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The workload control concept: theory and practical extensions of Load Oriented Order Release

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Keywords job shop, workload control, order release

Abstract. Workload control (WLC) has been elaborated in the early 1980s to a hierarchical production control concept for job shop manufacturing. In the 1990s the analytical research at the University of Groningen focused on assessing the strengths and weaknesses of this concept and on developing alternatives. Research at the University of Hannover focused on improving the practical applicability of the WLC concept. While the practical experiences confirm the strengths of the WLC concept, some extensions of the basic concept have been developed which may overcome some weaknesses suggested in literature. This paper aims at bringing the theoretical and practical knowledge regarding the WLC concept together. It gives a review and classification of strengths and weaknesses reported from analytical research and it discusses the extensions that have been developed based on practical experiences.

1. Introduction

Make-to-order companies and particularly those characterized by job shop production traditionally emphasize the importance of workload control. There, lack of workload control may lead to nontransparent shop floor situations with unreliable lead times and much expediting. In

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the early 1980s the principles of workload control were elaborated to a production control concept for job shop production. Three roughly comparable control concepts were developed in respectively Eindhoven (Bertrand and Wortmann 1981), Hannover (e.g. Bechte 1988) and Lancaster (e.g. Kingsman *et al.* 1989). In fact, each suggests a hierarchical approach with three control levels relating to phases in the order flow. Figure 1 shows how control of the accepted amount of work takes place at the order entry level, while control of the workload on the shop floor takes place at the release level. Priority dispatching remains for correcting progress disturbances among orders at the shop floor. At each level the decision must be made which orders can be allowed to proceed to the next stage (input control) and whether this requires capacity adjustments (output control). Since the early 1980s the order entry level has received particular attention in Lancaster (Hendry and Kingsman 1993), while researchers in Hannover elaborated several production control elements, such as load oriented lot sizing (Nyhuis 1991).

In the late 1980s, a discussion started on the value of controlled release (Kanet 1988, Melnyk and Ragatz 1989). Though job shop practice confirmed the value of controlled release, simulation studies showed adverse results. However, simulation studies generally focused on release methods that are less advanced than the methods used in the class of hierarchical concepts discussed above. These advanced methods are based on simultaneous control of the work released for several work centres, not only restricting but also balancing workloads. A further classification of release methods is given in (Bergamaschi *et al.* 1997). Elaborating this classification, the performance of some advanced methods has been compared in (Cigolini *et al.* 1998). Until the 1990s, studies analysing advanced release methods were published mainly in German literature (e.g. Adam 1988, Greiner 1989, Häfner 1992). Most criticisms in German literature deal with the particular calculations in the release method developed in Hannover. Land and Gaalman (Land and Gaalman 1996, 1998, Oosterman *et al.* 2000) compared and assessed the class of advanced

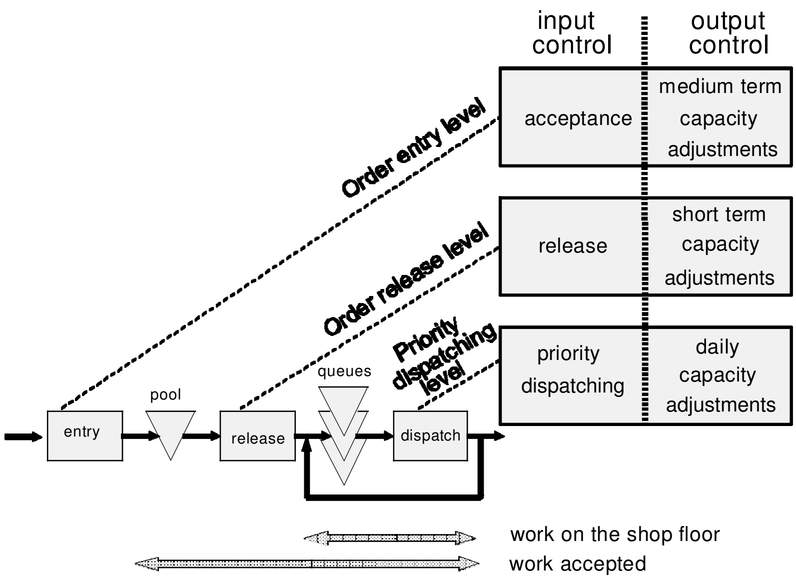

Figure 1. The general framework of the workload control concept.

release methods from a more conceptual point of view. Several strengths and weaknesses can be deduced from the analytic studies that have been performed.

The first implementations of the release method developed in Hannover (indicated as LOOR – Load Oriented Order Release) in industry are discussed in (Wiendahl 1991, 1993). By now, LOOR has been applied in a number of software packages. In a market analysis of 210 PP&C- and ERP-systems (Fandel *et al*. 1998) an overview of implemented order release methods is given (figure 2). Examples of well-known software-packages containing LOOR are SAP R/2 (SAP), debis-PPS (debis SHE), MAS 90 BWR (IBM), PIUSS PENTA and PIUSS-O (PSI).

The use of the LOOR method in industry has led to some extensions and adjustments that have not been reported in literature yet. This paper discusses these extensions and adjustments, which may overcome certain weaknesses that have been suggested in analytic studies. The next section starts with a discussion of order release within the workload control concept and the LOOR method in particular. Next, a brief review of the strengths and weaknesses suggested in literature is given. Finally, the contribution of three extensions based on experiences with the LOOR method is discussed.

2. The workload control (WLC) concept

2.1. *General principles*

The workload control (WLC) concept recognizes that job shop production inevitably shows queues of orders that compete for the capacity of each work centre. The WLC concept tries to create small and stable queues or, more precisely, low and stable levels of direct load. The direct load of a work centre is defined as the quantity of work resulting from waiting orders together with that of the order being processed.

The WLC concept smoothes the flow between the work centres by trying to release the right order at the right time. The complexity of this kind of input control results from the routing variety in job shops. After the release of an order, other operations may have to be completed before an order can be processed at a certain work centre. Thus, orders giving input to the direct load of a work centre may come either directly from release or indirectly from any other work centre. Several approaches have been suggested to smooth these combined inputs to the direct load.

The LOOR approach developed in Hannover is the most straightforward in controlling the direct load. It records the actual direct load of the work centres at the time of release and estimates the input to the direct load during the following planning period, using an estimation method called load conversion. The converted load, being the sum of the direct load and the estimated input, is kept at a norm level for each work centre by releasing the right amount of work. LOOR was first presented in the dissertation of Bechte (Bechte 1980) and extended by several authors (e.g. Wiendahl 1995).

Another approach is presented in the dissertation of Bertrand and Wortmann (Bertrand and Wortmann 1981) and in the dissertation of Tatsiopoulos (Tatsiopoulos 1983), later extended by Hendry and Kingsman (Hendry 1989, Hendry and Kingsman

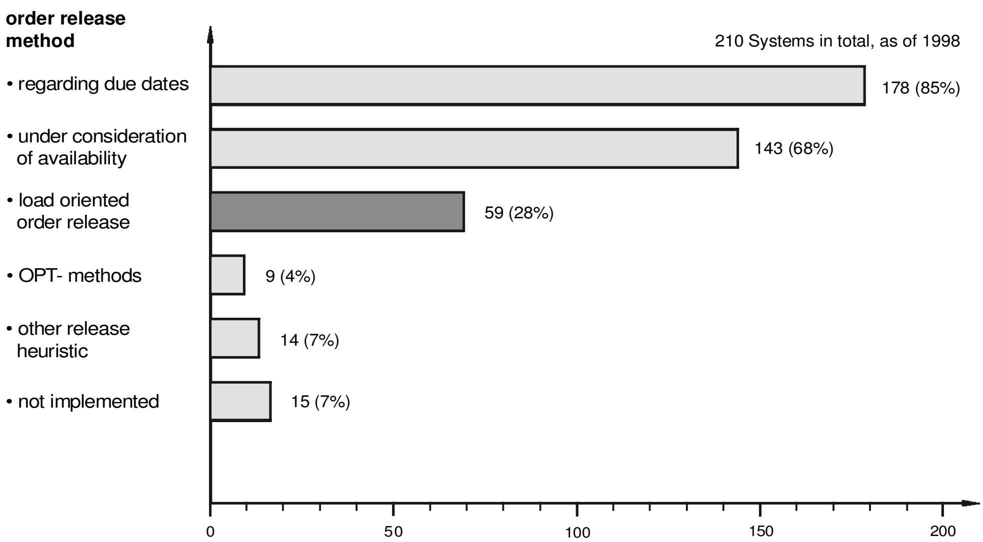

Figure 2. Implemented methods of order release in PP&C- and ERP-systems (Fandel *et al*. 1998).

1991). Their approach is to aggregate the direct load and the indirect load of a work centre. The indirect or upstream load of the work centre is defined as the quantity of (future) work coming from orders that queue at other work centres for preceding operations to be completed. The sum of its direct and indirect load is called the aggregate load of the work centre. The release methods of this second approach use norms for the aggregate loads, instead of estimating the inputs to the direct load.

A third approach (e.g. Oosterman *et al.* 2000) combines elements of the two other approaches, using norms for adjusted aggregate loads. The underlying idea is that the aggregate load of a work centre should be corrected for the variable position of this work centre within the routings of released orders. The applied correction is such that the adjusted aggregate load of a work centre can be seen as an estimate of its future direct load.

All approaches use workload norms to create a smooth flow of work, but differ with respect to the type of load that is bounded by norms. More specifically, the contribution of orders to the load is different. With LOOR the contribution depends on the upstream distance of the order to the work centre considered. If norms for aggregate loads are applied, one accounts for the full operation processing times as soon as an order is released, irrespective of the number of operations to be completed before the work centre is reached. The adjusted aggregate load includes just a fraction of the operation processing time in case of downstream operations. Contrary to LOOR, the size of the fraction is not altered during upstream progress of the order; the depreciation of the operation processing time is proportional to the work centre position. Figure 3 sketches the contribution of a job j to each type of load account in the course of time. The account concerns work centre c that performs the n_{jc}-th operation (in this case the third operation) of the job, with operation processing time t_{jc}.

Besides controlling the workload, the release methods look at the relative urgency of orders. This is realized by considering orders for release in sequence of a planned release date. As the controlled direct loads should result in relatively constant work centre lead times, the planned release dates can be determined relatively easy. The next section will discuss the LOOR approach in more detail.

2.2. *LOOR (Load-Oriented Order Release)*

Figure 4 overviews the release procedure of LOOR. This procedure, performed at the beginning of each planning period, requires a number of parameters to be predetermined: the length of the planning period, work centre lead-time allowances, an anticipation horizon, and loading percentages.

The first step in the release process is the backward scheduling of all issued shop orders that have not been released yet. It results in a list of urgent orders, sorted by planned release date. First, the planned release date for each order is determined as its due date minus all relevant work centre lead-time allowances. Next, all orders with a planned release date falling within the anticipation horizon (specified as a multiple of the planning period length) are classified as urgent. Only urgent orders will be considered for release in the following steps.

The second step determines the load contribution of the urgent orders by means of a procedure indicated as *conversion*. The conversion procedure accounts for the planned inventory conditions a job will meet, which depend on the level of the workload norms. Within LOOR, the workload norm of a work centre c is expressed as a percentage (>100%) of its planned output. It is called the *loading percentage* (LPG). The first operation of an order will be loaded onto the account of the corresponding work centre with its full operation processing time. To load a downstream operation of the order, the probability that the order will reach the corresponding work centre within the planning period is considered. The estimated probability ($POUT_p$) for the p-th operation to be completed within the next period is given by equation 1.

$$POUT_p = PINP_{(p+1)} = PINP_p \times \frac{100}{LPG_{c(p)}} \qquad (1)$$

where:

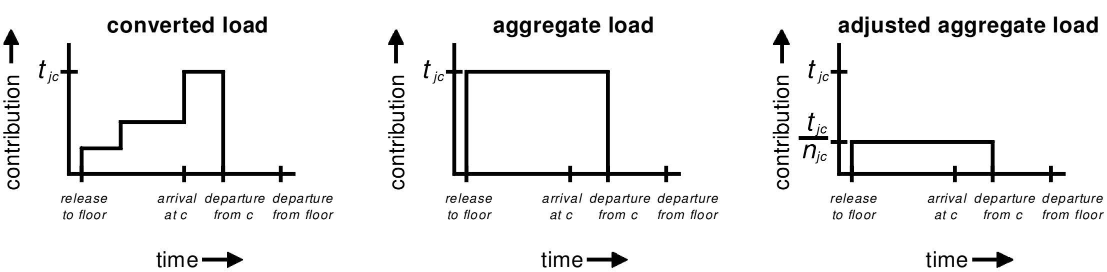

Figure 3. Contribution of an order to the load calculation in each of the approaches.

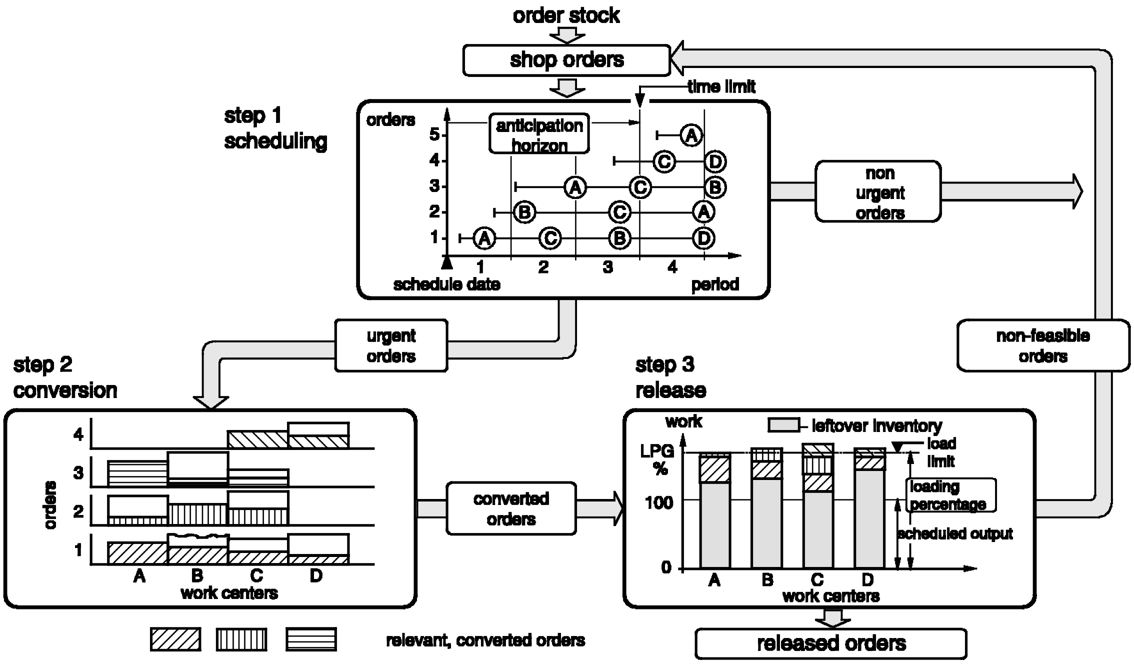

Figure 4. Steps of Load-Oriented Order Release (Wiendahl 1995).

$POUT_p$: Estimated output probability for the p-th operation

$PINP_p$: Estimated input probability for p-th operation

$LPG_{c(p)}$: Loading percentage of work centre c, which performs the p-th operation

By means of equation 2 the probability that an order waiting for operation 1 will reach the downstream work centre that performs the p-th operation in the subsequent period is estimated.

$$PINP_p = POUT_1 \times POUT_2 \times \cdots \times POUT_{(p-1)} \quad (2)$$

It is called the conversion factor CF_p. Based on equations 1 and 2, CF_p is calculated as follows:

$$CF_p = \frac{100}{LPG_{c(1)}} \times \frac{100}{LPG_{c(2)}} \times \cdots \times \frac{100}{LPG_{c(p-1)}} \quad (3)$$

If all work centres have the same loading percentage, the equation is simplified to:

$$CF_p = \left(\frac{100}{LPG}\right)^{p-1} \quad (4)$$

Finally, the contribution to a load account is determined for each operation by multiplying the operation processing time with the individual conversion factor CF_p.

In the third step, the urgent orders are successively considered for release. Starting with the order with the nearest planned release date, the converted operation processing times are loaded by trial onto the load accounts of the respective work centres. If none of the accounts of work centres required for processing of this order is blocked, it is released and loaded finally with its converted processing times onto the accounts of the corresponding work centres. As soon as the workload norm of an account is exceeded for the first time, this account will be blocked. Now the second order is tested in the same manner, followed by the third, fourth, etc.. If any operation of an order should be loaded to a blocked account, the entire order is entered into the list of non-feasible orders. Together with the non-urgent and possible rescheduled orders it is re-entered into the release procedure at the beginning of the next planning period.

The initial load account level, indicated as 'leftover inventory' in figure 4, contains the load resulting from previously released orders. Previously released orders that are still upstream of the work centre have been converted similar to new orders, but the output probabilities of completed preceding operations have been excluded from the factor CF_p.

The above procedure, executed periodically, determines the set of orders that is released, considering both the inventory conditions on the shop floor and the urgency of orders.

3. Strengths and weaknesses

Analytic and simulation studies have revealed several strengths and weaknesses, some relating to the basic concept of order release within WLC, others being more specific for the LOOR method. The next section briefly reviews the strengths and weaknesses reported in literature. The first subsection discusses aspects that relate to the basic concept of using workload norms. Next, the qualities of the WLC methods in reducing and balancing workloads are assessed and finally the LOOR-specific strengths and weaknesses are analysed. The main elements are marked boldly and will be summarized in section 5.

3.1. *Use of norms*

An important and obvious quality of the WLC concept is that *it buffers the shop floor against the dynamics of the order flow*. If orders were directly released to the floor, capacity bottlenecks and conflicts regarding order urgency should be solved on the shop floor. With WLC, the shop floor situation is kept within norms, while the pool of orders waiting for release can be used to visualize possible problems in an early phase (Bechte 1994). It facilitates taking adequate measures such as capacity changes and due date adjustments in the order acceptance stage (see figure 1). In fact, dynamics should be absorbed in the pool, while the shop floor is kept in a certain stationary state.

Many control approaches for job shop production risk the occurrence of a vicious cycle, resulting in an on-going increase of shop floor lead times. The *use of fixed workload norms in WLC avoids this so-called lead time syndrome*. (Plossl 1988) describes the vicious cycle which occurs if planned lead times automatically increase as loads increase:

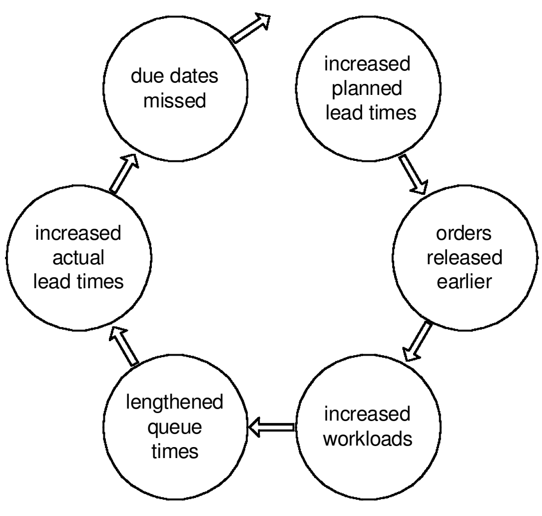

Figure 5. The vicious cycle of production control (based on Plossl 1988).

(1) Increasing planned lead times generates more orders for release immediately,
(2) earlier release of these orders increases work centre loads, thus queue times lengthen,
(3) actual lead times get longer also and more delivery dates are missed . . .

and the cycle repeats (figure 5). In fact this cycle occurs if a release method advances the release of orders when workloads increase. WLC breaks the vicious cycle in step 2, because release is restricted by the workload norms.

The workload norms provide a convenient means to communicate at the interface between overall planning and shop floor control. If the work released complies with the agreed workload norms, overall planning may rely on shop floor lead times. Thus, the parameters create clarity between the parties involved in planning and control. Nevertheless, setting parameters may be delicate matter. In the case of LOOR, workload norms for each work centre, planned output, the anticipation horizon, and the length of the planning period have to be determined. Setting all these parameters must be done carefully. At low levels of work-in-process, performance appears to be *very sensitive to small changes of workload norms* (Land and Gaalman 1998). Also *setting the anticipation horizon is delicate*. If the parameter strongly restricts the set of orders that can be considered for release, less balance of the workloads can be reached, and output will drop. Contrarily, a long anticipation horizon may result in a strong dispersion of due date deviations. For LOOR, the simulation results in (Perona and Portioli 1998) indicate that *performance is sensitive to the chosen length of the planning period*. Hendry *et al*. (1998) observe similar sensitivities in case of aggregate load norms.

It is shown in (Land and Gaalman 1996) that each norm brings about a series of assumptions regarding stationary characteristics of the order mix. To check whether assumed conditions still hold, WLC will require continuous monitoring and adjustment of workload norms and other parameters. The importance of continuous adjustment in a strongly dynamic environment is illustrated in (Zäpfel and Missbauer 1993) and (Perona and Portioli 1996). The SLAR method (Land and Gaalman 1998) has been developed to provide a starting-point for control of workloads without the need to determine norms.

3.2. *Reducing and balancing workloads*

The core of the WLC concept is the control of workloads. A WLC concept derives much of its strength from these controlled workloads. One obvious aspect is *that work-in-process is reduced*. In turn, the reduction of work-in-process leads to a *more transparent shop floor with less expediting* (Melnyk and Ragatz 1989, Wiendahl 1991), while the lean shop floor also *diminishes the dependence on sophisticated priority rules* (Bechte 1988). As a drawback, there will be *fewer opportunities to reduce sequence dependent set-up times* by choosing an efficient processing sequence on the shop floor.

If workloads were just reduced, the idle time of capacities could increase. Therefore, workload control does not just face the task to reduce workloads but also to balance workloads. Here, workload norms function as threshold values. Orders are selected for release, so as to approach the norms as well as possible. If an order does not fit into the workload norms due to a blocked account, the procedure will enable the selection of a less urgent order that does fit. Such an order improves the balance by filling the gap between the recorded workload levels and the workload norms. It creates a steadier load for the work centres. The steady direct loads prevent the shop from increased idleness, and furthermore help to *create lead time predictability* (Land and Gaalman 1996). With predictable lead times for each work centre, the improved timing of order release can in turn contribute to due date reliability.

Taking a different perspective, the influence of controlled release can be viewed in terms of order waiting times. Controlled release turns waiting time on the floor into waiting time in the pool. The advantages of this waiting time substitution have early been noticed (Irastorza and Deane 1974). As long as an order is waiting for its release it is generally just paperwork with no material attached to it. During that time there is more *flexibility to deal with changes or cancellations*. However, many simulation studies (e.g. Land and Gaalman 1998 in case of LOOR) have shown pool times that exceed the waiting time reductions on the floor. Though shop floor lead times decrease, total lead times increase relative to the situation without controlled release.

Generally, the poor lead time results of controlled release methods in simulation studies indicate a *lack of load balancing qualities*. It has been previously suggested that increased idle time or decreasing output would indicate a lack of balancing qualities for a (workload reducing) release method. But steady-state simulations generally use a predetermined (stochastic) order arrival process, which requires a certain long-term utilization level to be realized. The steady state does not allow increased idle time. Instead, a larger pool of orders (see figure 1), with an increased choice of orders to fit within the norms, must compensate for a lack of balancing qualities. As a consequence not idle time but the average pool time of orders increases in these simulations. The better the balancing qualities of the release method the smaller pool times can be. The balancing qualities of the release methods within WLC concepts are assessed in more detail in (Land and Gaalman 1998). Analytic research of Wein (Wein 1990, Wein and Chevalier 1992) shows that an optimal release policy must give priority to improvement of the workload balance, when the orders in the pool show a small difference in urgency.

Another point brought forward in (Land and Gaalman 1998) is *that certain load fluctuations are due to the nature of job shop production, which is neglected within WLC concepts*. Job shop will generally operate on utilization levels far below 100%. An utilization level of 90% means that no direct load is available at a work centre for 10% of the time. It is argued that bringing the loads continuously back from zero to the norm level may lead to superfluous load under these circumstances.

3.3. *LOOR-specific aspects*

More particular strengths and weaknesses relate to the load calculation methods used within the release method. The method of LOOR estimates new inputs to the direct load by looking at the upstream distance of each order. This is shown to be particularly *important in shops with a high routing variety* (Oosterman *et al*. 2000). The use of aggregate load norms neglects this routing variety and results in a poorer performance. On the contrary, the same research shows that *LOOR causes problems in shops with a dominant flow direction*, shops having typical upstream and downstream centres. There, undesirable effects are caused by the use of norms for the converted load of a typical downstream work centre. Cyclic behaviour occurs, with periods of overload alternated with periods of underload. This behaviour is related to the fact observed in (Knolmayer 1991) that *LOOR neglects the order influences after the planning period*.

Although norms on aggregate loads perform better in case of a dominant flow, the determination of adequate norm values is more difficult. The routings of orders must be considered, as typical downstream work centres require larger norms than upstream stations. *A norm for the (estimated) direct load of a work centre, as in LOOR, can more easily be related to the work centre lead-time allowance*. The development of norms for adjusted aggregate loads has led to a more robust method that works well for both shops with dominant flows and for high routing variety, while the norm values do not depend on order routings (Oosterman *et al*. 2000).

More particularly, points of criticism have been evoked by the assumptions of load conversion as a method for estimating inputs. A fundamental assumption is that each load account will reach its workload norm, as not the recorded level of the workload account but its norm level LPG (equations 1–4) is used to estimate input and output probabilities. Experiments in (Perona and Portioli 1996) indicate that the performance of LOOR can be improved by correcting for load deviations due to mix imbalances. In general when loose norms are applied, the norm level is not always realized, so the load conversion method will underestimate the probability that an operation can be completed during the imminent planning period. The results in (Oosterman *et al*. 2000) confirm that LOOR shows its best performance at tight norm levels, while *the performance at loose norm levels is relatively weak*.

Several researchers (e.g. Adam 1988, Knolmayer 1991) have criticized the input estimate from the perspective of a single order. Certainly, *other factors than the load level influence the output probability of a single order*, for instance its priority and its processing time. These are not considered in equation 1. Alternatively, the fact that complexity is avoided can be seen as one of the strengths of LOOR. Though for a single order, the estimation may not be realistic, the aggregated estimation of the inputs to a work centre may be close to reality. With load conversion each released order contributes a little to the converted load (see figure 2). If the estimation incorporated the processing time of upstream orders either fully or not, one would risk larger estimate deviations depending on whether a single big order does or does not arrive according to plan. Input estimations made by LOOR will never be completely right, but deviations are generally small. Thus, *load estimations of LOOR can be qualified as simple but reasonable*.

Still, it can be argued that the load conversion method is not completely consistent with the objectives of WLC (Land and Gaalman 1996). This based on the fact that the estimating quality of the load conversion factor (equation 4) improves when the operation processing times are small relative to the workload, reaching the highest accurateness for infinitely small orders. But it is the objective of WLC to reduce the load. Thus the relative lumpiness of operation times increases, and estimations may get poorer the more the general objectives are reached.

Some of the problems suggested in this section have been solved in practice by simple extension of LOOR. The next section will discuss these extensions.

4. LOOR – extensions based on experiences from practice

Regarding the strengths suggested in the preceding section, various experiences from practice confirm that LOOR is a powerful and easy applicable control method. User reports from industry show that lead times and work-in-progress can be reduced by up to 60% after the introduction of LOOR (Wiendahl 1991, Wiendahl *et al*. 1992).

However, practical experiences have indicated the relevance of individual adjustments and procedural extensions in some cases, in order to compensate for alleged weaknesses of LOOR or to consider factory-related circumstances. In this section some important extensions will be mentioned. Detailed information is provided regarding parameter setting for LOOR. The parameter determination, based on logistic operating curves, is explained by means of a case study within a job-shop of a printed-circuit-board producer (Wiendahl *et al*. 1998).

4.1. *Determination of appropriate parameter values*

Subsection 3.1 mentioned possible problems regarding the determination of appropriate values for control parameters and especially for the loading percentage (LPG), as performance is particularly sensitive to norm settings at low WIP-levels. In practical applications of LOOR the parameter adjustments have often been made by trial-and-error, decreasing the LPG until utilization losses get significant (Wiendahl 1991, 1993). Since strongly varying the parameters leads to unplanned losses in utilization, such a procedure has to be carried out very carefully (Wiendahl 1995).

A simple method has been developed due to requirements of industry to support parameter setting in practice. This method derives the relationship between performance and WIP-levels for particular work centres from its capacity and the operation processing times. With just this information one can construct the complete logistic operating curve as depicted in figure 6 (Wiendahl and Nyhuis 1996).

In figure 6 the idealized mean WIP minimum ($WIP_{m,\min}$) represents the WIP level that is necessary to run the system under idealized conditions, assuming that no arriving order has to wait and no interruptions in the material flow occur. The value of the idealized mean WIP minimum can be derived directly from the operation processing times (e.g. Nyhuis and Wiendahl 1999). The realistic curve differs from the idealized one. By means of the equations 5 and 6, developed in by Nyhuis, the realistic curve can be estimated for most job shop environments.

$$WIP_m(t) = WIP_{m,\min} \cdot (1 - (1 - \sqrt[4]{t})^4) + WIP_{m,\min} \cdot \alpha_1 \cdot t \tag{5}$$

$$OUT_m(t) = OUT_{\max} \cdot (1 - (1 - \sqrt[4]{t})^4) \tag{6}$$

with

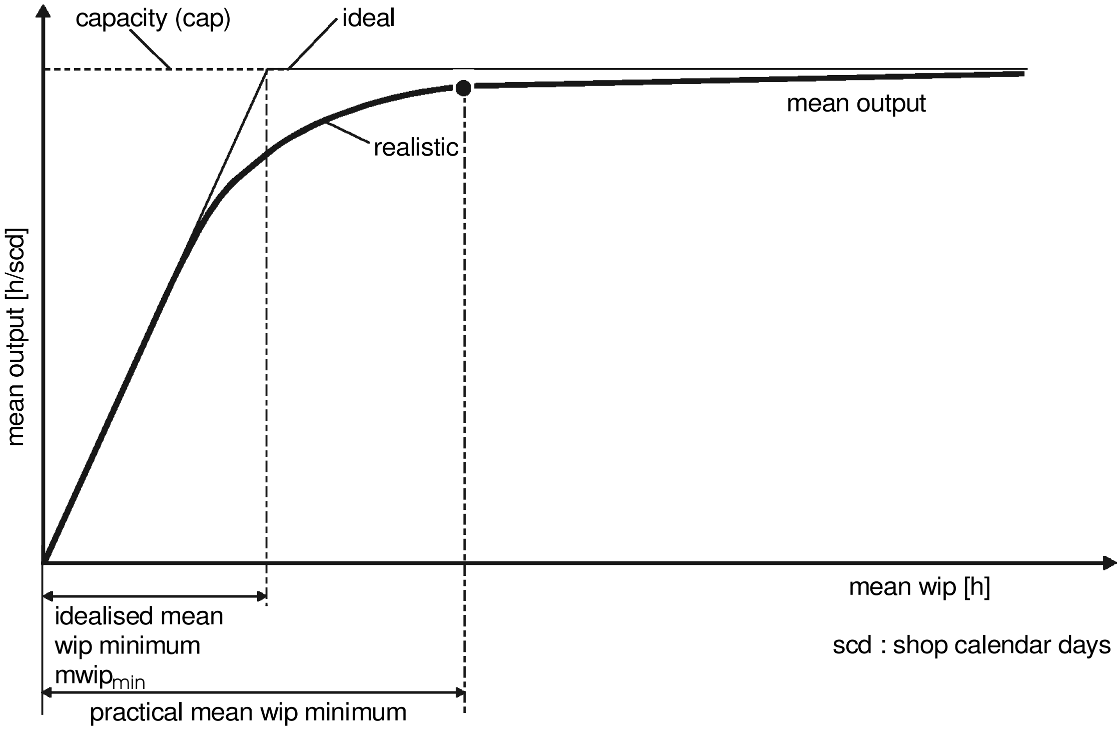

Figure 6. Interdependency between output and work-in-process (WIP) (Nyhuis 1991).

$WIP_m(t)$: mean work-in-process [h]
$OUT_m(t)$: mean output per shop calendar day [h/scd]
$WIP_{m,\min}$: idealized mean work-in-process minimum [h]
$OUT_{\max}$: maximally available output [h/scd]
α_1: stretching parameter [-]
T: running parameter $(0 < t < 1)$

A detailed derivation of these formulas is specified in (Nyhuis 1991, Nyhuis and Wiendahl 1999). With the aid of equation 5 and 6, a pair of values for WIP and output can be calculated dependent on the running parameter t. With these pairs, the course of the output is defined. The only parameter to specify is the α_1. Empirical research (Burmeister 1997, Nyhuis and Wiendahl 1999) and various case studies in aircraft industry, in the field of mechanical engineering and electronics industry (e.g. Wiendahl *et al*. 1998) have pointed out that an α_1-value of 10 is appropriate for a wide spectrum of job shop environments. A rough sketch of the applicability of α_1-values (figure 7) is given in (Nyhuis and Wiendahl 1999), based on data gathered in the cases studies. It is shown that only situations where a high short-term capacity flexibility strongly compensates for the loading deviations are better approached by output curves based on an α_1-value below 10. A higher α_1-value should only be considered in case of strongly fluctuating capacity requirements, resulting in high load deviations, while

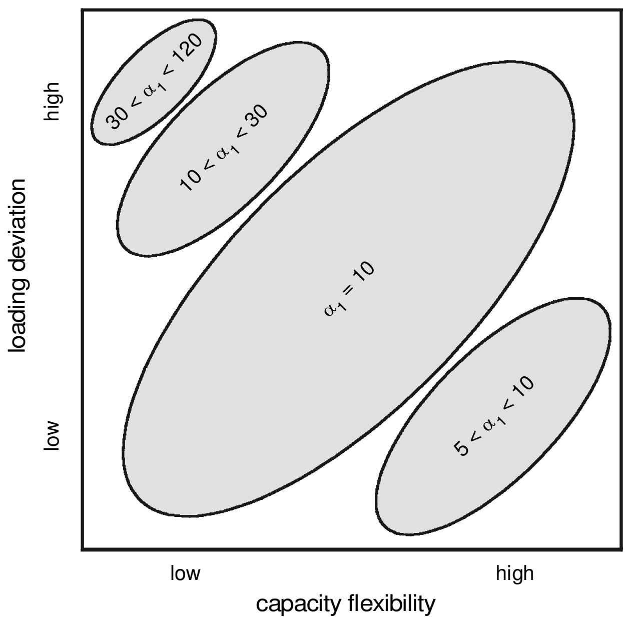

Figure 7. Influence of loading deviations and capacity flexibility on the streching parameter α_1 (Nyhuis and Wiendahl 1999).

no short-term capacity flexibility is available to absorb these fluctuations. For a more detailed discussion the reader is referred to Nyhuis and Wiendahl (1999).

Using equation 7, the course of the 'range' (which can be translated into the mean lead time) can be determined. The range can be seen as the average run-out-time of the mean work-in-process, and can be translated into the mean lead time (Nyhuis1991).

$$R_m = \frac{WIP_m}{OUT_m} \tag{7}$$

with

WIP_m: mean work-in-process [h]
OUT_m: mean output [h/SCD]
R_m: mean range [SCD]

The logistic operating curves allow to specify an appropriate operation point depending on the momentary general conditions. From that, target values for the mean range and the mean lead time can be determined easily (Nyhuis and Wiendahl 1999). Afterwards, these values can be converted into the required loading percentage by means of equation 1 (figure 8). The chosen operation point can be compared with the measured actual operation point.

This can be illustrated by a case study carried out by the Institute of Production Systems within a job shop of a printed-circuit-board-producer (PCB-producer). Within the job shop product groups such as inboard layers, non-through-contacted and through-contacted printed circuit boards and multilayers are produced. The evaluation period covers a period of five months within which about 4300 manufacturing orders with 65 000 operations have been completed at 33 work centres.

Figure 9 shows the calculated operating curve of the bottleneck system within the job shop mentioned above. The arrow indicates the actual operating point of the work centre. The WIP-level of the work centre is far too high. It can be reduced significantly without losses in utilization. The appropriate operating range is determined in relation to the idealized mean WIP. A WIP-level of double or triple idealized mean WIP has appeared to be suitable for most of the work centres. In case of very expensive or bottleneck work centres the WIP-level has to be increased in order to guarantee a higher utilization. Analogous to that, WIP can be reduced if the utilization of a work centre is not that important e.g. if the machine is already depreciated. The applicability of the operating curves to industrial problems has been confirmed in consulting projects at the Institute of Production Systems.

Adequately using operating curves can prevent LOOR from several weaknesses suggested in section 3. By means of easily determinable operating curves the problem of sensitivity to norm settings at low WIP-levels can be solved. Furthermore, it is quite easy using this technique to monitor the parameters continuously. With the aid of the operating curves the norms can be set sufficiently tight. Logistic operating curves have proven to be a powerful tool to determine appropriate values.

Another important parameter of LOOR is the anticipation horizon, which setting might be delicate (table 1). However, investigations of the Institute of Production Systems have shown, that 2 up to 3 periods are a reasonable value in many applications in the field of mechanical engineering and electronic industry (Wiendahl 1995). Up to now, also planning period lengths have generally been based on rules of thumb, despite the sensitivities observed in e.g. (Perona and Portioli 1998).

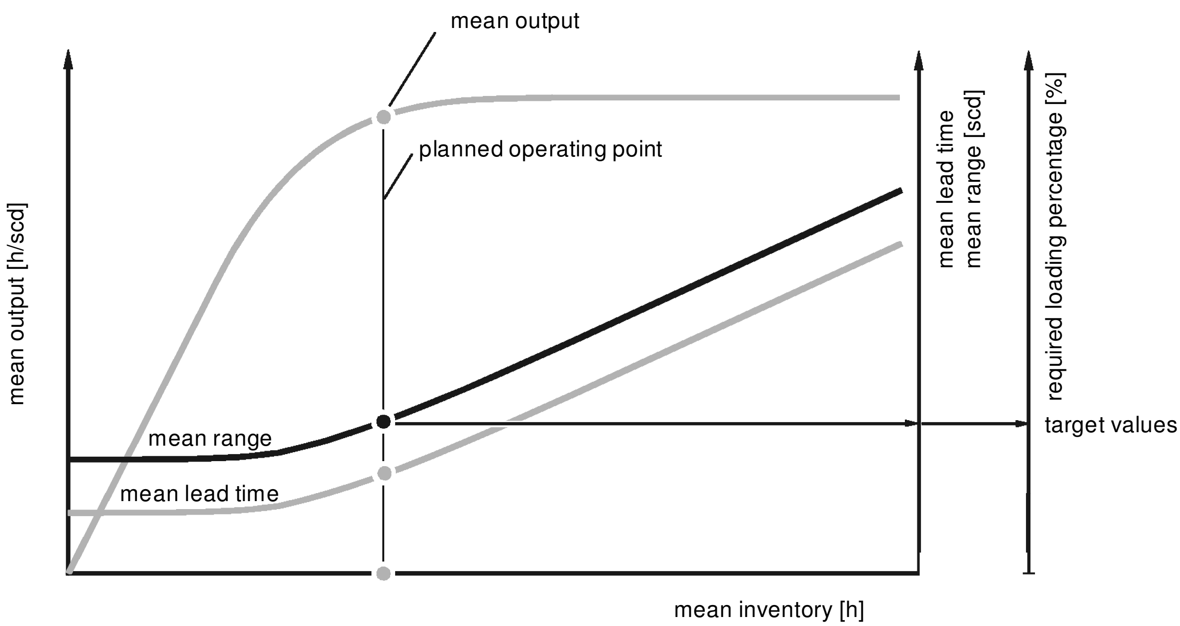

Figure 8. Interdependency between output, lead time and work-in-process (WIP) (Nyhuis 1991).

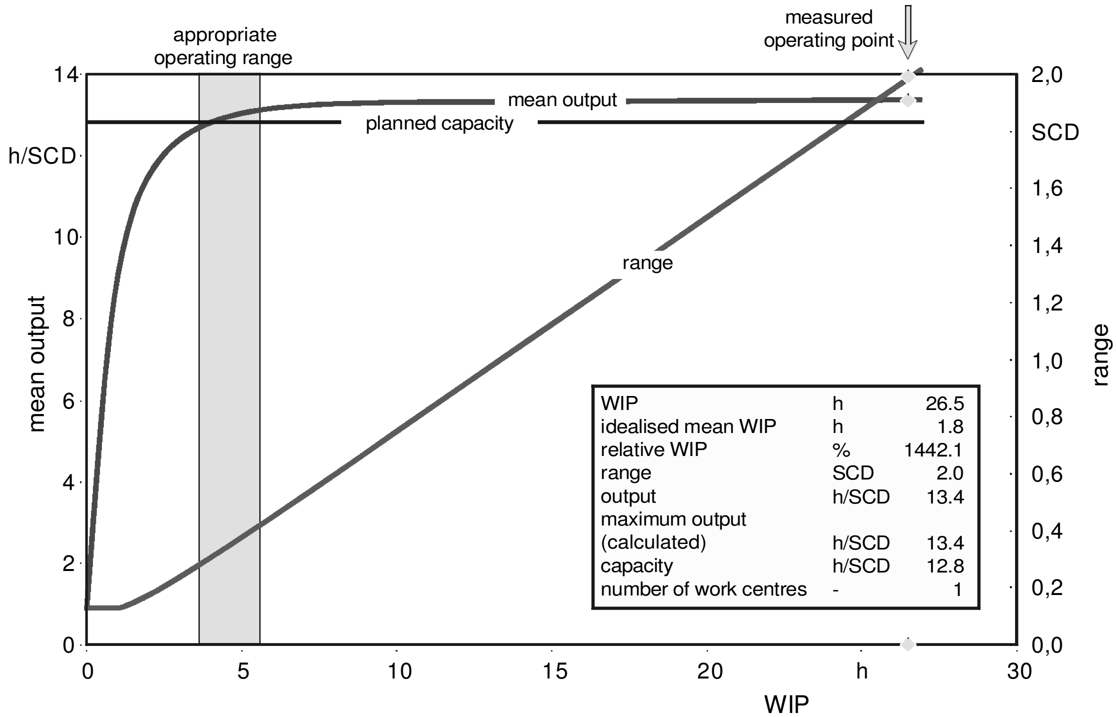

Figure 9. Logistic operating curves of the work centre 'resistant-coating'.

4.2. *Uncertainties during the load conversion procedure*

Subsection 3.2 mentioned possible balancing problems. In practice short-term capacity adjustments can often compensate for the fluctuating capacity requirements that lead to these balancing problems. These capacity adjustments can not be considered in LOOR without additional efforts. A simple change of the workload norm (e.g. by a specific change in the planned output of the following period) does not solve this problem completely, because the date of the order release does usually not correspond to the loading fluctuations at the affected centres.

In practical applications the above mentioned problem is normally solved by means of a dialog-oriented extension of the procedure (Wiendahl 1991). Orders not selected for release by the basic procedure discussed in section 2 are not rejected immediately. Rather, a list of work centres responsible for the rejection of orders will be created. Afterwards (e.g. in course of an agreement between sales department, production and manufacturing control) a check is made whether an order rejection is critical or if a short-term capacity adjustment is possible. This dialog-oriented extension allows to improve load balancing and so to prevent from insufficient output. It can also be used to anticipate on possible problems in future planning periods.

Besides, this extension solves a more practical problem, as in practice the number of shop calendar days (SCD) within a planning period may vary because of holidays etc. This may cause problems as WLC methods book orders on time-independent load accounts. This is illustrated by figure 10. Figure 10 depicts idealized throughput diagrams of a sample work centre, based on a reduction of the planning period length from five to four shop calendar days. Each throughput diagram contains two curves, one for the cumulative input pattern at the work centre and one for the cumulative output during the planning period. Time (in shop calendar days) is set on the horizontal axis, while cumulative input and output (in hours of work) are set on the vertical axis. Realistic cumulative input and output curves would show stepwise increases, but here idealized curves are used to represent planned values. Notice that the vertical distance between the curves corresponds to the WIP level, while the horizontal distance indicates the work centre lead-time. The inclination of the output curve represents the output rate. In case (a) 40 hours of new input will be needed during the planning period to maintain the original WIP level of 30 hours until the end of the release period. This means that the work centre must be loaded up to 70 hours, which is 175% of its planned output. When the planning period counts four instead of five days, the loading percentage should

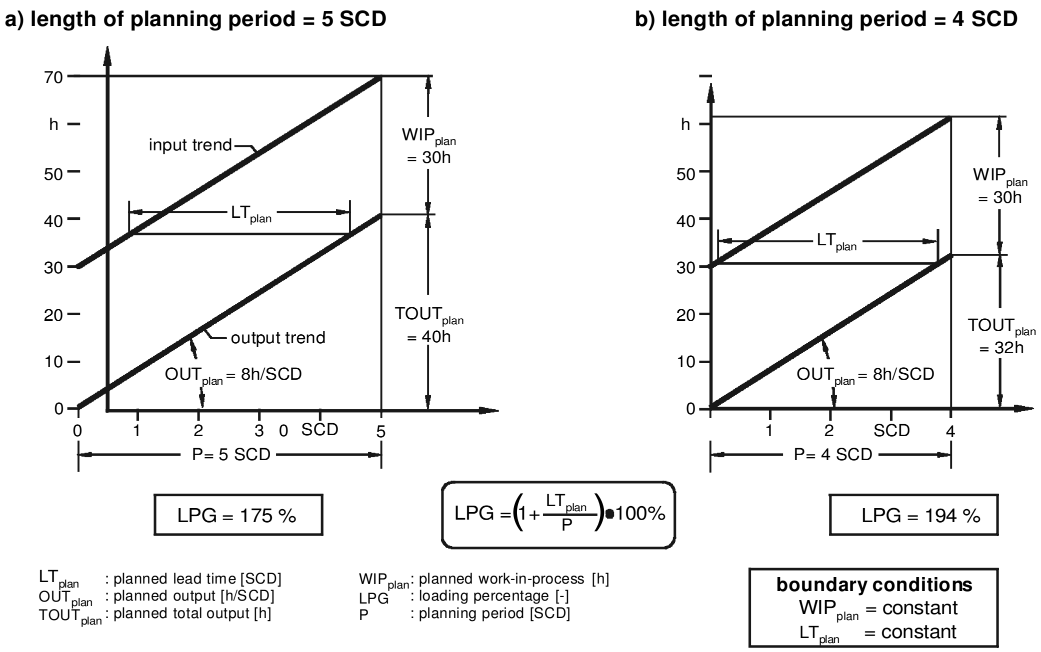

Figure 10. Influence of planning period length on the required loading percentage.

be increased from 175% to 194% to maintain the original WIP level, mean lead time and output rate. In these situations, the dialog-oriented extension allows for releasing an appropriate amount of work irrespective of the workload norms.

4.3. *Rejection of orders caused by overloaded downstream work centres*

Subsection 3.3 reviewed the results of simulation studies, which indicate a good performance of LOOR in typical job shops, but weaker performance in shops with a dominant flow direction. Also in practice it has been observed that unrestricted conversion of orders could initiate strong oscillations regarding the direct load for typical downstream stations. A simple but powerful solution has been found for this problem. The conversion procedure is applied only to a fixed number of process steps in advance, downstream from the current position. Thus, typical downstream operations are simply not considered when loading a job to the load accounts. Investigations of the Institute of Production Systems have confirmed that the effects mentioned above can be eliminated successfully by including only four process steps in the conversion procedure. On the one hand, this guarantees consideration of the actual loading situation at the work centres. On the other hand, events which will take place in the far future that influence the release of orders can be avoided. This simple adjustment makes LOOR applicable in a wider range of shop configurations.

5. Conclusions

In the early 1980s an integrated workload control concept has been developed for job shop production. Different approaches have been used to control the quantity of workload released to the shop floor, though all approaches use workload norms. The approach developed in Hannover (LOOR) has been applied in several software packages. Meanwhile, a number of researchers have assessed the release method both analytically and by means of simulation. This paper has given a review of the strengths and weaknesses of the workload control concept reported from these studies and it has discussed the extensions and adjustments that have been developed as a result of practical experiences with LOOR. The contribution of these extensions and adjustments has been related to weaknesses suggested in literature.

Table 1 summarizes the strengths and weaknesses mentioned in this paper. The strengths and weaknesses are subdivided into three categories. Category A deals with the strengths and weaknesses regarding the use of workload norms and other parameters. Category B relates to the capabilities of the WLC concepts with respect to the reduction and balancing of workloads. Category C

Table 1. Strengths and weaknesses.

Strengths	Weaknesses
A. Use of norms	
1. shop floor is buffered against disturbances	1. sensitive to norm setting at low WIP levels
2. lead time syndromes are excluded	2. anticipation horizon setting is delicate
3. the planning interface is facilitated by norms	3. sensitive to choice of planning period length
	4. continuous monitoring of parameters required
B. Reducing and balancing workloads	
1. WIP is kept at a low level	1. limited opportunities to choose efficient set-up sequences on the shop floor
2. Transparent shop without rush orders is enabled	2. output may drop or pool times may increase when load balancing is insufficient
3. No dependence on priority dispatching rules	3. constant norms do not consider natural load fluctuations in job shops
4. lead times are made predictable	
5. orders can be changed or cancelled lately	
C. LOOR-specific	
1. job shop routing variety is considered	1. dominant flows cause problems
2. lead times and norms are easily related	2. future planning periods are neglected
3. simple but reasonable direct load estimation	3. incapable of dealing with 'loose' norms
	4. neglects influences of priority and processing times on order progress

relates to the specific strengths and weaknesses of the LOOR method.

The extensions and adjustments discussed in this paper may overcome weaknesses from all three categories. To facilitate the determination and monitoring of workload norms in practice (A), a simple method has been developed, which requires only a minimal set of data to depict the relationship between the workload level and performance for each work centre. To avoid balancing problems (B), a dialog-oriented extension has been implemented in the practical applications LOOR. And finally, In shops with a more dominant flow direction, the performance of LOOR has been improved in shops with a dominant flow direction (C) by simply excluding typical downstream stations from release considerations.

This paper has given a rather explorative investigation of some industrial practices in relationship to alleged weaknesses of the WLC concept. Further research is required to evaluate workload control in practice more thoroughly and to evaluate the practical consequences of reported strengths and weaknesses.

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