look at robustness with respect to other modelled characteristics such as capacities and processing times.

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