International Journal of Production Research
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tprs20

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Version of record first published: 22 Mar 2010.

To cite this article: Matthias Thürer , Cristovao Silva & Mark Stevenson (2011): Optimising workload norms: the influence of shop floor characteristics on setting workload norms for the workload control concept, International Journal of Production Research, 49:4, 1151-1171

To link to this article: http://dx.doi.org/10.1080/00207541003604836

*International Journal of Production Research*
Vol. 49, No. 4, 15 February 2011, 1151–1171





# Optimising workload norms: the influence of shop floor characteristics on setting workload norms for the workload control concept

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(*Received 3 July 2009; final version received 8 January 2010*)

Workload control (WLC) is a leading production planning and control (PPC) solution for small to medium sized enterprises (SMEs) and make-to-order (MTO) companies, but when WLC is implemented, practitioners find it difficult to determine suitable workload norms to obtain optimum performance. Theory has provided some solutions (e.g., based on linear programming) but, to remain optimal, these require the regular feedback of detailed information from the shop floor about the status of work-in-process (WIP), and are therefore often impractical. This paper seeks to predict workload norms without such feedback requirements, analysing the influence of shop floor characteristics on the workload norm. The shop parameters considered are flow characteristics (from an undirected pure job shop to a directed general flow shop), and the number of possible work centres in the routing of a job (i.e., the routing length). Using simulation and optimisation software, the workload norm resulting in optimum performance is determined for each work centre for two aggregate load-oriented WLC approaches: the classical and corrected load methods. Results suggest that the performance of the classical approach is heavily affected by shop floor characteristics but no direct relationship between the characteristics and norm to apply could be established. In contrast, results suggest that the performance of the corrected load approach is not influenced by shop floor characteristics and the workload norm which results in optimum performance is the same for all experiments. Given the changing nature of MTO production and the difficulties encountered with the classical approach, the corrected load approach is considered a better and more robust option for implementation in practice. Future simulations should investigate the influence of differing capacities across work centres on the workload norm while action research should be conducted to apply the findings in practice.

**Keywords:** workload control; workload norm; shop floor characteristics; order release mechanism; optimisation

## 1. Introduction

Due to phenomena such as globalisation, many companies face increased competition and, in the context of the current economic recession, are competing for less available work.

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ISSN 0020–7543 print/ISSN 1366–588X online

DOI: 10.1080/00207541003604836
http://www.informaworld.com

To improve the ability to compete, companies need appropriate production management systems which can improve logistics performance, e.g., by reducing lead times or improving due date adherence. However, many approaches to improving performance are not practical for small to medium sized enterprises (SMEs) and/or make-to-order (MTO) companies which represent an important sector of the economy. Workload control (WLC), a production planning and control (PPC) concept based on input/output control (Plossl and Wight 1973), is one potential means of improving performance that is of relevance to MTOs and SMEs (Henrich *et al.* 2004a, Stevenson *et al.* 2005). Many simulation studies have demonstrated the ability of WLC to improve performance (e.g., Melnyk *et al.* 1994, Perona and Portioli 1998, Oosterman *et al.* 2000, Land 2006) but reports of its successful implementation in practice are limited. One of the key barriers to its successful implementation is determining appropriate workload norms, as identified in theory by Land (2004) and in practice by Silva *et al.* (2006), and Stevenson and Silva (2008).

Overcoming this challenge is vital given the importance of determining appropriate workload norms. For example, through simulation (e.g., Land 2004) it has been shown that: if workload norms are set too tight, shop floor throughput times will be reduced but only at the expense of an increase in the gross throughput time; and, if norms are set too loose, only a small reduction in the shop floor throughput time will be achieved. Hence, a norm set too high is ineffective and a norm set too low can adversely affect performance (Enns and Prongue Costa 2002). Despite this, only limited guidance has been provided in the literature on how to determine workload norms in practice and solutions proposed require the regular feedback of detailed information from the shop floor about the status of work-in-process (WIP), and are therefore often impractical.

Therefore, this paper seeks to predict workload norms without such feedback requirements, analysing the influence of shop floor characteristics, which are known to have a significant influence of the performance of WLC (Stevenson *et al.* 2005), on the workload norm. The shop floor characteristics considered are flow characteristics and the number of possible work centres in the routing of a job (i.e., the routing length). Few studies have analysed the influence of flow characteristics on the performance of the WLC system (e.g., Oosterman *et al.* 2000, Land 2004) and, to the best of our knowledge, the influence on workload norms has not previously been studied. The available literature has considered four different flows, the: pure job shop (PJS), restricted job shop (RJS), general flow shop (GFS), and pure flow shop (PFS); but instead of concentrating on these four 'pure shop floor configurations', this paper seeks to analyse the influence of hybrid configurations along the spectrum from the pure job shop to the general flow shop. The rationale behind this is that in practice it is more likely that a hybrid configuration lying somewhere between, for example, a restricted job shop and a general flow shop, will be in operation than one of the four pure configurations. This is supported, for example, by Portioli (2002) who stated that flow characteristics are unlikely to lie at one of these extremes, while several authors (e.g., Oosterman *et al.* 2000) have questioned whether the pure job shop, which is typically used to represent the appropriate configuration for many MTO companies (Muda and Hendry 2003), actually exists in practice. The problem of workload norm setting is particularly acute for the classical aggregate load method where a different norm for each workstation is necessary when routings become more directed (Oosterman *et al.* 2000, Land 2004). This is explained by the fact that when the routing has a dominant flow direction, e.g., from upstream to downstream, the indirect load begins to concentrate on the downstream work centres. Our focus is on aggregate load methods;

hence, the number of possible work centres in the routing of a job (the routing length) is also an important shop floor characteristic to consider.

The main objective of this study is to: analyse the influence of different shop floor characteristics on how workload norms should be set in order to obtain optimal performance; and, to use the results to provide guidance to support the determination of appropriate norms in practice. So far, to predict norms for the classical aggregate load approach, the norm for each work centre has been related to the recorded aggregate load of each work centre when the norm is not restricted (e.g., Oosterman *et al.* 2000). However, the results of recent studies (e.g., Thürer *et al.* 2009) have suggested that it is possible to obtain an optimal solution for the workload norm. Therefore, optimisation software (OptQuest ©) will be applied to find optimal norms for different shop floor characteristics. Furthermore, in practice, it may be difficult to maintain stable flow characteristics in an MTO context, thus a release mechanism which is robust and able to work well under different characteristics is required. Therefore, different release mechanisms will be compared under different flow characteristics and conclusions drawn regarding which release mechanism corresponds best to which flow characteristics.

The remainder of this paper is organised as follows. Section 2 reviews literature on norm setting and the effects of flow characteristics and routing length. Section 3 describes the simulation model, the use of optimisation software, and the different approaches we follow to address the problem of norm setting. Results from the simulations are presented and analysed in Section 4 before conclusions are drawn in Section 5.



## 2. Literature review

This review considers the two core elements of this paper: how to set workload norms; and, how shop floor characteristics, particularly flow characteristics and the number of work centres on the shop floor, influence performance. Note that when work centres are not revisited, the number of work centres on the shop floor is also equal to the maximum routing length. Section 2.1 reviews approaches to defining workload norms in theory and in practice before Section 2.2 explores how flow characteristics and routing length have been investigated to date. Finally, an assessment of the literature is presented in Section 2.3.

### 2.1 *Workload norm setting*

Workload norms are determined by considering the current load level at a given work centre, the planned output, and the degree of control desired over queues on the shop floor. There are two different workload norms. A maximum norm, also known as an upper bound, is the maximum workload restriction of the backlog and a minimum norm, also known as a lower bound, is the minimum workload restriction of the backlog. The lower bound is mainly used to avoid starvation and the upper bound to balance the shop floor (e.g., Stevenson and Hendry 2006). Although many authors have highlighted the importance of setting norms appropriately (e.g., Hendry *et al.* 1998, Land and Gaalman 1998, Perona and Portioli 1998), there is a lack of research which focuses specifically on norm setting and no attempts to provide a framework to support workload norm setting in practice have been presented.

One of the few attempts to relate workload norms to the parameters of a given production system was presented by Hendry (1989) who derived an empirical equation based on the relationship between the workload norms, percentage of urgent jobs, job operation completion time and total lead time. Zäpfel and Missbauer (1993) used linear programming techniques to determine the workload norm to be adopted in the future depending on the incoming order stream, thus applying a dynamic norm. However, the determination of a workload norm depends on firstly determining an appropriate load level for a work centre. Nyhuis and Wiendahl (1999), and Breithaupt *et al*. (2002) propose an empirically derived mathematical function based on the relationship between load norms, workload, output and throughput time, to estimate appropriate load levels. To the best of our knowledge, these are the only studies which try to establish a relationship between system parameters and load norms available in the literature to date.

The studies outlined above make a contribution towards predicting adequate norms as long as the feedback of information on the progress of WIP from the shop floor is constant and reliable. Using this feedback information, workload norms can be adapted dynamically based on the current load at each work centre; however, it is difficult to supply in practice (e.g., Henrich *et al*. 2004b). Therefore, if WLC is to be applied in practice, simpler solutions (e.g., with rigid norms), that do not rely on dynamic adaptations or regular feedback information are needed. Furthermore, simulations typically assume that the incoming flow of orders has known stationary characteristics (Land 2004) but, in practice, known stationary characteristics are unlikely. As a result, researchers have adopted a trial and error approach to norm setting when implementing WLC in practice (e.g., Silva *et al*. 2006, Stevenson and Silva 2008). However, an iterative trial and error approach can take a long time to find a satisfactory solution and, in a highly competitive production environment, is insufficient given that errors are unacceptable and decrease the confidence of the user in the system. Hence, setting workload norms remains an outstanding problem and research should be conducted to better understand the relationship between shop characteristics and workload norms. Therefore, this study seeks to analyse how shop floor characteristics influence the workload norm and to develop a framework to support the determination of workload norms.

At the job release stage of the WLC concept, jobs are considered for release from the pre-shop pool, e.g., according to shortest slack, by adding the contribution that the job will make to the workload of all work centres in its routing to the current loading and then comparing this against workload norms. In recent years, researchers and practitioners have mainly applied the following two approaches to account for the workload contribution of a job over time when it is considered for release:

- The probabilistic approach (or load conversion) estimates the input from jobs upstream to the direct load of a work centre. As soon as a job is released, its processing time partly contributes to the input estimation. The contribution increases as the job progresses on its routing downstream. The whole of the direct load and the estimated input is indicated as the converted load (Bechte 1994, Wiendahl 1995).
- Aggregate load approaches avoid estimating the input to the direct loads. The direct and the indirect workload of a station are simply added together (Tatsiopoulos 1983, Hendry 1989, Hendry and Kingsman 1991, Land and Gaalman 1996, Kingsman 2000, Stevenson and Hendry 2006).

Note that some alternative release mechanisms have been developed which avoid the need to determine rigid workload norms. For example, Land and Gaalman (1998) presented the superfluous load avoidance release (SLAR) procedure and Cigolini and Portioli-Staudacher (2002) described workload balancing. Initial results suggest that the methods are competitive but these approaches have been neglected in recent years and are not the approaches researchers have sought to implement in practice. Therefore, these approaches are not considered further in this paper. For a more comprehensive review of workload accounting over time and order review/release mechanisms, see: Philipoom *et al*. (1993), Wisner (1995), Bergamaschi *et al*. (1997), Sabuncuoglu and Karapinar (1999), and Fredendall *et al*. (2010).



### 2.2 *Flow characteristics and routing length*

Flow characteristics have proven to be important to the performance of WLC and affected the choice of the most appropriate release mechanism to apply (Oosterman *et al*. 2000). Oosterman *et al*. (2000) also showed that WLC improves the performance of the shop floor if the flow either corresponds to a pure job shop or a general flow shop, reducing the shop floor throughput time to more than compensate for any deterioration in gross throughput time performance. More recently, research has also shown that the routing length is of great importance to the performance of WLC (e.g., Thürer *et al*. 2009).

If the classical aggregate load approach is applied, for certain flow characteristics and routing lengths, different workload norms have to be determined for each work centre according to the position of a work centre in the routing of a 'typical' job (e.g., Land 2004) because the indirect load is concentrated on the downstream work centres. This task adds to the challenge of norm setting and becomes increasingly complex as the number of possible work centres in the routing of a job (i.e., the routing length) increases. How flow characteristics and/or routing length influence the workload norms that have to be applied in order to obtain the *optimum* performance has not previously been studied.

### 2.3 *Assessment of the literature*

Determining workload norms is one of the most important outstanding problems in the field of WLC if this PPC solution is to be successfully adopted in practice. Although this has been acknowledged in the literature, a suitable solution is yet to be provided. Contributions provided through simulation are difficult to apply in practice, resulting in trial and error being adopted in field research. This study seeks to contribute towards filling this important gap in the literature by analysing the influence of shop floor characteristics on workload norms. We consider the following research questions:

- How do shop floor characteristics influence the workload norms which have to be set in order to obtain the optimum performance of a WLC system?
- Can a simple framework be developed to support practitioners in the determination of appropriate workload norms?

Model-based research and optimisation are considered the best method of exploring this problem (as described in Bertrand and Fransoo (2002)). The flow is varied stepwise down from a completely undirected routing, the pure job shop, to a directed routing, the general flow shop. In a second step, the influence of the routing length (or the number of possible work centres in the routing of a job) is analysed. In order to find an optimum solution for each shop floor configuration and for different release mechanisms, the norms are optimised using optimisation software. Such an approach has not previously been presented in the WLC research literature.

## 3. Simulation model

### 3.1 *Overview of shop characteristics*

Using SIMUL8 © software, a simulation model has been developed. The model represents a shop with up to 12 work centres, where each is a single and unique capacity resource; capacity is equal for all work centres and remains constant. The model represents different flow characteristics along the spectrum between a pure job shop, according to the characteristics outlined by Melnyk and Ragatz (1989), and the general flow shop. As in most recent studies (e.g., Oosterman *et al*. 2000, Bertrand and Van Ooijen 2002, Land 2004), it will be assumed that a job does not visit the same work centre twice and all stations have an equal probability of being visited. The routing length, i.e., the number of operations per job, is variable and depends on the number of work centres or capacity groups; e.g., eight work centres would imply a routing length uniformly distributed between one and eight. Each operation requires one specific work centre and the routing and operation processing time characteristics are known upon job entry. As in many other studies, e.g., Land (2004), a first-come-first-served (FCFS) dispatching rule is used on the shop floor.

### 3.2 *Flow characteristics*

The routing for the pure job shop is determined using a uniform distribution. Thus, all work centres have the same probability of being, e.g., the first, the second or the last work centre in the routing of a job. The routing sequence is summarised in a routing vector where the first position represents the first work centre to visit, the second position represents the second work centre to visit, and so on. To obtain a directed routing (e.g., the general flow shop), the elements of the routing vector (which represent the work centres) are sorted in ascending order. The sorting does not affect the mean routing length or the probability of a work centre being visited; these are maintained equal for each work centre (as for the pure job shop).

The routing vectors for the flow characteristics between the undirected and the directed routing are obtained by sorting the routing vector for the undirected routing only to 25%, 50% and 75%. During the sorting procedure, a random number is generated to decide whether a work centre moves to a new (sorted) position in the routing of a job or whether it maintains its old uniformly distributed position. This is in contrast, for example, to Oosterman *et al*. (2000) who sorted the vector only to 100% (the general flow shop) and to 0% (the pure job shop). The transition probability between work centres can be shown in a routing matrix (see Land 2004). In this routing matrix, the probability of a job moving to a certain work centre or exiting the shop floor ($X$) from a given work centre or upon entering the shop floor ($Y$) is given by the element ($X$, $Y$). Table 1 provides an example of a routing matrix, which has been obtained numerically using MatLab ©, for a 50% directed routing and a 100% directed routing (the general flow shop) of a shop floor consisting of six work centres.

Table 1. Routing matrix: (a) 50% directed routing; (b) general flow shop (Oosterman *et al*. 2000).

From work centre/entry

(a)

| To work centre/exit | Entry | WC 1 | WC2 | WC 3 | WC 4 | WC 5 | WC 6 |
|---|---|---|---|---|---|---|---|
| Exit | 0 | 0,1 | 0,12 | 0,13 | 0,17 | 0,21 | 0,27 |
| WC 1 | 0,37 | 0 | 0,03 | 0,03 | 0,04 | 0,05 | 0,06 |
| WC 2 | 0,24 | 0,17 | 0 | 0,03 | 0,04 | 0,05 | 0,06 |
| WC 3 | 0,16 | 0,11 | 0,16 | 0 | 0,04 | 0,05 | 0,06 |
| WC 4 | 0,10 | 0,09 | 0,12 | 0,16 | 0 | 0,05 | 0,06 |
| WC 5 | 0,08 | 0,06 | 0,09 | 0,12 | 0,18 | 0 | 0,06 |
| WC 6 | 0,06 | 0,05 | 0,07 | 0,09 | 0,12 | 0,18 | 0 |

(b)

| To work centre/exit | Entry | WC 1 | WC2 | WC 3 | WC 4 | WC 5 | WC 6 |
|---|---|---|---|---|---|---|---|
| Exit | 0 | 0,03 | 0,04 | 0,05 | 0,1 | 0,2 | 0,58 |
| WC 1 | 0,58 | 0 | 0 | 0 | 0 | 0 | 0 |
| WC 2 | 0,2 | 0,39 | 0 | 0 | 0 | 0 | 0 |
| WC 3 | 0,2 | 0,09 | 0,38 | 0 | 0 | 0 | 0 |
| WC 4 | 0,05 | 0,04 | 0,1 | 0,39 | 0 | 0 | 0 |
| WC 5 | 0,04 | 0,02 | 0,04 | 0,1 | 0,39 | 0 | 0 |

### 3.3 *Release mechanisms*

As in previous studies (e.g., Perona and Portioli 1998, Bertrand and Van Ooijen 2002, Henrich *et al*. 2006), it is assumed that all orders are accepted, that materials are available, and that the process plan (which includes all necessary information regarding routing sequence, processing times, etc.) is known. No special order review methodology is applied: orders flow directly into the pre-shop pool; hence, as in most previous studies, a pool of confirmed orders is the starting point. At release time '*t*', jobs waiting in the pre-shop pool are considered for release according to shortest slack. Slack represents the time between the latest release date and the current date.

The operation workload of a job is attributed to the load of the work centres corresponding to its routing at the moment of release. If this aggregated load fits within the workload norm, the job is added to the load of the work centres in its routing and is released to the shop floor. If one or more norms would be exceeded, the job remains in the pre-shop pool and must wait until at least the next release period. This procedure is repeated until all jobs in the pre-shop pool at release time '*t*' have been considered for release once. The check period is periodical and set to 5 time units, which means jobs in the pool are considered for release every 5 time units. To enable a clear insight into the performance of the system, no special planning horizon is applied.

There are different approaches to how the workload is accounted over time but, in this study, the following two aggregate load approaches are applied:

- The (classical) aggregate load approach (B) (Tatsiopoulos 1983, Hendry 1989), which attributes the workload of a job to the backlog of each work centre that processes it at the moment of release by simply adding it. The backlog at a work centre, hence, includes indirect load and load-on-hand (i.e., the direct load) without distinguishing between the two, irrespective of the routing of a job prior to arrival at a work centre.
- The corrected aggregate load approach (B′) was developed to take account of the routing (and routing length) of jobs in the aggregation procedure (Land and Gaalman 1996, Oosterman *et al.* 2000). The contributed load is depreciated (or corrected) according to the position of a work centre in the routing of a job. The further downstream a work centre is positioned, the higher the depreciation factor. In contrast to the classical aggregate load approach (B), only one norm has to be determined for the corrected aggregate load approach (B′).

The corrected aggregate load approach (B′) is similar to the probabilistic approach; however, it does not require sophisticated statistical data to determine the depreciation factor which is simply represented by the position of a work centre in the routing of a job – the workload contribution is depreciated by dividing the original load by the position of a work centre in the routing of a job. However, the probabilistic approach is not considered further because it requires detailed and regular feedback from the shop floor to predict the depreciation factor, which is difficult to satisfy in practice (Tatsiopoulos 1983, Henrich *et al.* 2004b). A similar approach to the classical aggregate load approach (B) is the extended aggregate load approach which was developed by Tatsiopoulos (1983), who adapted the classical approach in response to a lack of feedback information from the shop floor. This approach also includes work already completed at a work centre but still downstream, thus a job contributes to the job loads of all stations in its routing until it leaves the shop floor. However, this is not considered further because of its poor performance in several studies (e.g., Land 2004). The focus is on those methods which are simple to apply in practice yet achieve good performance. Therefore the classical and the corrected aggregate load approach are especially relevant.

### 3.4 *Job characteristics and due date setting procedure*

The simulation is run with five different numbers of work centres or capacity groups (4, 6, 8, 10 and 12), resulting in a routing length uniformly distributed between 1 and: 4, 6, 8, 10 or 12, accordingly. Due to the change in the routing length and thus the number of work centres or capacity groups on the shop floor, the processing times and inter-arrival time must be adjusted in order to maintain comparable results and a shop floor occupation of 90% (as used in most studies, e.g., Land 2004, Henrich *et al.* 2006). This is demonstrated in (1) below:

$$\text{occupation} = \frac{\text{mean processing time} \cdot \text{mean routing length}}{\text{inter-arrival time} \cdot \text{capacity of the shop floor}}. \quad (1)$$

Three adjustments (I–III) are applied:

- Adjustment I: firstly, the inter-arrival time or entry time of jobs is adjusted and the mean processing time is maintained at one time unit.
- Adjustment II: secondly, the processing time is adjusted and the inter-arrival time is maintained at the value valid for six work centres (i.e., the number of work centres used in most WLC simulation studies, e.g., Hendry and Wong 1994, Park and Salegna 1995, Land 2004).
- Adjustment III: finally, the processing time and the inter-arrival time are adjusted and the mean job size is maintained at 3.5 time units (the value valid for six work centres and a mean processing time of one time unit).

In the first two adjustments, it could be argued that the resulting larger job size requires an increased check period (CP). This is an argument supported by Land (2004) who explained that a short release period can hinder the progress of large jobs. However, in this study the number of work centres and thus the available capacity on the shop floor is increased; therefore, the work content which each job contributes to a particular work centre is not increased significantly.

To set due dates for jobs, we use the same approach as described in Land (2004): adding a random allowance to the job entry time. The minimum value will be sufficient to cover a work centre throughput time which corresponds to the maximum processing time plus one time unit for the maximum number of possible operations. The maximum number of possible operations depends on the number of work centres (of the current simulation), and thus on the maximum routing length, plus a waiting time before release of 5 time units.

In many recent studies, processing times have been modelled using a two-dimensional Erlang distribution (e.g., Oosterman *et al.* 2000); previously, a negative exponential distribution was typical. It has been argued that the 2-Erlang distribution is a better approach to modelling the processing times found in real-life job shops and this approach has been adopted in what follows. The characteristics of our job shop model are summarised in Table 2; the characteristics of jobs are summarised in Table 3.

### 3.5 *Optimisation software*

Optimisation software (OptQuest ©) is used to find the optimum values for the workload norms. Such software is an important tool if optimum solutions are to be quickly obtained. OptQuest © is a general-purpose optimiser developed by Glover *et al.* (1996) based on the scatter search methodology – a population based approach (for a detailed description, see, e.g., Laguna 1997). Commercial versions of OptQuest © are available in several discrete event simulators, e.g., SIMUL8 ©, which is the simulation software used in

Table 2. Summary of simulated shop characteristics.

| Shop characteristics | |
|---|---|
| Shop type | Pure job shop → general flow shop |
| Shop characteristics (real or hypothetical) | Hypothetical |
| Routing variability | Random routing, no re-entrant flows |
| Number of machines | 4, 6, 8, 10, 12 |
| Interchange-ability of machines | No interchange-ability between machines |
| Machine capacities | All equal |
| Machine utilisation rate | 90% |
| Shop floor dispatching policy | First-come-first-served |

Table 3. Summary of simulated job characteristics.

| Job characteristics | |
|---|---|
| Number of operations per job | Uniform [1, number of work centres on the shop floor] |
| Operation processing times | 2-Erlang distribution |
| Inter-arrival times | Exponential distribution |
| Set-up times | Not considered |
| Due date determination procedure | Job entry time + *a*; *a* according to the routing length |
| Complexity of product structures | Simple independent product structures |
| Job characteristics (real or hypothetical) | Hypothetical |

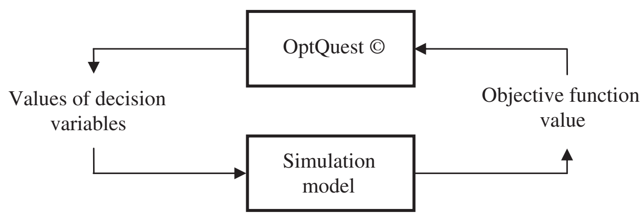


Figure 1. OptQuest © – optimisation process.



this study. The simulation software calculates the value of the objective function. OptQuest © then evaluates this value and defines new parameters for the simulation which then repeats the calculation of the objective function with the newly defined parameters. This optimisation process (as depicted in Figure 1) can be repeated over a limited time period, a certain number of trials or until the optimum solution has been found. In this study, the optimisation procedure is stopped after 200 iterations when improvements had stopped occurring, allowing us to obtain good results whilst keeping the simulation time short.

In this paper, the objective function (2) is defined as the sum of the shop floor throughput time and the gross (or total) throughput time, which represent the key performance measures used in WLC simulation research. The shop floor throughput time provides information about the performance of the job on the shop floor, and the gross throughput time, which includes the pool delay, provides information about the performance of the job across the whole system and indicates the percentage of late jobs:

$$\text{objective function} = \text{shop floor throughput time} + \text{gross throughput time}. \quad (2)$$

Given that the gross throughput time consists of the shop floor throughput time and the pool delay, the objective function is weighted in favour of reducing the shop floor throughput time. Basing the objective function on the gross throughput time only leads (in most cases) to an optimal result when no WLC procedure is applied. If WLC is applied then, in most cases, a reduction in the shop floor throughput time does not imply a reduction in the gross throughput time as this reduction is offset by the waiting time of the job in the pool – WLC shifts the time that a job waits in front of the work centre on the shop floor to the pool (Melnyk and Ragatz 1989). However, reducing the amount of time that a job waits on the shop floor reduces the level of WIP and makes lead times more predictable. Moreover, while jobs remain in the pool, changes to design specifications can be accommodated at less inconvenience. Other objective functions could arguably be used; however, this one is considered to be the most adequate and is simple, which aids reliability and allows us to interpret the results with more confidence.

The decision variables are the workload norms to be imposed at each work centre on the shop floor. For example, if the simulation model represents a shop floor which consists of eight work centres, OptQuest © will consider eight decision variables. To reduce the area of search, only discrete variables are defined, i.e., the search for the load norms is restricted to integer values.

### 3.6 *Experimental design*

Each simulation is run using differing flow characteristics: undirected routing, 25% directed, 50% directed, 75% directed and fully (100%) directed routing. For the corrected aggregate load approach (B′), results are obtained by tightening the norm level stepwise down from infinity, represented by the right-hand starting point of the curves which will follow in Sections 4.1 and 4.2. A norm level of 100% is equivalent to the 'critical workload norm'. The critical workload norm represents the point where the shop floor throughput time ceases to decrease while the gross throughput time continues to rise; this will be determined empirically. For the classical aggregate load approach (B), results are obtained using OptQuest © because differing norms for each work centre are necessary. We focus on the setting of the upper bound; a lower bound is not required because of the high occupation rate we assume for the shop floor.

Results are then analysed to determine the influence of shop floor characteristics on the workload norm and on performance. We expect to establish a link between: the position of a work centre in the routing of a job and the workload norm (for the classical aggregate load method); and, the routing length and the workload norm, in order to provide appropriate guidance to predict the optimum norms.

As in Thürer *et al.* (2009), each experiment consists of 100 runs and results are collected over 10,000 time units. The warm-up period is set to 3000 time units to avoid start-up effects. These simulation parameters enable us to obtain stable results whilst keeping the simulation run time short. After 100 runs, no significant change in the values obtained was observed, thus conducting further runs was unnecessary. In total, 150 experiments have been conducted. They are full factorial and explore the influence of: the five different flow characteristics, the three different adjustment procedures for the processing and inter-arrival time (according to the routing length), and the five different routing lengths on the workload norms of the classical and the corrected aggregate load approaches.

## 4. Results

### 4.1 *Norm setting for the classical aggregate load method (B)*

If the routing becomes directed and does not represent a pure job shop, the workload norm for each work centre has to be adapted according to the position in the routing. This is consistent with the results found by, e.g., Oosterman *et al.* (2000). If only one workload norm for all work centres is applied, the performance deteriorates if the routing becomes directed. The norm for the whole shop floor has to be adapted according to the work centre most downstream in the routing. This work centre has a large proportion of indirect load, which consists of work still upstream and this high load norm leads to the upstream work centres being largely uncontrolled.

The optimisation of the load norms was conducted using OptQuest © for SIMUL8 ©. As previously outlined, the optimisation procedure is an iterative process which starts with an initial solution proposed by the user and, by applying the scatter search methodology, selects input parameters for the simulation model with the aim of optimising the objective function. The evolution of the objective function for a shop floor consisting of six work centres with directed and undirected flow characteristics is shown in Figure 2.

It can be seen that the optimum for a pure job shop is achieved after only 16 iterations without any further improvement thereafter. If the routing is directed, like in the general flow shop, a norm for each work centre has to be determined and more iterations are necessary in order to achieve the optimum solution. The use of optimisation software significantly reduces the objective function, thereby improving performance. It can also be seen that if the routing is directed, better performance can be achieved. A directed routing increases control over the indirect load which is concentrated at downstream work centres.

The optimisation process was conducted considering 4, 6, 8, 10 and 12 work centres and five different types of flow characteristics (from the pure job shop or 0% directed to the general flow shop or 100% directed flow), which results in 25 different optimisation processes. The results of this process are summarised in Table 4. All three adjustment procedures for the processing and inter-arrival times (Section 3.4) showed similar results. Therefore, only the results when the processing times are maintained at a mean of one time unit and the inter-arrival time is adjusted are presented (Adjustment I).

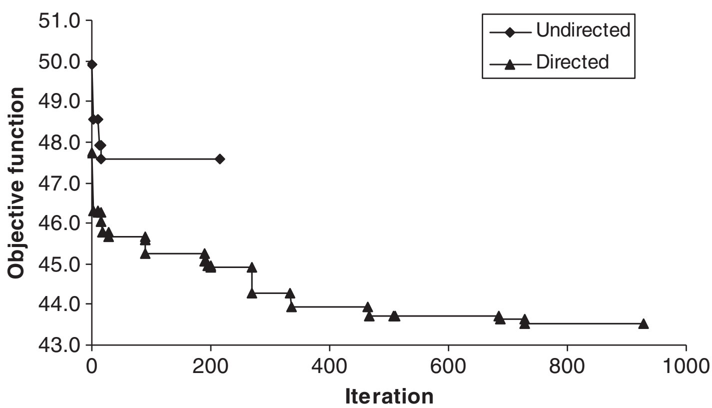


Figure 2. Evolution of the objective function.

The results show that, if the routing is directed, the further downstream a work centre is positioned, the higher the workload norm that must be applied in order to obtain optimum results. This is due to the higher indirect load of a downstream work centre. The problem is, as outlined by Land (2004), predicting this indirect load; it is impossible to define a stable relationship between the mean position in the routing and the workload norm.

If the routing is undirected, all work centres have statistically the same percentage of direct and indirect load and the optimum norm tends to be the same for all work centres, as expected. It is even possible to establish a linear relationship between the optimum workload norms and the routing length or the number of possible work centres in the routing of a job (see Figure 3). If the mean routing length increases, the part of the workload of a job which represents indirect load also increases. Therefore, the greater the routing length, the higher the workload norm that must be applied.

The simulation results illustrate the problems encountered in defining an optimum norm for the classical aggregate load approach (B). Although optimisation software has been applied, the optimum solution found did not outperform the corrected aggregate load approach (B′), the results for which are presented in Section 4.2. This approach (B′) takes the routing properties of the job itself into account. The workload that a job contributes to the load of a particular work centre is converted, which means that the load does not fully contribute to the work centre but is adjusted according to the position of the work centre

Table 4. Optimisation results for the classical aggregate load approach (B).

| No. of WCs | Flow | Workload norm | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | WC 1 | WC 2 | WC 3 | WC 4 | WC 5 | WC 6 | WC 7 | WC 8 | WC 9 | WC 10 | WC 11 | WC 12 |
| 4 | 0% | 14 | 14 | 14 | 14 | – | – | – | – | – | – | – | – |
| | 25% | 13 | 14 | 15 | 15 | – | – | – | – | – | – | – | – |
| | 50% | 12 | 14 | 16 | 18 | – | – | – | – | – | – | – | – |
| | 75% | 10 | 12 | 15 | 18 | – | – | – | – | – | – | – | – |
| | 100% | 8 | 11 | 15 | 18 | – | – | – | – | – | – | – | – |
| 6 | 0% | 21 | 21 | 21 | 21 | 21 | 21 | – | – | – | – | – | – |
| | 25% | 20 | 22 | 23 | 25 | 27 | 27 | – | – | – | – | – | – |
| | 50% | 15 | 19 | 19 | 22 | 25 | 26 | – | – | – | – | – | – |
| | 75% | 11 | 14 | 17 | 20 | 23 | 29 | – | – | – | – | – | – |
| | 100% | 9 | 12 | 19 | 22 | 24 | 27 | – | – | – | – | – | – |
| 8 | 0% | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | – | – | – | – |
| | 25% | 24 | 26 | 27 | 28 | 29 | 31 | 31 | 31 | – | – | – | – |
| | 50% | 21 | 23 | 25 | 28 | 29 | 31 | 33 | 34 | – | – | – | – |
| | 75% | 18 | 19 | 21 | 27 | 27 | 31 | 31 | 37 | – | – | – | – |
| | 100% | 12 | 12 | 17 | 24 | 29 | 30 | 33 | 34 | – | – | – | – |
| 10 | 0% | 33 | 33 | 33 | 33 | 33 | 33 | 33 | 33 | 33 | 33 | – | – |
| | 25% | 29 | 30 | 31 | 33 | 33 | 34 | 35 | 35 | 36 | 37 | – | – |
| | 50% | 23 | 25 | 28 | 30 | 32 | 33 | 34 | 36 | 36 | 38 | – | – |
| | 75% | 18 | 21 | 23 | 26 | 28 | 32 | 33 | 35 | 37 | 40 | – | – |
| | 100% | 13 | 16 | 19 | 23 | 25 | 30 | 32 | 34 | 36 | 41 | – | – |
| 12 | 0% | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 |
| | 25% | 36 | 38 | 39 | 40 | 41 | 42 | 44 | 44 | 45 | 46 | 47 | 47 |
| | 50% | 29 | 29 | 34 | 34 | 36 | 38 | 40 | 43 | 47 | 47 | 50 | 52 |
| | 75% | 19 | 24 | 26 | 30 | 32 | 35 | 38 | 42 | 45 | 47 | 48 | 51 |
| | 100% | 13 | 20 | 21 | 22 | 25 | 32 | 36 | 38 | 41 | 46 | 49 | 52 |

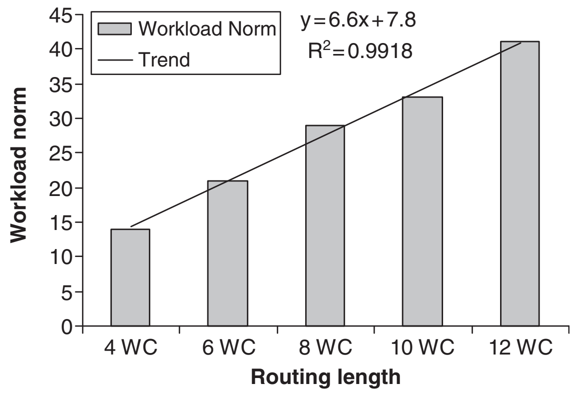


Figure 3. Relationship between the maximum routing length and the workload norm.



in the routing of the job. This is the reason why one norm can be applied for all work centres. In contrast, the classical aggregate load approach (B) adjusts the load on the work centre, taking into account its mean position in the routing of jobs and not considering particular jobs which do not follow a strict routing according to the mean flow. This deteriorates the performance of the method, particularly if the routing is undirected or only partially directed. If the routing is undirected, the percentage of indirect load is much smaller if the load of the job is converted according to its position in the routing (approach B′), thus improving performance significantly.

### 4.2 *Norm setting for the corrected aggregate load method (B′)*

As outlined in the previous section, the corrected aggregate load approach (B′) requires only one workload norm to be determined; experiments were conducted to optimise the workload norm for each single work centre but no improvement over applying only one workload norm for all work centres could be obtained. This reduces the number of decision variables and makes workload norm setting a simpler task when compared with the classical aggregate load approach (B). Again, all three adjustment procedures for the processing and inter-arrival times showed similar results. Therefore, only the results when the processing times are maintained at a mean of one time unit and the inter-arrival time is adjusted are presented (Adjustment I.). Figure 4 shows the results obtained for the different flow characteristics and six work centres (or capacity groups) on the shop floor for the corrected aggregate load approach (B′) and for comparison with the classical aggregate load approach (B). The utmost right starting point represents the infinite workload norm which is tightened stepwise down to the critical workload norm where the shop floor throughput time stops decreasing while the gross throughput time continues to increase (see Section 3.6 for a reminder of the experimental design).

The most interesting conclusion that can be drawn from the figure is that the performance of the corrected aggregate load approach (B′) is not influenced by the flow characteristics. If the routing length changes (from six), the curves which depict the performance follow a similar path as for six work centres, thus they are not depicted here. Instead, Table 5 summarises the reduction based on the results obtained for the infinite

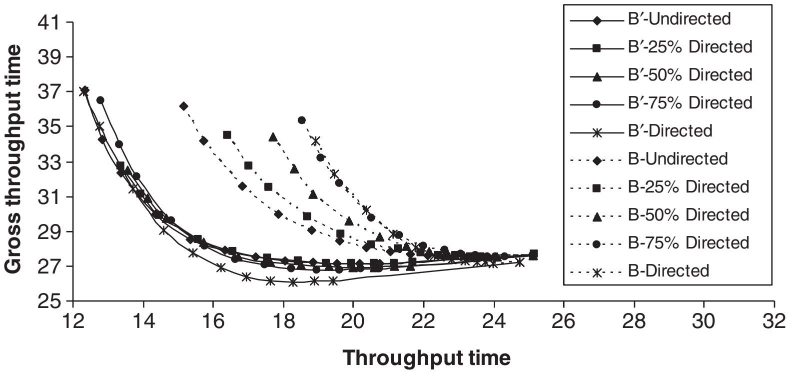


Figure 4. Results for the corrected aggregate load approach (B′) and the classical aggregate load approach (B) with six work centres.

Table 5. Optimisation results for the corrected aggregate load approach (B′).

| | 4 work centres | | | 6 work centres | | | 8 work centres | | | 10 work centres | | | 12 work centres | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Norm | $T_t$ (%) | $T_{gt}$ (%) | Norm | $T_t$ (%) | $T_{gt}$ (%) | Norm | $T_t$ (%) | $T_{gt}$ (%) | Norm | $T_t$ (%) | $T_{gt}$ (%) | Norm | $T_t$ (%) | $T_{gt}$ (%) |
| 0% | 7.2 | 41.9 | −1.0 | 7.8 | 38.8 | −3.4 | 7.2 | 35.9 | −4.7 | 7.4 | 30.8 | −2.8 | 7.5 | 27.9 | −2.9 |
| 25% | 7.2 | 41.6 | −1.3 | 7.2 | 38.2 | −3.1 | 7.2 | 35.5 | −4.7 | 7.4 | 30.2 | −2.6 | 7.5 | 26.9 | −2.5 |
| 50% | 7.2 | 41.1 | −0.9 | 7.2 | 37.5 | −2.6 | 7.2 | 34.2 | −3.6 | 7.4 | 29.6 | −1.8 | 7.5 | 26.2 | −1.6 |
| 75% | 7.2 | 41.2 | −0.9 | 7.2 | 37.2 | −1.9 | 7.2 | 33.6 | −2.7 | 6.8 | 32.1 | −3.8 | 7.0 | 28.4 | −3.0 |
| 100% | 7.5 | 38.5 | 1.1 | 7.5 | 34.4 | 1.1 | 7.5 | 31.1 | 1.6 | 7.2 | 28.9 | 1.1 | 7.2 | 26.8 | 0.9 |

workload norm (the utmost right starting point in Figure 4), in percent obtained for the shop floor throughput time ($T_t$) and the gross throughput time ($T_{gt}$) which corresponds to the optimum norm (also given in the table). This optimum norm is determined by the objective function. In all cases, the shop floor throughput time is significantly reduced whereas the gross throughput time is maintained. However, the reduction is greater when the routing length is short.

From the table, the optimum workload norm for all scenarios stays almost the same. The corrected aggregate load approach (B′) seems not to be influenced either by flow characteristics or routing length. This was not anticipated prior to the study and is explained by the fact that the indirect load is converted, thus the workload norm is mainly determined by the direct load which stays the same.

It could be argued that the corrected aggregate load approach (B′) only controls the upstream work centres and not the downstream work centres for which the workload at the release time is depreciated and therefore more workload is released than the capacity of the work centre. The simulation showed that the inventory in front of a work centre tends to be higher the more downstream the work centre is positioned if the routing shows a certain directed flow; in a pure job shop with an undirected routing, the inventory in front of all work centres is the same.

To prove this argument, the classical aggregate load approach (B) was applied whilst controlling, firstly, only the first and, secondly, only the first three work centres of a general flow shop with six work centres. In comparison with the results obtained by controlling the workload norms for all six work centres, controlling only the first three resulted in a performance deterioration of 5% and controlling only the first one resulted in a performance deterioration of 12%. This performance loss is due to jobs which do not follow a strict flow. If the routing becomes less directed than in a general flow shop, the number of these jobs increases as does the performance loss if only the first work centres are controlled. As expected from previous studies, in all cases the corrected aggregate load approach (B′) outperformed the classical aggregate load approach (B).

### 4.3 *Determining the workload norms in practice*

One of the objectives of this study was to elaborate a framework to support the determination of workload norms in practice. The simulation results showed that:

- Workload norms can be determined easier for the corrected aggregate load approach (B′) than for the classical aggregate load approach (B) and the corrected aggregate load approach (B′) consistently outperforms the classical aggregate load approach (B). Workload norms for the corrected approach are not influenced by flow characteristics or the maximum routing length and workload norms can be set equal for all work centres. The one workload norm is largely dependent on the directed load due to the converted indirect load. It is therefore concluded that this approach is particularly relevant to practice given its simplicity and superior performance. Hence, there in fact is no need for a framework.
- If the classical aggregate load approach (B) is applied, it is necessary to adapt the workload norm in all cases. If the number of work centres increases, the workload norm also has to increase. If the routing becomes directed, different norms for all work centres, according to their position in the routing of a job, have to be applied. It was found to be almost impossible to define a stable relationship between workload norms and shop floor characteristics, thus making it difficult to find an optimum solution in practice. The only rule that can be proposed is that the further downstream the work centre is positioned, the higher the norm that has to be applied.

In all cases, and for both the classical and the corrected aggregate load methods, it can be concluded that if the routing becomes directed, the inventory or the queue in front of the work centre increases the further downstream a work centre is positioned. Only the upstream work centres are 'under control' due to the lower percentage of indirect load. Additionally, for the classical aggregate load approach (B), it can be concluded that the norm can be set looser if the work centre is a downstream work centre. This deteriorates the performance but does not seriously affect the WLC system because the shop floor stays controlled by the first (gateway) work centre. However, if the workload norm for one work centre is set too tight, a bottleneck is created which deteriorates performance; this is particularly detrimental if the work centre is towards the upstream end.

### 4.4 *The influence of flow characteristics and the routing length on performance*

The different flow characteristics have a significant effect on performance when the classical aggregate load approach (B) is applied. The corrected aggregate load approach (B′) performed equally well under all flow characteristics and always outperformed the classical aggregate load approach (B); this result is consistent with Oosterman *et al.* (2000), and Land (2004). The results obtained for the flow characteristics are also consistent for all routing lengths. If the number of possible work centres in the routing of a job increases, the performance deteriorates slightly when compared to the performance of the shop floor with a shorter maximum routing length. However, in all cases, a significant reduction in shop floor throughput time without a significant deterioration in gross throughput time can be obtained, thereby demonstrating the potential of WLC to improve shop floor performance.

The different adjustments made to the processing and inter-arrival times, in order to maintain a 90% occupation level as the number of work centres on the shop floor changes, was found to have almost no influence on the results. The results were similar for all three adjustment procedures.

### 4.5 *Discussion of results*

The results presented have shown that it is almost impossible to establish a stable relationship between workload norms and shop floor characteristics for the classical aggregate load approach (B). Thus, in order to obtain optimum performance measures, the workload norms have to be adapted dynamically, e.g., by applying linear programming techniques such as those presented by Zäpfel and Missbauer (1993). However, considering that the workload norm for each work centre has to be predicted, the high feedback requirements and the number of influencing parameters make it difficult to implement this approach in practice. If, for example, the flow characteristics change, all workload norms have to be recomputed. In addition to outperforming the classical aggregate load approach (B) in all experiments, the corrected aggregated load approach (B′) relies on determining only one norm – a significant practical advantage especially if WLC is newly implemented and the shop floor is 'out of control' at the time of implementation. Moreover, results show that the optimum value of the workload norm is not affected by flow characteristics or routing length. The workload norm to set in order to obtain optimum performance was the same for all work centres in all experiments for the corrected aggregate load approach (B′).

The main challenge in determining appropriate workload norms for the classical aggregate load approach (B) in practice is predicting the indirect load of a work centre and receiving adequate feedback from the shop floor (Henrich *et al.* 2004b). This problem can be avoided if the corrected aggregate load approach (B′) is used; the method is argued to be simpler and easier to apply both in practice and theory.

Considering the instability of MTO companies, where the flow characteristics of the shop floor can change, e.g., in an extreme case from a pure job shop with undirected routing to a general flow shop with directed routing, the corrected aggregated load approach (B′) represents the best method to apply in practice. The method allows a company to adopt only one stable rigid norm which is simple to predict. The differing characteristics of the incoming order stream are handled at the release stage one-by-one by converting the load accordingly.

## 5. Conclusion

In theory and, significantly, in practice, determining the workload norm to be applied for a WLC system is one of the most important problems affecting the implementation of the method. Setting inappropriate workload norms has a direct detrimental effect on performance. Theory has provided methods to predict the workload norms; for example, the norms can be adapted dynamically according to the up-to-date situation on the shop floor but assume regular feedback from the shop floor. This is a condition which in practice is difficult to satisfy. WLC has been shown to improve shop floor performance significantly but more practical solutions are required to determine simple rigid upper workload norms which are more manageable for practitioners and yet enable optimum performance to be achieved.

The objective of this paper was to determine how shop floor characteristics influence workload norms for the two aggregate load methods which are most suitable for practical implementation in order to help practitioners predict appropriate workload norms. The research has found that:

- The workload norm for the classical aggregate load approach (B) is heavily influenced by flow characteristics. If the flow characteristics change, all workload norms for all work centres have to be adjusted if they are to remain optimal. Given that the workload norm for this method is heavily influenced by the indirect load, which is difficult to predict without detailed feedback from the shop floor, this often turns out to be an unsolvable problem in practice and practitioners have to adopt a trial and error approach. However, adopting a trial and error approach for each work centre on the shop floor increases the risk of applying an inadequate workload norm which influences the shop floor performance negatively or adopting norms that are good locally at the work centre level but do not lead to good overall shop performance.
- The corrected aggregate load approach (B′) allows one workload norm to be applied for all work centres on the shop floor, avoiding the problem caused by the indirect load. The striking finding of this study, however, is that this approach is not influenced by flow characteristics or by the routing length. The optimum value for the workload norm corresponding to the optimum performance of the WLC system is similar for all experiments; this finding simplifies the application of WLC in practice significantly.

Considering that the characteristics of real-life shops, e.g., MTO companies, often change, the corrected aggregate load approach (B′) represents a better choice than the classical aggregate load approach (B) if WLC is implemented in practice. The corrected aggregate load approach results in superior performance in all experiments; this finding is consistent with the results achieved in Thürer *et al*. (2009). We also considered whether it is possible to establish a framework or a set of rules to help practitioners to predict appropriate norms. Results indicate that this is only of relevance for the classical aggregate load approach (B) where a workload norm must be determined for each work centre. No direct relationship between the different workload norms and flow characteristics could be established. However, when there is a dominant flow direction from up to downstream, the further downstream a work centre is, the higher the norm must be in order to compensate for the greater indirect load which concentrates at downstream work centres.

The results of this study question whether it is possible to predict appropriate workload norms for the classical aggregate load approach (B), thereby also questioning the applicability of the approach in practice. Future research should therefore focus on the corrected aggregate load approach (B′). In particular, action research should be conducted to implement the approach in practice using the insights into workload norm setting presented in this paper. Further simulation research is also required. For example, most studies assume that the capacity of each work centre on the shop floor is equal but this is unlikely to be the case in practice where, for example, bottlenecks are commonplace. Research should analyse the effect that differing capacities at work centres has on workload norms and whether the corrected aggregate load approach maintains its superior performance.

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