

University of Groningen

Applicability aspects of workload control in job shop production

Henrich, P.

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version

Publisher's PDF, also known as Version of record

Publication date:

2005

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Henrich, P. (2005). *Applicability aspects of workload control in job shop production*. [Thesis fully internal (DIV), University of Groningen]. Labyrinth Publication.

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Chapter 3 Reducing feedback requirements of workload control

Published in the International Journal of Production Research, 2004, vol. 42, no. 24, pp. 5235-5252, with Martin Land, Gerard Gaalman, and Durk-Jouke van der Zee as co-authors.

Abstract

The workload control (WLC) concept is known as a robust shop floor control concept. It is especially suited for the dynamic environment of small and medium-sized enterprises (SMEs) within the make-to-order (MTO) sector. Before orders are released to the shop floor, they are collected in an 'order pool'. To make the release decision, information regarding the actual situation on the shop floor is required. Within SMEs, this information is often incomplete, incorrect, or delayed. However, the workload control approaches discussed in literature assume precise feedback information. The paper discusses the opportunities for information feedback from the shop floor for centralised order release within SMEs and analyzes the information requirements of WLC approaches. These approaches are adapted based on more realistic assumptions regarding information supply within SMEs. The different approaches are compared and assessed by a simulation study. Results show that additional investments in more accurate information supply lead to decreasing marginal improvements in overall shop performance. Additionally, they indicate that the choice of the right workload control approach might have important effects on performance.

3.1 Introduction

Workload control (WLC) is an elaborated shop floor control (SFC) concept especially suited for small and medium-sized enterprises (SMEs) within a make-to-order (MTO) environment (Hendry and Kingsman 1989). SFC has to deal with all kinds of production and demand uncertainties. This makes the control of the shop floor, often the main source of value creation, rather complex. Its functioning is crucial for the economic success of any SME. SMEs generally ask for uncomplicated and robust shop floor control concepts (Muda and Hendry 2002 A/B). The easy and intuitive use of the WLC concept is attractive for SMEs, as these companies often show characteristics in between craftsmanship and industry.

The WLC concept is based on the principles of input/output control as defined by Plossl and Wight (1973). The concept heavily depends on the use of 'order review and release' techniques as defined by Bergamaschi et al. (1997), where the arrival of an order does not necessarily involve the release to the shop. Before orders enter the shop floor they are collected in a so called 'order pool'. A central planner releases these orders periodically to the shop floor in such a way that the workload in front of the capacity groups on the floor will be balanced. Balancing and restricting the load on the floor leads to a transparent shop floor with predictable throughput times. A description of the characteristic elements of WLC and their application in SMEs is given in Henrich et al. (2004B)[⊗].

The central planner needs various types of information for the order release decision. This information comes from the customer (e.g. due date) or can be derived from the incoming order itself (e.g. process plan). For controlling and balancing the workload on the shop, information on the current shop status (i.e. the actual distribution of the workload - measured in operation processing time - across the individual capacity groups) is also necessary (Bergamaschi et al. 1997). More precisely the central planner needs feedback from the shop floor, indicating the detailed status and position of each order.

During the last two decades, much research has been done on the WLC concept. In the early 1980s, simultaneously different WLC approaches were developed. These concepts (Bertrand and Wortmann 1981, Tatsiopoulou 1983, Bechte 1984 and Wiendahl 1995) have been extensively discussed (Bechte 1994, Cigolini, Perona, and Portioli 1998, Perona and Portioli 1998, Kingsman 2000) and compared (Land and Gaalman 1996B, Land and Gaalman 1998, Oosterman et al. 2000). For a recent overview of research on this topic we refer to Gaalman and Perona (2002). Perona and Miragliotta (2000) conclude that most of the research on WLC focuses on theory building and not on the practical aspects of the different WLC approaches. In addition, Breithaupt et al. (2002) indicate a lack of WLC implementations in practice. Up to now, little is known about the implementation of WLC approaches and its actual functioning in SMEs. Due to special needs of SMEs, structural adaptations of the WLC concept that could lead to an improvement for the practical relevance of the WLC approach are scarce.

One of the first implementations of WLC in a small company was described by Tatsiopoulou (1983). While implementing his WLC approach, he struggled with the lack of sufficient feedback information from the shop floor necessary for order release. As a rigorous solution, he proposes an adapted approach limiting the need for feedback information to the registration of job completion. Unfortunately this solution

[⊗] Chapter 2.

may lead to an unacceptable performance loss (Oosterman et al. 2000). In addition, Melnyk and Ragatz (1989) describe that the timeliness and accuracy/completeness of shop floor information is crucial for the functioning of the order release mechanism. But after 1983, no better solutions have been proposed in literature for situations lacking accurate feedback. One might expect that the enormous improvements of information technology (IT) in the last decade would have erased this problem. Nevertheless, many obstacles still exist around the introduction and use of IT, especially within the environment of SMEs. While introducing WLC, we especially experienced that the requirements of the WLC concept regarding feedback information might still hinder its functioning in many SMEs. We observed several shortcomings in the supply of feedback information in practice. The available feedback information is often inaccurate (delayed, incorrect, incomplete) or insufficiently detailed.

Two alternative approaches can be used to solve the above mismatch: either the information feedback can be improved or the WLC concept can be adapted according to a more realistic information feedback within SMEs. In this paper, the latter approach is followed in line with Melnyk and Carter (1987), who confirmed the need for designing the supply of feedback information appropriately. Thus, the objective of the present paper is to enable the WLC concept to deal with the limited feedback information available in SMEs. A redesign of WLC release methods is presented that can handle limited feedback information. It is tested in a simulation study to quantify its impact on the shop floor performance.

The paper is organized as follows. Section 3.2, discusses the mechanisms of information feedback in SMEs. Section 3.3 first analyses the use of feedback information within WLC. This leads us to a redesign of several existing WLC approaches according a more realistic supply of information. Section 3.4 presents a simulation study to test our redesign by investigating the impact of the detail level of feedback information on the performance of the shop floor. The results of this simulation study are presented and discussed in Section 3.5. Section 3.6 has conclusions.

3.2 Information feedback in SMEs

For order release, it is important that the central planner knows what order is queuing (or being processed) at what capacity groups. The planner needs a detailed overview of the shop floor status. For detailed information feedback within the WLC concept, any status change on the shop floor has to be registered and transmitted to the central planner, so that he/she can get the actual status overview of the shop floor.

The process of information feedback thus includes the registration of status changes, the transmission of these data and its interpretation by the central planner.

In practice, it can be observed that particularly within ‘smaller’ SMEs, it is the central planner who performs this process of information feedback. Another group of SMEs has grown from a ‘smaller’ shop floor. An expanding shop floor generally leads to an increase in machines, operators, numbers of orders being simultaneously on the floor, etc. and cannot be monitored completely by the planner anymore. It asks for a more formalized approach to handle the increased complexity. To reduce this complexity, the floor often is subdivided into some production units (PUs), monitored by unit leaders or foremen. In these situations, a commonly observed structure for the generation of feedback information is that of regular meetings between foremen and planner, with the foremen reporting the progress of jobs. The status change registration and transmission part of information feedback is moved away from the planner to the foremen.

The exact knowledge of status changes in these more mature shop floor structures is distributed across the functions and the related tasks on the floor (Table 3.1). For instance, the main task of the foremen is to control the material flow within the PUs, therefore they can register any order entering or leaving ‘their’ department. Only the operators exactly know which individual job is actually queuing or being processed at their machines.

Table 3.1 Status change knowledge related to functions

function	order release/ order completion	start/completion in PU	start/completion in the shop
planner	x		
foremen		x	
operators			x

Within the informal planning concepts of many SMEs, it is sufficient that only the foremen have an exact knowledge of which jobs are being processed in their unit, combined with a rough notice of the internal PU job progress. But the introduction of a more formalized WLC concept requires the feedback of detailed information on completed operations to the planner. This generally leads to the involvement of the operators in the feedback process. Either manual (e.g. notes on the routeing sheet) or automated (scanning) solutions are introduced to transmit the information to the planner. Typically, this feedback appears to be an important obstacle in the introduction of the WLC concept.

Several reasons can be distinguished for the disfunctioning of feedback systems involving all operators. On the one hand, complex motivational problems and reservations against organizational (and/or technological) changes may occur. As the status change registration is not the core task of the production-focused operators or as, for example, operators may feel being 'watched' regarding their productivity, it can become difficult to motivate all the operators to give accurate (reliable, correct, on time) feedback of any performed operation all the time. On the other hand, a couple of practical problems arise with the registration and transmission of the relevant data. Manual data registration and transmission leads to an exhaustive data set that cannot be interpreted entirely by the planner on time. Though IT is state of the art and broadly available, different obstacles exist around its introduction and use in SMEs (Henrich 2000). Often the specific knowledge and know how on IT is not present within SMEs. In addition, different computer systems and data formats may not be integrated, which makes data exchange difficult. In addition, very practical problems such as how to scan an operation processed in parallel by two operators occur. However, putting effort in the instruction and monitoring of operators can solve nearly all problems. But with a substantial number of operators, it raises the question whether the information need of the concept is worth these efforts.

Within informal planning systems the intermediate role of foremen in providing feedback has been proven successful. The foremen generally feel more involved in job progress issues and at least the number of foremen to keep involved is relatively small. However, involvement of foremen will be best facilitated when only the shipments between the PUs have to be registered. Though the foremen will also have an indication of the detailed progress of jobs within their PU, formal registration may require much more effort.

We assume that the organizational division of the shop floor helps in structuring feedback on PU level. This information is not as detailed as feedback information on performed operations (given by the operators). However, it might be much more accurate (reliable, complete, on time) and easier to collect. The arising conflict between this way of information feedback and the need for status information by WLC is discussed in more detail below.

3.3 Redesign of the feedback information need in WLC

This section first analyses the WLC concept. Here it focuses on the elements that depend on feedback information. A deeper understanding of these elements enables one to restructure the concept according to the more realistic information supply. This redesign is described and motivated in the second part of this section.

Use of feedback information in WLC

Order release is the most central control element within the WLC concept. To understand the use of feedback information, it is necessary to focus on this control element.

As depicted in Figure 3.1, after the acceptance of an order some pre-shop operations (engineering/process planning) may be necessary before the order is ready for release to the shop floor. The order will generally have to wait before it is selected for release. Waiting before release takes place in a so-called order pool. The decision to release an order is based on two aspects: the urgency of the order itself and its influence on the momentary shop floor situation. The latter is determined by comparing the workloads with norms. The norms can be defined for each capacity group and are usually expressed in time units. They should guarantee a small but stable buffer of work in front of the resources within the capacity groups. A stable buffer in front of a capacity group allows for constant operation lead times. In turn these constant lead times are used for determining accurate planned release dates. The planned release date of an order is calculated as its due date minus the planned lead times for its operations. Thus, the urgency of orders in the pool can be compared. Orders in the pool are considered for release in the sequence of their planned release dates.

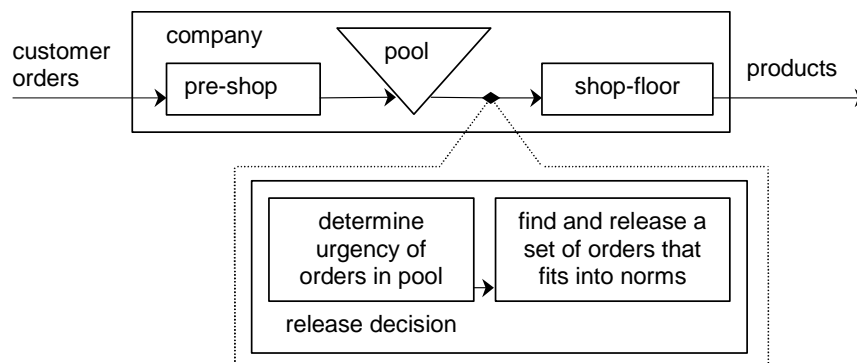


Figure 3.1 Central order release

The order being considered is added to the release selection as long as its release will not cause any workload norm to be exceeded. Otherwise, the order will have to wait in the pool until the next release opportunity. An order with a later planned release date may be selected when it does fit in the norms. After this procedure is completed, the selected orders are released to the shop floor. They remain on the floor until all the operations have been finished.

The decision to allow an order for release depends on the shop floor situation, which is reflected in workloads. In the literature, two different concepts for calculating the workloads are discussed (e.g. Graves et al. 1995). Bechte (1984) derives a 'projected workload' over the planning horizon. A capacity group's projected workload consists of its direct load plus the 'discounted' indirect load. The direct load is the amount of work actually queuing or in process at the capacity group. The indirect load is the released work upstream the regarded capacity group (Jendralski 1978). The discount factor can be used to derive the probability that an order that is upstream will reach the capacity group during the release period.

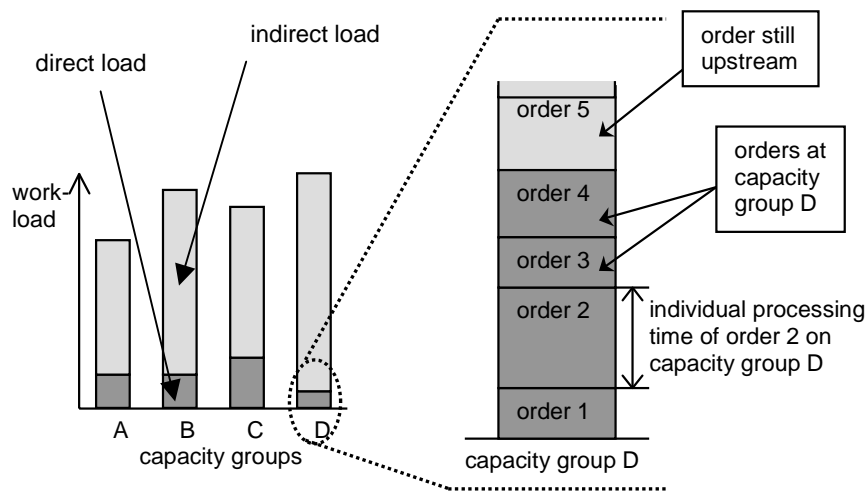


Figure 3.2 The use of aggregate loads to estimate the work per capacity group

The second approach is developed by Bertrand and Wortmann (1981). They calculate the workload as an aggregate of individual processing times. To determine the 'aggregate workload', the central planner counts up (at the beginning of a release period) the processing times of orders waiting in front of a capacity group (direct load) and those of orders upstream (indirect load) (Figure 3.2). The present paper will adopt this approach to a more realistic situation of feedback information, as described in Section 3.4.

The aggregate workload $WL_{s,t}^{agg}$ for capacity group s at time t is calculated as follows:

$$WL_{s,t}^{agg} = \sum_{i \in J} p_{is} I(t) [t_i^1, t_{is}^3], \quad (1)$$

where

- J the set of all orders,
- p_{is} processing time of order i on capacity group s ,
- $I(t)_{[...]}$ indicator: I at the defined interval (otherwise 0),
- t_i^1 release time of order i ,
- t_{is}^3 completion time of order i at capacity group s .

The central planner can only calculate the aggregate load if the feedback information, i.e. the information about the completion of the operation at each capacity group s , has been collected and transmitted. This becomes clearer if we look at the description of the order flow of a single order i in more detail (Figure 3.3).

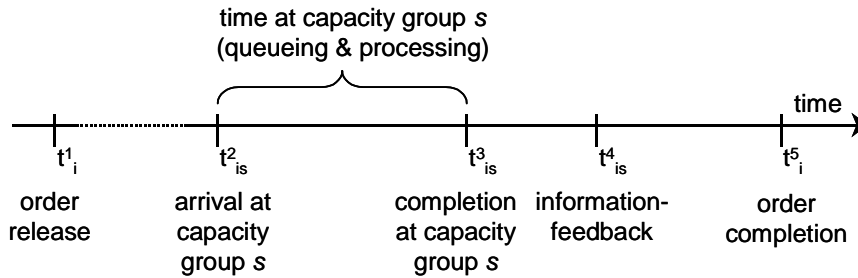


Figure 3.3 Order flow

Order i is released at t_i^1 to the shop floor. At this moment, its operation processing time (p_{is}) on capacity group s becomes part of the indirect load of the capacity group s as defined in Figure 3.2. At t_{is}^2 the order i arrives at capacity group s and becomes part of the direct load of capacity group s . t_{is}^3 is the moment of completion at capacity group s . During the time in between t_i^1 and t_{is}^3 p_{is} is part of the aggregate workload (the indirect or direct load) of capacity group s . To derive the aggregate workload of capacity group s , for each order that is going to be operated on s the order release- (t_i^1) and the completion moment (t_{is}^3) have to be registered, respectively to add or subtract p_{is} from the aggregate load of capacity group s . To calculate the aggregate load for each capacity group, the order release and all the intermediate completion moments for each order have to be registered.

Redesign

The WLC approach discussed above assumes $t_{is}^A = t_{is}^3$ for all capacity groups (Figure 3.3): t_{is}^3 is the completion moment at the capacity group and t_{is}^A the moment of actual information feedback. This means that the information feedback points (FBPs) have to be placed at each single capacity group to update the aggregate workload continuously. As discussed in Section 3.2, in many SMEs, the FBPs are often placed at the ‘border’ of a PU. Thus, only if an order leaves a PU, the shop status is updated by the foremen. Hence, it is more realistic to assume $t_{is}^A \geq t_{is}^3$. The WLC approach is not prepared to handle this less detailed information feedback. Therefore, we adapt the existing WLC approach in such a way that it becomes possible to handle the less detailed information. This implies that capacity groups within the same PU have the same FBP. Given the notion of common FBPs per PU, we propose an adapted WLC approach.

This leads to the aggregate PU load $WL_{s,t}^{aggrPU}$:

$$WL_{s,t}^{aggrPU} = \sum_{i \in J} p_{is} I(t) [t_i^1, t_{is}^A], \quad (2)$$

where

t_i^1 release time of order i ,

t_{is}^A arrival time of order i at the first FBP after capacity group s .

The aggregate PU load is the sum of the processing times of the orders in between order release and the FBP behind the considered capacity group s . t_{is}^A is equal for all s in the same PU. In contrast to the aggregate load (1) the ‘aggregate PU’ load (2) gives a less detailed indication of the actual workload status per capacity group, but can be assumed to be more accurate (reliable, complete, on time) (Figure 3.4).

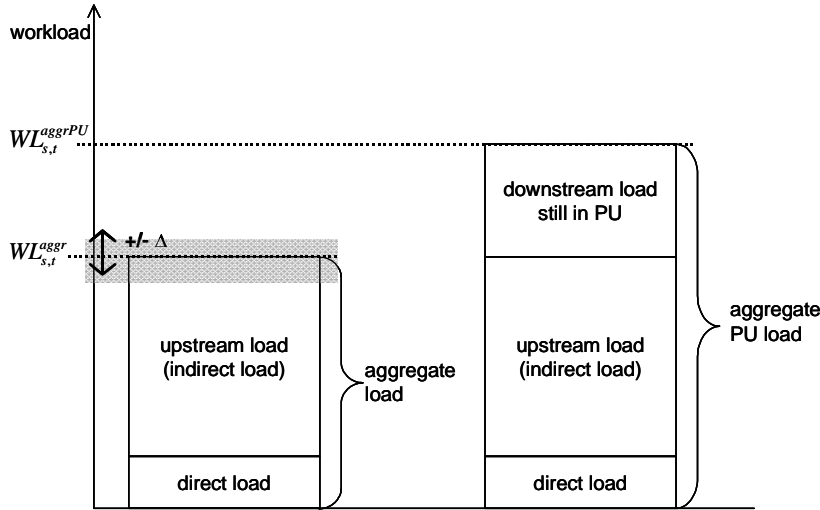


Figure 3.4 Aggregate load ($WL_{s,t}^{aggr}$) versus aggregate PU load ($WL_{s,t}^{aggrPU}$)

Figure 3.4 shows the differences between the aggregate load described by Bertrand and Wortmann (1981) and the aggregate PU load. The workload on the left shows the aggregate load ($WL_{s,t}^{aggr}$) for a fictive capacity group. Due to the often delayed, incorrect or incomplete feedback at t_{is}^4 (relative to the completion of the performed operation in t_{is}^3), the actual aggregate workload may differ from the assumed aggregate workload ($WL_{s,t}^{aggr}$) (the difference is indicated as Δ). On the right the aggregate PU load ($WL_{s,t}^{aggrPU}$) is shown. Obviously, $WL_{s,t}^{aggrPU}$ is higher than $WL_{s,t}^{aggr}$, as also the downstream load up to the next FBP is added. Additionally, we assume $\Delta=0$ as the feedback information on PU level is more accurate and easier to collect than the feedback information on performed operations (see Section 3.2). By adding the downstream load, we include all orders in between operation completion at the capacity group (t_{is}^3) and the following accurate FBP (t_{is}^4). This leads to the accurate aggregate PU load ($WL_{s,t}^{aggrPU}$). The example of Figure 3.4 is based on an average capacity group. This capacity group is not placed at the beginning of the order routing in the case of a flow dominant routing structure (otherwise the indirect load would be equal to zero) nor placed at the last place within each order routing relative to the relevant PU (otherwise the downstream load would be equal to zero).

An extreme case of this approach has been discussed by Tatiopoulos (1983), who assumes that the information feedback is only possible at the end of the last operation

in the routing before the order is sent to the customer (t_i^5 in Figure 3.2). Thus, the shop floor is ‘subdivided’ into just one PU.

This has been indicated as extended aggregate load $WL_{s,t}^{ext.aggr}$ (Oosterman et al. 2000):

$$WL_{s,t}^{ext.aggr} = \sum_{i \in J} p_{is} I(t) [t_i^1, t_i^5], \quad (3)$$

where

t_i^1 release time of order i ,
 t_i^5 completion time of order i .

The extended aggregate load is the sum of the processing times (p_{is}) of the orders in between order release and order completion. Oosterman et al. (2000) compare the effect of the extended aggregated load with alternative WLC approaches (e.g. the projected workload (by Bechte), and the aggregate load (by Bertrand and Wortmann)). Within several shop floor structures, the extended aggregate load shows an unacceptable performance loss.

To develop a simple and robust WLC concept, Land and Gaalman (1996A) present an improvement to the calculation of aggregate loads discussed above (1) called corrected aggregate load. For a more detailed description of this WLC approach, including a performance evaluation of this method, see Oosterman et al. (2000) and Land (2004B). This approach considers the job routing characteristics in the workload calculation without asking any additional feedback information from the shop floor.

The corrected aggregate load $WL_{s,t}^{cor.aggr}$ is defined as follows:

$$WL_{s,t}^{cor.aggr} = \sum_{i \in J} q_{is} I(t) [t_i^1, t_{is}^3], \text{ where } q_{is} := p_{is} (t_{is}^3 - t_{is}^2) / (t_{is}^3 - t_i^1), \quad (1')$$

where

t_i^1 release time of order i ,
 t_{is}^2 arrival time of order i at capacity group s ,
 t_{is}^3 completion of order i at capacity group s .

Notice that the contribution of order i to the time average direct load of station s during an interval $[0, z)$ - with z sufficient large - is equal to $1/z \int_0^z p_{is} I(t) [t_{is}^2, t_{is}^3] dt$.

Since $\frac{1}{z} \int_0^z p_{is} \frac{t_{is}^3 - t_{is}^2}{t_{is}^3 - t_i^1} I(t) [t_i^1, t_{is}^3] dt = \frac{1}{z} \int_0^z p_{is} I(t) [t_{is}^2, t_{is}^3] dt$ the time average corrected

load will approach time average direct load in the long term. The corrected contribution q_{is} includes the ratio between (1) the time the order i is directly queuing or in process at capacity group s ($t_{is}^3 - t_{is}^2$), and (2) the time in between order release

and operation completion $(t_{is}^3 - t_i^1)$. However the corrected contribution q_{is} must be determined at the time of release. At that moment, only the release time t_i^1 is known, so an estimation must be made. A simple approach for a shop floor with roughly comparable throughput time levels per capacity groups is to estimate q_{is} by p_{is}/n_{is} , with n_{is} being the position of the capacity group s within the routing of order i . In other words, to derive the corrected aggregate load (1') the aggregate load (1) is corrected by the individual position of the operation within the routing of the individual order. For the calculation of the corrected aggregate loads the same amount of feedback information is needed as for the calculation of the aggregate load. It requires a FBP at each single capacity group to update the (corrected) aggregate workload continuously.

The calculation of workloads based on the load correction is proved to be beneficial in several production environments as it especially considers the individual order routing characteristics during release (Oosterman et al. 2000). For the calculation of the correction factor n_{is} , no additional feedback information from the shop floor is necessary. The correction factor can be derived from the order routing/process plan that is already known at the moment the order enters the pool (see Figure 3.1). We saw in various simulation experiments that the factor n_{is} is robust within even unbalanced shop floor structures, i.e. unequal station throughput times across capacity groups.

The correction can also be applied to the aggregate PU load $WL_{s,t}^{aggrPU}$ (2) and the extended aggregate load $WL_{s,t}^{ext.aggr}$ (3). The corresponding formulas are:

$$WL_{s,t}^{corr.aggrPU} = \sum_{i \in J} \tilde{q}_{is} I(t)_{[t_i^1, t_{is}^4]}, \text{ where } \tilde{q}_{is} := p_{is} (t_{is}^3 - t_{is}^2) / (t_{is}^4 - t_i^1) \quad (2')$$

$$WL_{s,t}^{corr.ext.aggr} = \sum_{i \in J} \tilde{q}_{is} I(t)_{[t_i^1, t_i^5]}, \text{ where } \tilde{q}_{is} := p_{is} (t_{is}^3 - t_{is}^2) / (t_{is}^5 - t_i^1) \quad (3')$$

where

- t_i^1 release time of order i ,
- t_{is}^2 arrival time of order i at capacity group s ,
- t_{is}^3 completion of order i at capacity group s ,
- t_{is}^4 arrival time of order i at the first FBP after capacity group s ,
- t_i^5 completion time of order i .

Again the time average corrected aggregate PU load is equal to the time average direct load at the capacity group s in the long term. \tilde{q}_{is} relates the time an order spends directly at the capacity group $(t_{is}^3 - t_{is}^2)$ to the time it stays in between order release and feedback $(t_{is}^4 - t_i^1)$. In comparison with (1'), the feedback is not required at

the order completion anymore and the downstream load up to the next FBP (Figure 3.4) is considered in the estimation of \tilde{q}_{is} as well. Obviously, the time interval the order i remains part of the workload is longer than with immediate feedback at operation completion (t^3). Now, p_{is}/\tilde{n}_{is} is the estimator of \tilde{q}_{is} , where \tilde{n}_{is} equals the number of capacity groups that have to be visited according to the routing of order i in between the order release (at t^1_i) and the actual FBP of operation s (t^4_{is}).

The same holds for the corrected extended aggregate load (3'). The only difference occurs with the length of the time span an order is considered as being part of the workload ($t^5_{is} - t^1_i$). Therefore the correction factor \tilde{q}_{is} has to be adapted into p_{is}/\tilde{n}_i , with \tilde{n}_i being the number of operations in between order release and order completion. Order completion is assumed to be the only FBP on the shop floor. Notice that \tilde{n}_i is the routing length of order i .

Consider the example that an order has to be operated on capacity group A, B and C, with the respective operation processing times p_A , p_B , and p_C ; the first two operations have to be executed on two capacity groups that belong to PU 1 and the final operation is executed within PU 2. For this example, the contribution of the operation processing times to the workloads of the different capacity groups is presented in Table 3.2 for the different workload calculations.

Table 3.2 Contribution to the workload

Contribution to the workload	(1') Corrected aggregate load	(2') Corrected aggregate PU load	(3') Corrected extended aggregate load
Capacity group A	$p_A/1$	$p_A/2$	$p_A/3$
Capacity group B	$p_B/2$	$p_B/2$	$p_B/3$
Capacity group C	$p_C/3$	$p_C/3$	$p_C/3$

For calculating the corrected aggregate load (1') p_A has to be divided by 1, p_B by 2 and p_C by 3. This WLC approach assumes a FBP at the end of each capacity group that performs an operation. For calculating the corrected aggregate PU load (2'), p_A and p_B have to be corrected by the factor 2, as two is the number of capacity groups in the routing of the order in between order release and the actual FBP of the capacity groups A and B. The operation processing time on machine C has to be corrected by three. In the case of the corrected extended aggregate load (3') the correction factor for all operation processing times is three. Although the calculations are different, all of them are seen as an estimate of the time average direct load. Therefore the correction factor must be higher when more orders are included in the calculations.

Actually, the existing WLC approaches using the calculations (1) and (3) can be considered extreme cases of the aggregate PU load (2) (the same holds for (1'), (3') and (2')): situation (1) can be seen as each capacity group forming a single PU. In other words, the number of FBPs on the floor is equal to the number of capacity groups. In (3), the whole shop floor is treated as one single PU with a single FBP at order completion. (2) shows the intermediate possibilities with less detailed feedback than necessary for (1) but more detailed than in (3).

To conclude, we analysed the information need of existing WLC approaches and developed two WLC approaches (2, 2') by adapting the existing ones. The new approaches take into account the actual information feedback opportunities within SMEs. The following simulation study investigates how disadvantageous the lack of detailed information might be by comparing the alternative approaches.

3.4 Simulation study

A discrete event simulation model is developed to facilitate testing the effects of different detail levels of information feedback. Here we distinguish alternative shop floor structures and investigate the influence of the discussed WLC approaches on shop performance.

Experimental model

The simulation model is built in *eM-Plant* (Tecnomatix 2001). The inter-arrival time of orders at the pool is distributed negative exponentially. The model consists of a shop floor with 12 capacity groups (machines). The number of operations per job is uniformly distributed between one and 12, resulting in an average of 6.5 operations per job. The processing times at each capacity group follow a Gamma distribution ($\alpha=2$, $\beta=0.5$) with a mean of 1 (time units) and a variance of 0.5. This results in an average shop floor utilization of 0.9. The set up times are defined to be sequence independent and are modelled as a part of the operation processing times. Orders are processed at the capacity groups on a first-come first-served (FCFS) basis. Only one order can be operated at each capacity group at the same time. The externally set due dates of the orders are determined by the order arrival time at the pool plus a uniformly distributed due date allowance.

Order release

Every 5 time units all the orders in the pool are considered for release by comparing the workloads with the workload norms of the relevant capacity groups. For all orders in the pool the complete process plan is known. The process plan includes the routing, the operation processing times and the externally set due dates. As described in Section 3.3 the orders in the pool are ordered by urgency. To indicate this urgency a planned release date is determined by subtracting the planned shop floor throughput time from the due date. To derive the planned shop floor throughput time of an order a constant parameter (5 time units), representing an estimated average throughput time per operation, is multiplied with the routing length (\tilde{n}_i).

Routing assumptions

Two different shop floor structures are modelled:

- (a) A general flow shop (Enns 1995) with 12 capacity groups; the general flow shop is different from a pure flow shop. In the theoretical pure flow shop, each order has exactly the same routing. However, in the general flow shop, a movement between any combinations of two stations may occur, but the flow will always have the same direction.
- (b) Combination of two pure job shops with 6 capacity groups each. First, an order visits job shop 1 then job shop 2. A back flow of orders between the two shops is not considered, although an order may also skip one of the shops. The routing sequence within each pure job shop is completely random and the flows through the shops are undirected. Each capacity group within the pure job shop has an equal probability of being selected as the first capacity group within shop one or shop two. After the first operation has been performed the probabilities of going to any of the other capacity groups are equal and depend on the probability of leaving the shop, which in turn depends on the routing length. This flow structure represents a company situation within which the orders have to flow through several production units that are organized like pure job shops.

In both simulated shop floor structures, the average routing length is 6.5 operations per order. No capacity group performs more than one operation of an order.

Routing in most companies lies somewhere between the pure job shop and pure flow shop extremes. Seldom would all jobs visit all machines in a fixed sequence (pure flow shop) nor would it be realistic to assume a pure job shop within which each machine is equally likely to be required for the next operation (Enns 1995). In accordance to Perona and Miragliotta (2000) and the present authors' experiences in practice, the above defined flow dominant routing structures were implemented.

Information feedback

There are different possibilities to position the FBPs in the two shop floor structures described above. The FBPs have to be related to the PUs on the floor. For the general flow shop (a), five different structures were tested. We simulate a subdivision into 12, four, three, two and one equally sized PUs. This means that we tested structures with 12, four, three, two and one FBPs. The definition of four FBPs, for example, leads to a FBP after the third, sixth, ninth and 12th capacity group. The first three capacity groups belong to PU 1, the fourth to sixth capacity group to PU 2, and so on. For the second flow structure (b), we only consider the use of one, two and 12 FBPs. With 12 FBPs, we arrive at the traditional load calculation, with immediate feedback at the completion of each operation, whereas each capacity group is seen as a single PU. Figure 3.5 shows flow structure (b). The figure relates the different FBPs, divided across the two PUs, to the flow of an individual order.

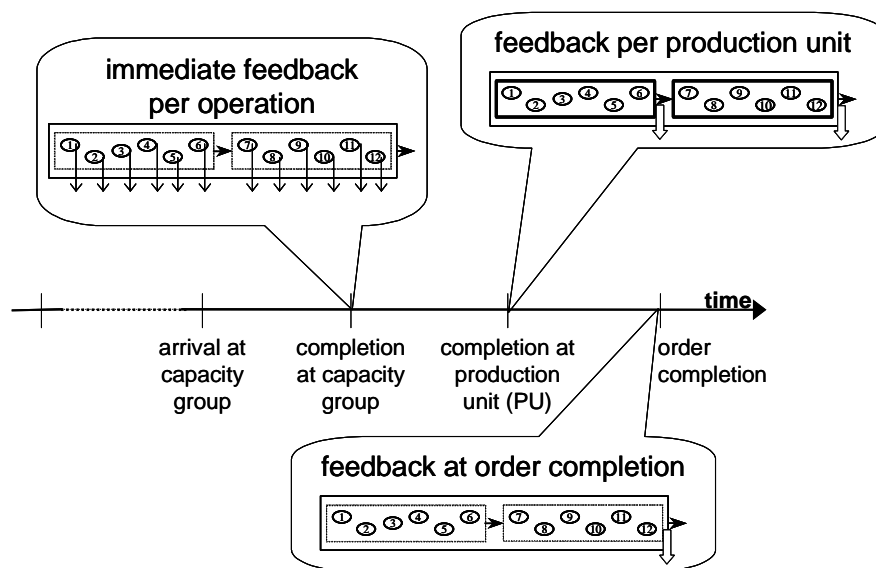


Figure 3.5 Comparison of the different feedback points (FBPs)

Design of experiments

Table 3.3 shows that the different experimental settings as described above lead to 16 different experiments.

Table 3.3 Experimental settings

routing structure	(a) general flow shop	(b) two pure job shops
number of FBPs	12, 4, 3, 2, 1	12, 2, 1
WLC approach	aggregate load & corrected aggregate load	
resulting experiments	10	6

For each of the 16 combinations, different workload norms, determining the amount of orders to be released, are simulated. Thus, for instance the experiment ‘general flow shop/3 FBPs/corrected aggregate load’ are tested under different workload norms, going stepwise down from infinity. The workload norms form an important control parameter during order release (Land, 2004A). For a more detailed description, see the appendix.

For each norm that is tested within the experiments 100 independent replications are performed. The replication length is 13000 time units, with observations from the first 3000 time units being deleted to avoid start up effects. Common random numbers are used as a variance reduction technique across all experiments (see e.g. Law and Kelton 2000).

3.5 Results and analysis

Performance measurement

The simulation study helps us to compare and understand the different WLC approaches with respect to the role and means of FBPs for system performance. The Figures 3.6 and 3.7 show some of the results. The horizontal axis is floor time, which is the average time an order stays on the shop floor: it is the time in between order release and order completion. It is used as an instrumental variable to indicate norm tightness. The vertical axis shows total throughput time. To derive total throughput time, the pool waiting time, i.e. the average time an order is waiting in the order pool,

is added to the floor time. It is used to indicate overall shop performance. As described in Section 3.4, each experimental setting (routing structure/number of FBPs/WLC approach) has been tested under different levels of norm tightness. The resulting points that refer to the same experiment are connected by curves, called performance curves. The representation method used is similar to that used in other research (e.g. Sabuncuoglu and Karapinar 1999, Oosterman et al. 2000, Enns and Prongué Costa 2002).

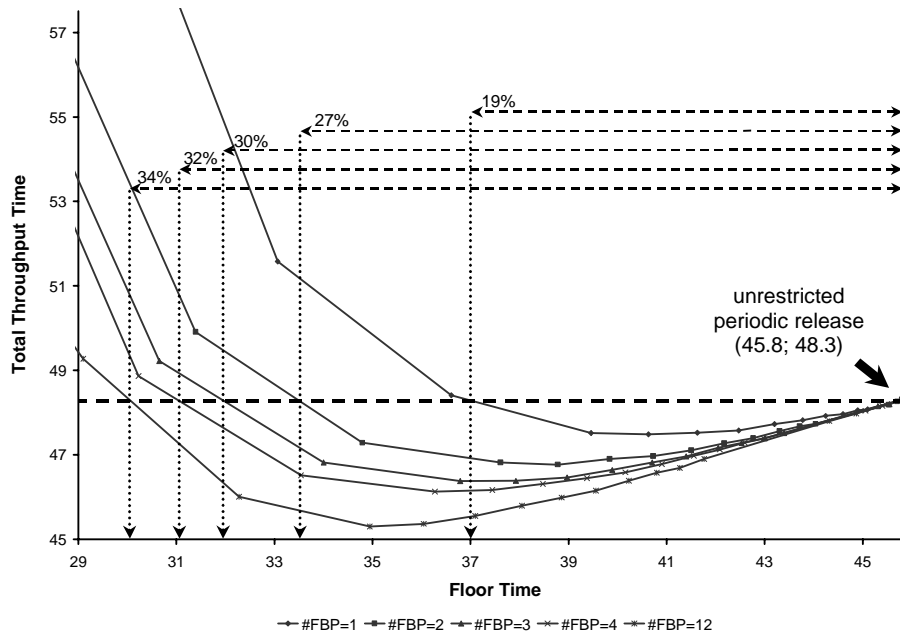


Figure 3.6 General flow shop (corrected workloads)

Analysis of results

Figure 3.6 shows the performance curves of a general flow shop with 12 identical capacity groups. The simulated WLC approach is based on the use of corrected workloads. The experiments without load correction are not presented as the results of the two load types hardly show any differences in the general flow shop. The upper curve shows the outcomes of the experiment with only one FBP at the end of the order routing to register the completed orders. The lowest curve shows a shop floor with feedback at the end of each operation (12 FBPs). The other curves depict

intermediate situations with two, three and four FBPs. All four curves start at the point (45.8; 48.3). This is the point using 'infinite' norms resulting in unrestricted periodic release. At this point the total throughput time is 2.5 time units longer than the floor time, exactly half the length of a release period. By narrowing the norms (narrowing the inflow of orders to the shop floor), the depicted points move from right to left. Moving too far left, the norms are so tight that orders have to wait extremely long in the pool. This results in short floor times based on the low WIP level on the shop floor combined with long total throughput times due to long waiting times within the order pool. Obviously, the curves that lie the closest to the origin of the coordinate system show the best shop floor performance as it is possible to realize a shop floor state that combines short floor times and short total throughput times simultaneously.

The different experiments show that a wide variety of shop floor states can be achieved. It is possible to compare these curves in many different ways (e.g. minimum of each curve, etc.). We compare the uncontrolled situation of unrestricted periodic release with the different experiments by drawing a horizontal line. We see, that by using tighter norms the floor time can be decreased to some extent without increasing the total throughput time. With the effective use of just one FBP, one even can decrease the floor time by 19% without causing total throughput times to increase relative to unrestricted periodic release. With two FBPs, a total reduction of 27% is possible before the total throughput raises above its start value at periodic release. As expected, the highest floor time reduction (34%) can be realised with 12 FBPs, the situation with the most detailed information supply.

Figure 3.6 shows there is a decreasing marginal performance win by adding additional FBPs. For example, it is possible to reduce the floor time by an extra 8% by just switching from one to two FBPs. To move from a 32 to a 34% floor time decrease, a switch from 4 to 12 FBPs is necessary. A decreasing marginal performance win can be realized with each additional investment in FBPs. This leads to an obvious trade-off between the costs of FBPs in terms of data collection and the increase of shop floor performance.

In practice, it is difficult to set the different workload norms. Often the exact norms are determined by experiments. The situations with more FBPs (the lower curves) are less sensitive to this 'trial and error' approach. That is, the more FBPs are used, the more norms can be chosen without risking an unacceptable increase of total throughput time. If companies find a controlled shop floor of more importance than the value of the floor time as such, the region with a moderate decrease, e.g. 10-15%, could be of importance. Within this range, the performance curves are quite similar, which means that they are quite independent from the chosen amount of information feedback.

Figure 3.7 depicts the simulation outcomes of the WLC approaches tested in a shop floor subdivided into two pure job shops with six capacity groups each. The dashed curves show the use of aggregate loads. The other curves are based on the corrected loads. The performance curves show patterns similar to those in Figure 3.6.

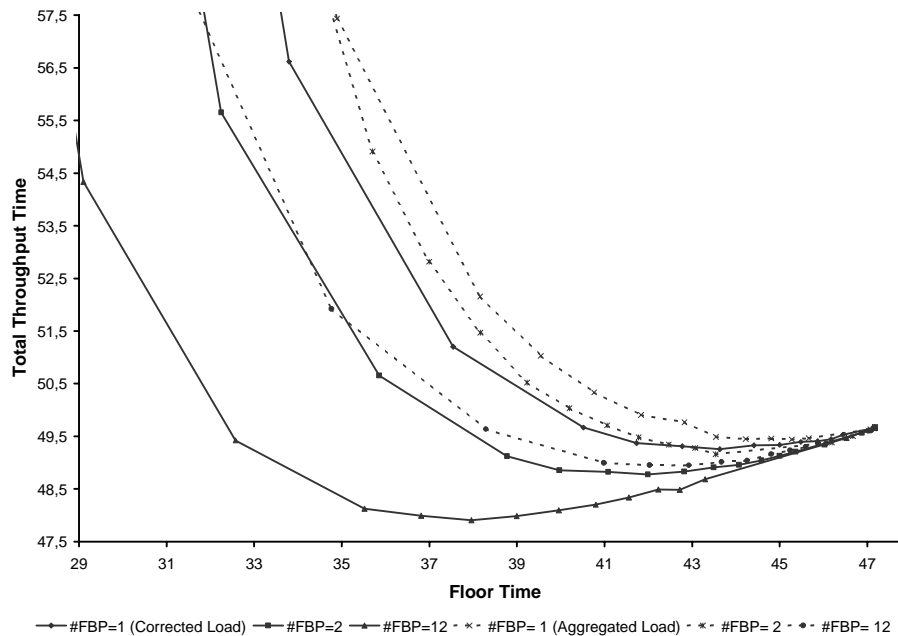


Figure 3.7 Two pure job shops (aggregate load vs. corrected load)

The approaches based on the corrected load show a better performance than those based on aggregate loads. Apparently, the additional information on the position of each operation within the order routings is used very efficiently. For instance, the use of this order information combined with 2 FBPs leads to comparable or even better outcomes than the strategy with 12 FBPs based on aggregated loads. These outcomes are in line with the outcomes in Oosterman et al. (2000). The WLC approach based on corrected loads fits well in more undirected shop floor flow structures. This shows that not only the number of FBPs, and thus the precision of information supply, but also the choice of the WLC approach is important for effective shop floor control.

3.6 Conclusions

The presented paper first investigated the opportunities for information supply within SMEs in the MTO sector. Due to several reasons, it is difficult to collect accurate (reliable, complete, on-time) and detailed shop status information per completed operation. Nevertheless, it is possible to create more accurate but less detailed shop status information by dividing the shop floor into organisational units (PUs). As the WLC approaches discussed in literature assume detailed feedback information per completed operation, we adapted these approaches according to a more realistic information supply within SMEs based on these PUs. These different approaches have been compared by aid of a simulation study. The results of the simulation study visualise the trade-off between additional investments in data collection and overall shop performance. This may help SMEs to decide on future investments. It has been shown that additional investments in data collection result in decreasing marginal performance gains. Combinations of floor time and total throughput time that are close to the situation of unrestricted periodic release are relatively insensitive to the chosen policy of information feedback. The marginal performance win based on WLC is larger within a general flow shop than within a combination of two pure job shops. The experiments also show that using routing information adequately in the load calculation is particularly important for shop floor performance. Hence, the choice of the WLC approach particularly with respect to the load aggregation method can be of crucial influence for shop performance.

3.7 Appendix

Norm setting

The workload norms (WLN) are varied, going stepwise down from infinity. In the simulation model we distinguish 12 capacity groups, for each capacity group s , a workload norm (WLN_s) has to be determined.

The WLC approach based on ‘corrected loads’ enables to set identical workload norms for each capacity group, as it estimates the time average direct load per capacity group. Given the flow structure of the shop floor configurations applied, this does not hold for WLC approaches using non-corrected loads. Here, each capacity group may ask for different workload norm calculations.

In the latter case we define a ‘reference’ workload norm (WLN_{ref}). This reference value is related by a norm ratio (NR_s) to the workload norms of each capacity group s :

$$WLN_s = NR_s \cdot WLN_{ref} ,$$

where

NR_s Norm ratio for capacity group s ,

WLN_{ref} ‘reference’ workload norm,

WLN_s workload norm level at capacity group s .

By varying the reference workload norm level (WLN_{ref}) going stepwise down from infinity, the workload norms (WLN_s) for the different capacity groups s change analogously. Table 3.4 shows the norm ratios per capacity group for the different experimental settings.

Table 3.4 Norm ratios

Norm Ratio \ #FBPs	1	2	3	4	12	1	2	12
	General Flow Shop					Two Pure Job Shops		
NR ₁	6.5	3.5	2.5	2	1	6.5	3.5	1
NR ₂	6.5	3.5	2.5	2	1.5	6.5	3.5	1.5
NR ₃	6.5	3.5	2.5	2	2	6.5	3.5	2
NR ₄	6.5	3.5	2.5	3.5	2.5	6.5	3.5	2.5
NR ₅	6.5	3.5	4.5	3.5	3	6.5	3.5	3
NR ₆	6.5	3.5	4.5	3.5	3.5	6.5	3.5	3.5
NR ₇	6.5	6.5	4.5	5	4	6.5	6.5	4
NR ₈	6.5	6.5	4.5	5	4.5	6.5	6.5	4.5
NR ₉	6.5	6.5	6.5	5	5	6.5	6.5	5
NR ₁₀	6.5	6.5	6.5	6.5	5.5	6.5	6.5	5.5
NR ₁₁	6.5	6.5	6.5	6.5	6	6.5	6.5	6
NR ₁₂	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5

For the WLC approaches using non-corrected loads the applied norm ratios (NR_s) are exactly equal to the average correction factors, as used in the related WLC approach based on corrected workload calculations. This improves the comparability of the simulated approaches.