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Published in:
Production Planning & Control

DOI:
[10.1080/09537287.2017.1302102](https://doi.org/10.1080/09537287.2017.1302102)

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

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2017

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

Citation for published version (APA):

Thürer, M., Land, M. J., Stevenson, M., & Fredendall, L. D. (2017). On the integration of due date setting and order release control. *Production Planning & Control*, 28(5), 420-430.
<https://doi.org/10.1080/09537287.2017.1302102>

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Production Planning & Control

The Management of Operations

ISSN: 0953-7287 (Print) 1366-5871 (Online) Journal homepage: <http://www.tandfonline.com/loi/tppc20>

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To cite this article: Matthias Thürer, Martin J. Land, Mark Stevenson & Lawrence D. Fredendall (2017) On the integration of due date setting and order release control, Production Planning & Control, 28:5, 420-430, DOI: [10.1080/09537287.2017.1302102](https://doi.org/10.1080/09537287.2017.1302102)

To link to this article: <http://dx.doi.org/10.1080/09537287.2017.1302102>



Published online: 14 Mar 2017.



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On the integration of due date setting and order release control

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ABSTRACT

This paper calls for a paradigm shift in the production control literature away from assuming due date setting and order release are two independent decision levels. When order release is controlled, jobs do not enter the shop floor directly but are retained in a pre-shop pool and released to meet certain performance targets. This makes the setting of accurate planned release dates – the point at which jobs transition from the pool to the shop floor – a key consideration when setting due dates. We develop a new approach to estimating planned release dates to be embedded in the Workload Control (WLC) concept. Our approach is unique as it anticipates the release decision as part of the due date setting procedure. This makes a second independent release decision superfluous and avoids a major cause of tardiness – deviations between (i) the planned release date used when calculating the delivery time allowance and (ii) the actual, realised release date. Simulation is used to compare the performance of WLC using two decision levels with the new single-level approach where the release decision is anticipated when setting the due date. Performance improvements are shown to be robust to uncertainty in processing time estimates.

ARTICLE HISTORY

Received 4 March 2016
Accepted 11 February 2017

KEYWORDS

Due date setting; order release; workload control; simulation

1. Introduction

This study examines the performance of due date setting and order release control in job shops. A basic assumption within the production planning and control literature is that due date and order release decisions are taken sequentially and independently. In other words, it is assumed that due dates are set first and then jobs flow into a pre-shop pool to await the release decision. This study questions this fundamental assumption. We argue that, rather than taking these two decisions independently, the release decision should be an integral part of the due date setting procedure.

Most literature on the estimation of due dates or delivery time allowances in job shops assumes the immediate release of jobs, i.e. that the delivery time is given by the time a job spends on the shop floor only (e.g. Weeks 1979; Ragatz and Mabert 1984; Ahmed and Fisher 1992; Vig and Dooley 1993; Moses et al. 2004; Thürer et al. 2013). This has limited applicability to shops where the release of jobs is controlled. When order release is controlled, jobs do not enter the shop floor directly. Instead, they are retained in a pre-shop pool and released using criteria that allow the shop to achieve certain performance targets, e.g. to restrict the level of work-in-process inventory and/or maximise due date adherence. Consequently, the realised delivery time is split into two parts: (i) the time a job waits in the pre-shop pool prior to being released (i.e. the pool waiting time); and (ii) the time a job spends on the shop floor (i.e. the shop floor throughput time). Both elements contribute to the overall delivery time and should therefore be considered when setting delivery time allowances or due dates to

ensure that they are both competitive and feasible (Thürer et al. 2014a). This makes the setting of accurate planned release dates – the point at which jobs are transferred from the pre-shop pool to the shop floor – a key priority (Thürer et al. 2016).

Workload Control (WLC) – a production planning and control concept specifically developed for job shops (Kingsman, Tsiopoulos, and Hendry 1989; Zäpfel and Missbauer 1993; Kingsman and Hendry 2002; Stevenson, Hendry, and Kingsman 2005) that combines delivery time estimations during customer enquiry management with order release control (Thürer et al. 2014a) – is used as a starting point for this study. The concept has been shown to significantly improve the performance of job shops both through simulation (e.g. Thürer et al. 2012, 2014a) and, on occasions, in practice (e.g. Wiendahl, Glässner, and Petermann 1992; Bechte 1994; Hendry, Huang, and Stevenson 2013). We first develop a new approach to calculating planned release dates. This unique approach anticipates future release decisions as part of the due date setting procedure. Since a release decision is already taken when due dates are set, it is argued that another, independent release decision becomes superfluous. Jobs can simply be released on their planned release date, which can be determined as part of the due date setting procedure. This integrates the release decision into the due date setting procedure and avoids variability between the planned release dates used to determine delivery time allowances and the release date actually realised.

This paper has the following two objectives:

- (1) To develop a new approach to calculating planned release dates that anticipates future release decisions,

which can be integrated into Workload Control's due date setting procedure.

- (2) To assess the performance of Workload Control based on two independent decision levels – one for delivery time estimation and one for order releases – and based on one decision level, where jobs are released on their planned release dates, which makes the release decision an integral part of the due date setting procedure.

The remainder of this paper is structured as follows. Section 2 reviews the literature to identify the WLC due date setting procedure and order release method to be considered in our study. Section 3 then develops a new approach to effectively estimating planned release dates. A simulation model to assess performance is presented in Section 4 before simulation results are presented in Section 5. Finally, the paper concludes in Section 6, where future research directions are also outlined.

2. Literature review

Section 2.1 provides a brief overview of how due dates are set in the literature on job shops in general and outlines WLC's due date setting procedure – the procedure into which our new approach to setting planned release dates will be integrated. WLC's load-limiting order release method is then outlined in Section 2.2. This method determines the structure of our new approach to setting planned release dates since it is the release dates realised by this method that we have to predict.

2.1. Due date setting rule

In terms of setting and assessing due dates, two types of jobs can be identified: (i) jobs where the due date is proposed or quoted by the company and, therefore, negotiable; and (ii) jobs where the due date is specified by the customer and, therefore, reasonably fixed (e.g. Ragatz and Mabert 1984; Cheng and Gupta 1989; Kingsman 2000). The main focus of this study is on setting due dates and thus on the former. A feasible due date (d_j) is generally determined by forward scheduling when a new job j arrives by summing the following three elements to the current time t (see Equation (1)): an allowance α_j for the time that a job has to wait in the pre-shop pool prior to release; an allowance β_{ij} for the operation throughput time of each operation i in the routing R_j of a job to allow for the shop floor throughput time; and an external allowance γ_j that compensates for variability between the estimated lead time and the delivery time that is ultimately realised. The process of setting each of these three allowances is outlined in the following three subsections.

$$d_j = t + \alpha_j + \sum_{i \in R_j} \beta_{ij} + \gamma_j \quad (1)$$

2.1.1. Setting allowances for the pool waiting time

The literature on due date setting rules typically assumes that jobs are released immediately, i.e. that the pool waiting time α_j is zero. Similarly, the WLC literature that has considered the estimation of due dates and order release simultaneously assumes that the pool waiting time is either zero (e.g. Enns 1995a; Ahmed

and Fisher 1992) or constant for all jobs (Hendry, Kingsman, and Cheung 1998; Thüerer et al. 2013, 2014a). To the best of our knowledge, the only study to date to present a method that estimates a dynamic allowance for the pool waiting time was presented by Land (2009). Following Little's Law (Little 1961), Land (2009) estimated the pool waiting time based on the total processing time units waiting in the pool to be released to the station that is most likely to restrict the release of a job, i.e. the station that had the largest load waiting to be released across the stations in the routing of a job. The pool waiting time is given as the quotient of this maximum pool load and the maximum output of the station. Land's (2009) approach will be included as a benchmark for the new approach to calculating pool waiting times – and thus planned release dates – developed in this study.

2.1.2. Setting allowances for operation throughput times

The shop floor throughput time is the sum of the operation throughput times in the routing of a job. Most due date setting rules presented in the literature differ in the way that allowances are determined for operation throughput times. For example, forward infinite loading assumes operation throughput times are constant (e.g. Weeks 1979; Ragatz and Mabert 1984; Vig and Dooley 1993). Meanwhile, other studies link the processing time and shop load to the delivery time based on historical data via regression (e.g. Ragatz and Mabert 1984; Ahmed and Fisher 1992; Vig and Dooley 1993; Moses et al. 2004) or link the workload at a station to the allowance for the operation throughput time (e.g. Nyhuis and Wiendahl 2009).

Bertrand (1983a) and (1983b) determined a dynamic allowance for operation throughput times by successively scheduling operation due dates d_{ij} for each operation i in the routing of a job j , where d_{0j} is defined as the current date. Using the time-phased accepted workload (W_{st}^A) and time-phased capacity (C_{st}) of the corresponding station s – both measures calculated cumulatively up to time bucket t – the operation due dates are calculated as follows. Starting with the first station in the routing of a job:

- If the time bucket into which the operation due date would fall if capacity were infinite – that is $d_{ij} = d_{i-1,j} + p_{ij}$ has enough free capacity to include the workload p_{ij} of the i th operation of job j at the relevant station s – that is $W_{st}^A + p_{ij} \leq C_{st} \cdot u_s$ with u_s equal to the utilisation rate – then the operation is loaded into the time bucket and the operation due date is given by this time bucket.
- If no or insufficient capacity is available, the next time bucket $t + 1$ is considered until the workload has been successfully loaded.

This procedure is then repeated at the next station in a job's routing until all operation due dates have been determined. An operation remains loaded into a time bucket – and thus contributes to the cumulative workload – until it has been completed.

This forward finite loading procedure was recently identified as the best solution for the WLC concept (see, e.g. Thüerer et al. 2013) and will thus be included in our study to set allowances for operation throughput times.

2.1.3. Setting an external allowance to compensate for variability

The external allowance y_j is often included in the allowance for operation throughput times (Hopp and Sturgis 2000). Notable exceptions that have differentiated between an internal (or production) due date and an external (or customer) due date – which is the internal due date plus the external allowance – are the studies by Bertrand (1983a), Enns (1995b), and Hopp and Sturgis (2000). The latter compared the use of a constant external allowance with the use of alternative, dynamic external allowances. Numerical results suggested that there are no significant performance differences between the use of a constant allowance and the best performing dynamic allowance approach. In general, the external allowance accounts for any unforeseen variability. If it were predictable – as assumed when a dynamic external allowance is calculated – it would be better to incorporate this into the allowances for the pool waiting time and/or operation throughput times. This makes the use of a constant external allowance an effective option in practice. WLC uses an explicit constant external allowance since its forward finite loading procedure estimates an internal due date.

2.2. Order release control

There are many order release methods in the WLC literature, for examples, see the reviews by Wisner (1995), Land and Gaalman (1996), Bergamaschi et al. (1997) and Fredendall, Ojha, and Patterson (2010). In this paper, the LUMS COR (Lancaster University Management School Corrected Order Release) method is used as the basis for further developments because it was recently shown to be the best order release solution for WLC in practice (Thürer et al. 2012). LUMS COR uses a *periodic* release procedure executed at fixed intervals to control and balance the shop floor workload. This procedure keeps the workload W_s^R released to a station s within a pre-established workload norm, as follows:

- (1) All jobs in the set of jobs J in the pre-shop pool are sorted according to their planned release date, as calculated at customer enquiry management.
- (2) The job $j \in J$ with the earliest planned release date is considered for release first.
- (3) Take R_j to be the ordered set of operations in the routing of job j . If job j 's processing time p_{ij} at the i th operation in its routing – corrected for station position i – together with the workload W_s^R released to station s (corresponding to operation i) and yet to be completed fits within the workload norm N_s^C at this station, that is $\frac{p_{ij}}{i} + W_s^R \leq N_s^C \forall i \in R_j$, then the job is selected for release. That means it is removed from J , and its load contribution is included, i.e. $W_s^R := W_s^R + \frac{p_{ij}}{i} \forall i \in R_j$.

Otherwise, the job remains in the pool and its processing time does not contribute to the station load.

- (4) If the set of jobs J in the pool contains any jobs that have not yet been considered for release, then return to Step 2 and consider the job with the next highest priority. Otherwise, the release procedure is complete and the selected jobs are released to the shop floor.

A released job contributes to W_s^R until its operation at this station is completed. Early studies on WLC typically focused on comparing the aggregate load of a station, i.e. the sum of all of the processing times of jobs released but not yet completed at a station, against an upper workload limit or norm (e.g. Bertrand and Wortmann 1981; Hendry and Kingsman 1991). But this ignored variance in the amount of upstream work (i.e. the indirect load), which is dependent on the position of a station in the routing of jobs. Therefore, the load contribution to a station in LUMS COR is calculated by dividing the processing time of the operation at a station by the station's position in the job's routing. This 'corrected' aggregate load method (Oosterman, Land, and Gaalman 2000) recognises that a job's contribution to a station's direct load is limited to only the proportion of the total time the job spends on the shop floor that it is actually at the station.

In addition to the above periodic release mechanism, LUMS COR incorporates a *continuous* workload trigger. If the load of any station falls to zero, the first job in the pool sequence with that station as the first in its routing is released irrespective of whether this would exceed the workload norms of any station. The continuous trigger avoids premature station idleness (see, e.g. Kanet 1988; Land and Gaalman 1998). When the continuous workload trigger releases a job, its workload contribution to a station is calculated using the same corrected aggregate load approach as used for the periodic release time element of LUMS COR.

3. Integrating due date setting and order release control

This section first develops a new approach to calculating planned release dates (Section 3.1) before we discuss how this new approach facilitates the integration of due date setting and order release control (Section 3.2).

3.1. A new procedure for calculating planned release dates

From the formalisation of our release procedure in Section 2.2, it can be observed that three variables determine the final release date of a job: the corrected workload contribution of the job, the released workload and the workload norm. The estimation of processing times – and thus the corrected workload contribution – cannot be influenced by production control. Meanwhile, the workload norm is a variable that is predetermined by management. Thus, the major determinant of the planned release date is the released workload. Therefore, at the moment that the due date is set, we calculate the projected released workload (W_{st}^R) expected for a station s at any future time t . Time is discretised in time buckets of a size equivalent to the release interval; where t is the end of the release interval. The workload is calculated similar as the actual released workload in Section 2.2, i.e. the released workload is measured in terms of the corrected workload and includes jobs released but not yet completed at station s . The difference is that the workload calculation in Section 2.2 relates to the instantaneous situation at the actual release time; whereas, in the new procedure, the workload is calculated for the projected situation at each future time t .

The set of jobs that is projected to be released at time t includes all jobs currently released and those jobs currently waiting for

release in the pool with a *planned release date* at or before t . Meanwhile, the set of jobs projected to be completed by station s at time t refers to all jobs already completed by the station plus those jobs that have an *operation due date* at or before time t . The projected released workload is then calculated based on the jobs that are projected to be released minus the jobs projected to be completed at each station.

Starting with the current release interval, the planned release date can then be determined by checking whether $\frac{p_i}{i} + W_{st}^R \leq N_s^C$ $\forall i \in R_j$ for each successive time t , until the first time t^* is found where the equation is not violated. The planned release date of job j is then given by t^* .

3.2. The order release decision as an integral part of the due date setting procedure

The procedure for determining planned release dates anticipates the periodic release decision of LUMS COR as part of the due date setting procedure. This suggests the possibility of applying a simplified release procedure, whereby jobs are released on their planned release date without further review rather than being subjected to LUMS COR again as part of an independent release decision.

A major criticism of due date based order release is that it is unable to regulate the work-in-process (Lödding 2013). For example, work is released to the shop floor when the planned release date is reached even if there is an overload; and stations can remain starving because the planned release dates of orders in the pool have not been reached. The former is overcome in our method by its finite loading mechanism, which considers capacity availability. The latter is overcome by the continuous starvation avoidance mechanism. Meanwhile, making the release decision an integral part of the due date setting procedure avoids variability between the planned release date used to determine delivery time allowances and the actual release date that would be realised by an independent release decision.

Simulation will next be used to:

- Assess the performance impact of our new approach to determining planned release dates; and,
- Compare the performance of Workload Control based on the use of two sequential and independent decision levels – one for delivery time estimation and one for order release – with the use of one decision level, i.e. as described above, where jobs are released on their planned release dates without further review, making the release decision an integral part of the due date setting procedure.

The model characteristics will be described next before Section 5 presents and discusses the results of the simulation experiments.

4. Simulation model

4.1. Overview of modelled shop and job characteristics

A simulation model of a randomly routed job shop or pure job shop (Melnyk and Ragatz 1989) has been implemented in Python© using the SimPy© module. The shop contains six stations, where each is a single resource with constant capacity.

Keeping capacity constant means that output control is not exercised as our focus is on input control. The routing length of jobs varies uniformly from one to six operations. Thus, the routing of a job is determined by first drawing the routing length (i.e. the number of stations in the routing) from a discrete uniform distribution; and, second, by selecting the stations by randomly drawing the required number from the set of stations without replacement. All stations have an equal probability of being visited and a particular station is required at most once in the routing of a job. Operation processing times follow a truncated 2-Erlang distribution with a maximum of 4 time units and a mean of 1 time unit after truncation. Set-up times are considered sequence independent and part of the operation processing time. Sequence independence is required to ensure an equal throughput of work across experiments. The arrival of orders follows a stochastic process. The inter-arrival time of jobs follows an exponential distribution with a mean of 0.648, which – based on the average number of stations in the routing of a job – deliberately results in a utilisation level of 90%. These settings facilitate comparison with earlier studies on both WLC (e.g. Oosterman, Land, and Gaalman 2000; Thürer et al. 2012, 2014a) and due date setting (e.g. Thürer et al. 2013).

4.1.1. Stochastic processing times – simplifying the need for processing time estimates

As in previous simulation studies on WLC (e.g. Melnyk and Ragatz 1989; Land and Gaalman 1998; Cigolini and Portioli-Staudacher 2002; Fredendall, Ojha, and Patterson 2010; Thürer et al. 2014a), it is assumed that materials are available and all necessary information regarding shop floor routing is known upon the arrival of a job. Previous simulation studies have also generally assumed that processing times are known upon arrival; i.e. deterministic. This is unlikely to be the case in practice. Therefore, we also include experiments in which realised processing times remain unknown; i.e. stochastic. Stochastic processing times are typically modelled in the literature by surrounding the processing time estimate used at the planning stage by a stochastic element. The processing time estimate itself remains thereby at a high level of accuracy. We argue that this does not reflect practice where high variability between processing time estimate and realised processing time actually leads to a simplified procedure for processing time estimation.

Thürer, Land, and Stevenson (2014b) recently demonstrated that the need for processing time estimations at order release can be simplified by grouping processing times into classes. For example, with three classes, it becomes only necessary to distinguish between small, medium and large processing times, where each class represents a certain range of load contributions. Rather than using the exact workload contribution in the load calculation, a class average is used to estimate this workload contribution. Therefore, in addition to the scenario where realised processing times are known when the planning process takes place (deterministic), we will also experiment with 2, 3, 4 and 5 predetermined classes to evaluate the influence of processing time uncertainty. For these experiments, management does not know the realised processing times (which follow a 2-Erlang distribution) but uses a rough-cut estimate (e.g. small, medium and large for three classes). In doing so, we will assess the robustness of our results to uncertainty in processing time estimates. Table 1 summarises

Table 1. Definition of the different processing time classes used in this study.

	Class configuration ^a /(%)	Average contribution in the interval; and the range of contributions represented by each class				
Full processing times	2/50	0.48 (0, 0.85]	1.52 (0.85, 4]			
	3/33	0.36 (0, 0.60]	0.86 (0.60, 1.15]	1.79 (1.15, 4]		
	4/25	0.30 (0, 0.49]	0.66 (0.49, 0.85]	1.08 (0.85, 1.36]	1.97 (1.36, 4]	
	5/20	0.26 (0, 0.42]	0.56 (0.42, 0.70]	0.85 (0.70, 1.02]	1.24 (1.02, 1.51]	2.10 (1.51, 4]
Corrected load	2/50	0.18 (0, 0.36]	0.88 (0.36, 4]			
	3/33	0.13 (0, 0.23]	0.37 (0.23, 0.54]	1.10 (0.54, 4]		
	4/25	0.11 (0, 0.18]	0.26 (0.18, 0.36]	0.50 (0.36, 0.69]	1.26 (0.69, 4]	
	5/20	0.09 (0, 0.15]	0.21 (0.15, 0.28]	0.36 (0.28, 0.46]	0.61 (0.46, 0.81]	1.39 (0.81, 4]

^aNumber of classes/percentage represented by each class.

the classes and the range of workload contributions represented by each class for the full processing time and the corrected load.

The ranges of contribution for each class were deliberately chosen such that each range would represent an equal percentage of the load contributions. These ranges and the average contribution in each range could be determined analytically for the full processing times. As the corrected load divides these processing times by the routing position resulting from another stochastic process, the ranges for the corrected load contributions have been determined numerically. Of course, in practice, classes will not be determined this exactly, but additional experiments have shown that our results are highly robust to the choice of range.

4.2. The due date determination procedure

A due date is determined when a job arrives. In addition to our new approach to setting planned release dates (as outlined in Section 3.1), we also include the approach presented in Land (2009) – see Section 2.1.1 – as a benchmark. Both rules apply the same method for setting allowances for the operation throughput times and the external allowance, as identified in Section 2.1.2 and 2.1.3 above. They differ in the way that the pool waiting time and, consequently, the planned release date is estimated.

As in previous research, the time buckets for determining the allowances for the operation throughput times are set to 1 time unit (e.g. Thürer et al. 2013, 2014a). The external allowance was set through preliminary simulation experiments such that the average of the quoted delivery lead time is 30 time units for all experiments. The quoted delivery lead time is defined as the customer due date minus the time when the job was received.

4.3. Order release control

Once the due date is determined, the job flows into the pre-shop pool to await release. Two approaches to controlling the release of jobs are considered: (i) two-level WLC, where the periodic release decision is taken independently from the due date setting procedure according to LUMS COR (see Section 2.2); and (ii) integrated WLC, where the periodic release decision is taken as part of the due date setting procedure and jobs are released on their calculated planned release dates without further review. The time interval between releases for the periodic part of order release is set to 4 time units. Eight workload norm levels are applied, ranging from 5 to 12 time units. As a baseline measure, experiments without controlled order release have also been executed, i.e. where jobs are released onto the shop floor immediately upon arrival.

4.4. Priority dispatching on the shop floor

For the due date setting rules to be effective, the dispatching rule applied on the shop floor should be related to the way in which operation due dates are determined. This ensures that capacity control takes place, i.e. that capacity is used as planned (see, e.g. Bertrand 1983a). Therefore, the job with the earliest operation due date (as calculated by the due date setting procedure) is chosen from the queue in front of a station.

4.5. Experimental design and performance measures

The performance of WLC based on one decision level will be compared with the use of WLC based on two decision levels. Two different versions of WLC based on two decision levels will be simulated to compare our new planned release date calculation (Section 3.1) with the calculation proposed in Land (2009), as specified in Section 2.1.1. Thus, in total, three approaches – as summarised in Table 2 – will be used: two-level WLC Land, two-level WLC and integrated (single-level) WLC. Eight workload norm levels and five levels of classes for processing time estimates (deterministic and stochastic with 5, 4, 3, and 2 classes) are considered for each approach, resulting in an experimental design with 120 cells, where each cell is replicated 100 times. Results are collected over 10,000 time units following a warm-up period of 3000 time units. These parameters allow us to obtain stable results while keeping the simulation run time to a reasonable level.

Four main performance measures are used to assess both workload balancing and delivery performance: (i) the lead time (i.e. the time when a job is completed minus the time when it arrived at the company); (ii) the percentage of tardy jobs; (iii) the mean tardiness; and (iv) the standard deviation of lateness. The *average lead time* is used as the main indicator of the workload balancing capabilities of the approaches being tested. It also reflects the average lateness of jobs, which can be derived directly from this measure and is equal to the average of the realised lead time minus the average of the quoted delivery lead time (which is 30 time units across all experiments). The main indicators of delivery performance are the *percentage of tardy jobs* and the *mean tardiness*, which are influenced by both the average lateness and the dispersion of lateness across jobs, as measured by the *standard deviation of lateness*. In addition to these four main performance measures, we also measure the *average shop floor throughput time* as an instrumental performance variable. While the overall lead time includes the time that a job waits in the pool

Table 2. Summary of the different approaches to workload control applied in this study.

Workload control (WLC) approach	Calculation of planned release dates during the due date setting procedure	Order release	
		Periodic element	Continuous element
Two-level WLC Land	The planned release date is calculated based on the maximum of the load waiting to be released to a station across the stations in the routing of a job; based on Land (2009)	The release decision is taken independently at order release; jobs are released up to the workload norm	All equal; jobs are pulled onto the shop floor if a station is starving in-between periodic reviews
Two-level WLC	The planned release date is determined by forward finite loading, fitting the projected released workload into the workload norms	The release decision is taken independently at order release; jobs are released up to the workload norm	
Integrated WLC	The planned release date is determined by forward finite loading, fitting the projected released workload into the workload norms	The release decision is anticipated when due dates are set; jobs are released on their planned release date, as calculated by the due date setting rule	

prior to release, the shop floor throughput time only measures the time after release to the shop floor. According to Little's law (Little 1961), the shop floor throughput time is linked directly to the level of work-in-process. All of these performance measures are job related. This is justified by the fact that the throughput of work (and thus the major shop related performance measure) is kept equal across experiments to ensure comparability.

5. Results

Statistical analyses of our results were conducted using an ANOVA based on a block design. The different approaches to WLC and the workload norm level are both blocking factors since each approach to WLC and each norm level can be considered a different system. Thus, ANOVA was restricted to the main effects of the three experimental factors considered in this study. All were shown to be statistically significant except the norm level factor for the lead time results. The significance of the differences between the outcomes of individual experiments has also been verified by paired *t*-tests, which comply with the use of common random number streams to reduce variation across experiments. Whenever we discuss a difference in outcomes between two experiments, the significance can be proven by a paired *t*-test at a level of 97.5%.

Section 5.1 provides detailed performance results for the scenario with deterministic processing times. This includes an in-depth analysis of the performance differences observed. Section 5.2 then assesses the robustness of the results by focusing on the experiments where the need for processing time estimates is simplified.

5.1. Performance assessment under deterministic processing times

Figure 1(a)–1(d) present our results under deterministic processing times for the lead time, the percentage tardy, the mean tardiness and the standard deviation of lateness over the throughput time results, respectively. The results are presented in the form of performance curves, where the left-hand starting point of each curve represents the tightest workload norm level (5 time units). The workload norm increases stepwise by moving from left to right, with each data point representing one norm

level (from 5 to 12 time units); loosening the norms increases the workload levels and, as a result, the throughput times on the shop floor become longer. In addition, the result obtained with IMMEDIATE release (IMM) is shown as a single point labelled 'X'. It is located to the right of the curves as it leads to the highest level of throughput times on the shop floor.

By comparing the performance of two-level WLC Land with two-level WLC, it can be observed that our new approach to estimating planned release dates that is incorporated in two-level WLC significantly enhances performance across all measures considered in this study when compared to the approach proposed by Land (2009). However, the improvement that warrants the most attention is the strong impact on tardiness performance when due date setting and order release are integrated, which can be observed by comparing the performance of two-level WLC with that of integrated WLC. For example, a comparison of their performance in terms of the percentage tardy (Figure 4(b)) and mean tardiness (Figure 4(c)) at the point where both reduce the throughput time by 35% compared to immediate release (from 20.5 to 13.2 time units) shows that integrated WLC reduces the percentage tardy by more than 50% (from 2.9 to 1.3%) and the mean tardiness by more than 90% (from 0.31 to 0.02). This improvement in tardiness performance is due to the large reduction in the standard deviation of lateness. At this point of throughput time reduction, integrated WLC reduces the standard deviation of lateness by 35% when compared to two-level WLC (from 6.9 to 4.3 time units) at the expense of only a 5% increase in the lead time (from 20.3 to 21.1 time units), which is due to a reduced load balancing capability. This raises the following question: *Why is the standard deviation of lateness for integrated WLC so much lower than for two-level WLC?*

5.1.1. Performance analysis: two-level WLC vs. integrated WLC

Both two-level WLC and integrated WLC use the same method for calculating planned release dates. This method schedules the release of jobs into a release interval that should allow for their release on the planned release date. However, under two-level WLC, the planned release date only determines the sequence in which jobs are considered for release. A job is only released when it actually fits the norm at this moment in time. A minor deviation from the schedule may prevent the release of a job on its planned release date. If a job is not released on its planned

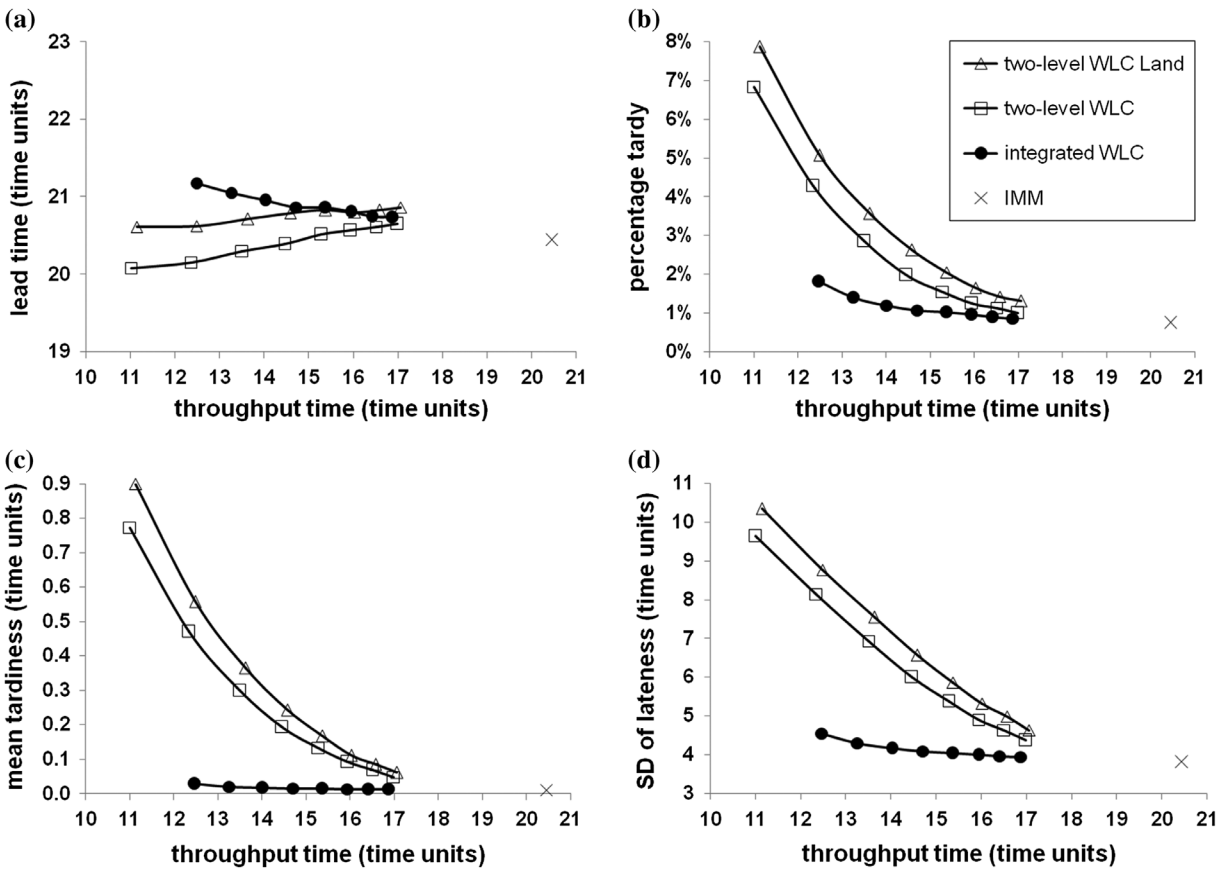


Figure 1. Performance comparison for deterministic processing times: (a) lead time; (b) percentage tardy; (c) mean tardiness; and (d) standard deviation of lateness over the shop floor throughput time.

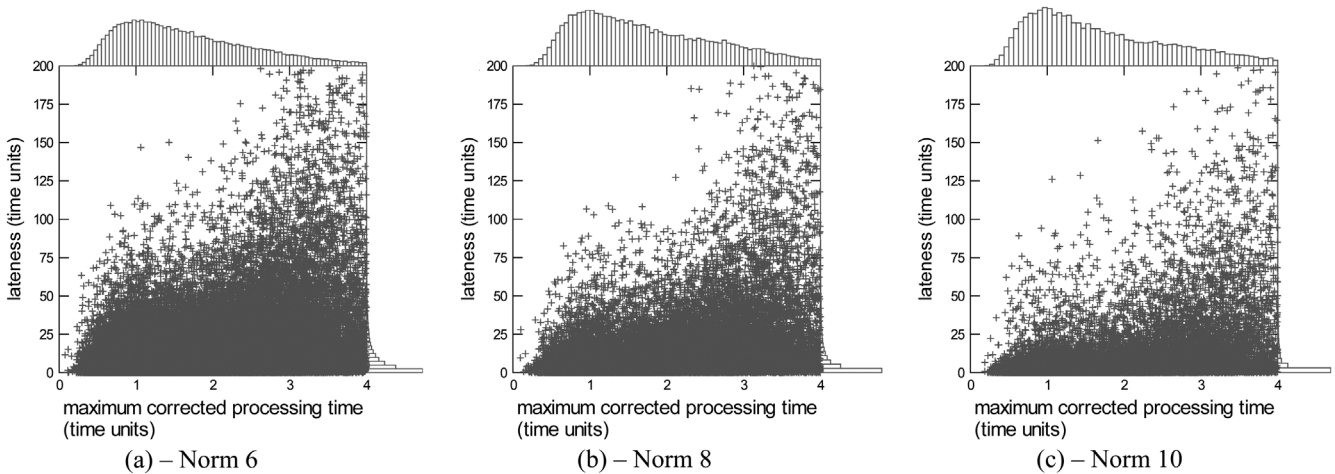


Figure 2. Scatter plot of tardy jobs showing the relationship between the maximum corrected processing time in the routing of a job and lateness for two-level WLC.

release date, it may become difficult to fit within the norm again. This can increase the size of the deviation between the planned and actually realised release date, especially for jobs with large corrected processing times, because:

- (i) The average capacity available at each station per release interval – measured in corrected processing times – is only 4 time units divided by 2.67, i.e. the average position of a station in the routing of jobs; and,

- (ii) LUMS COR releases all of the work that fits within the norm each release interval, even though a large job with an earlier planned release date may be left waiting because it does not fit within the norm. The released jobs replenish the load back up to the norm level and may then block the release of the large job at the next release interval, particularly in periods when many jobs arrive to the system.

To illustrate the above effect, we recorded the properties of all tardy jobs for two-level WLC and for integrated WLC. First, the scatter plots for job lateness vs. the maximum corrected processing time across all operations in the routing of a job are given for two-level WLC in Figure 2(a)–2(c) at a norm level of 6, 8 and 10

time units, respectively. Each scatter plot also gives the frequency distribution in the form of a histogram.

It can be observed that there is a significant number of jobs suffering from high tardiness at all three norm levels. Further, jobs with an operation in their routing that has a large corrected

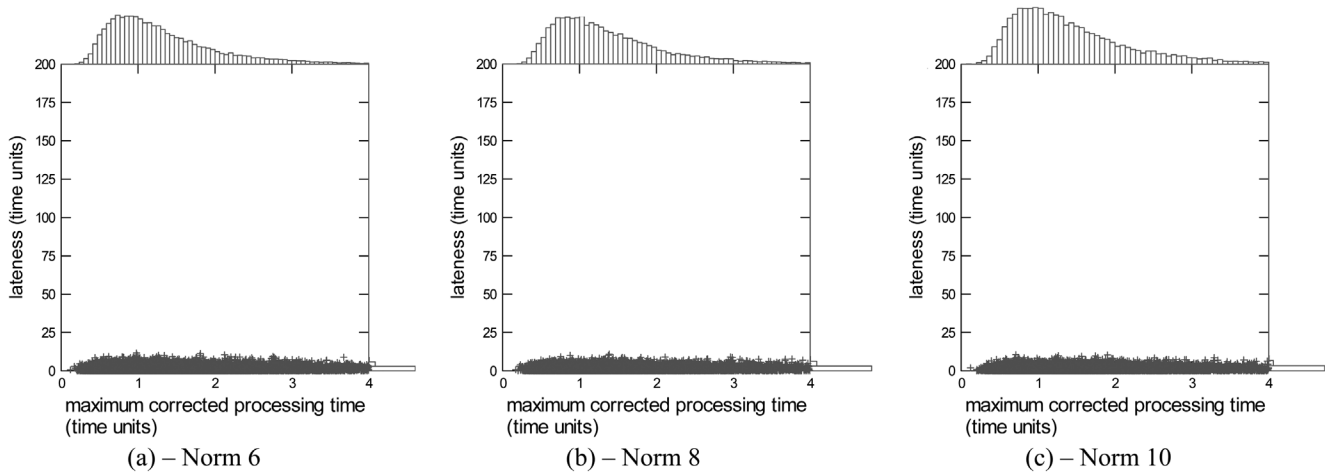


Figure 3. Scatter plot of tardy jobs showing the relationship between the maximum corrected processing time in the routing of a job and lateness for integrated WLC.

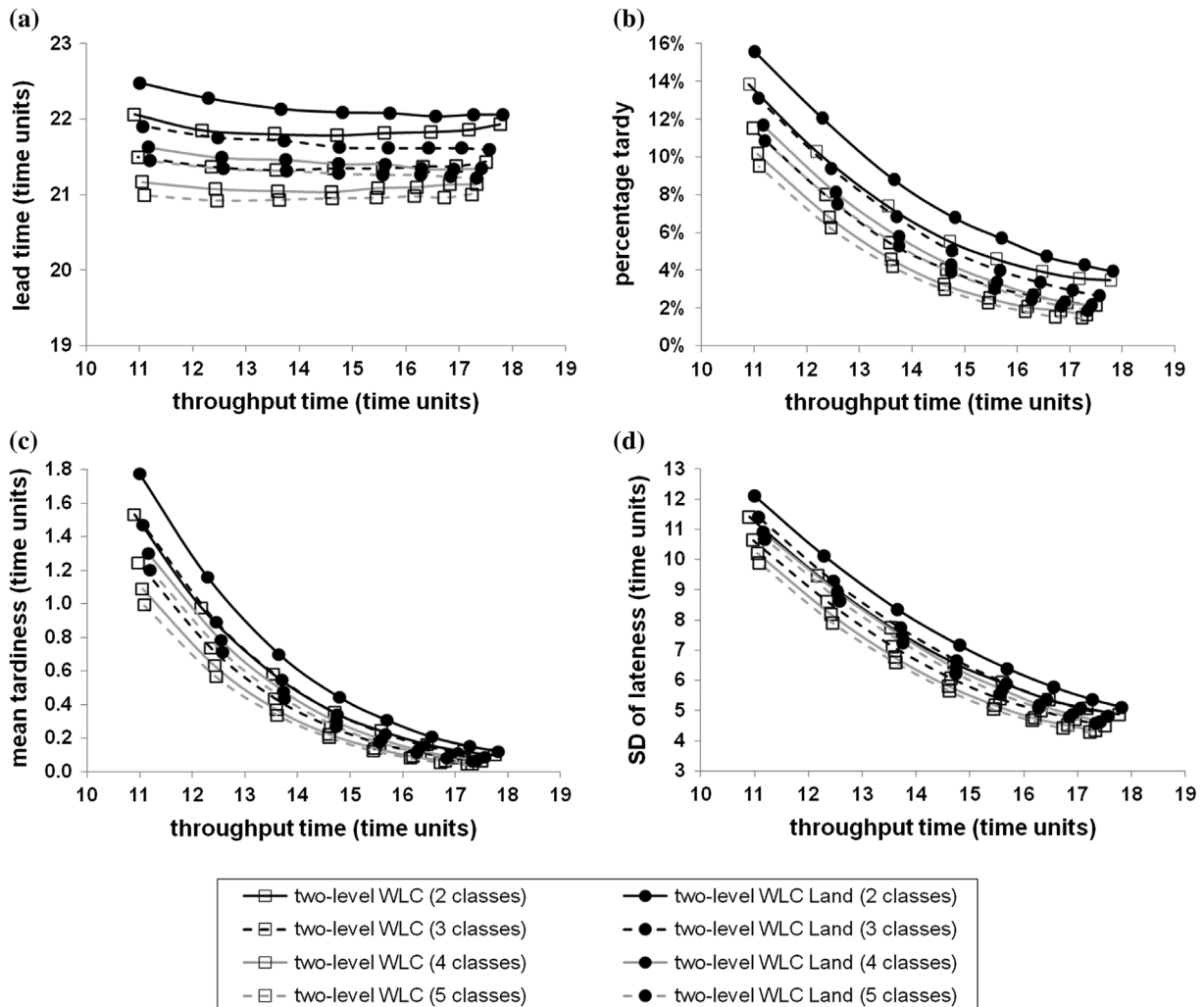


Figure 4. Performance comparison for simplified processing time estimations (two-level WLC vs. two-level WLC Land): (a) lead time; (b) percentage tardy; (c) mean tardiness; and (d) standard deviation of lateness over the shop floor throughput time.

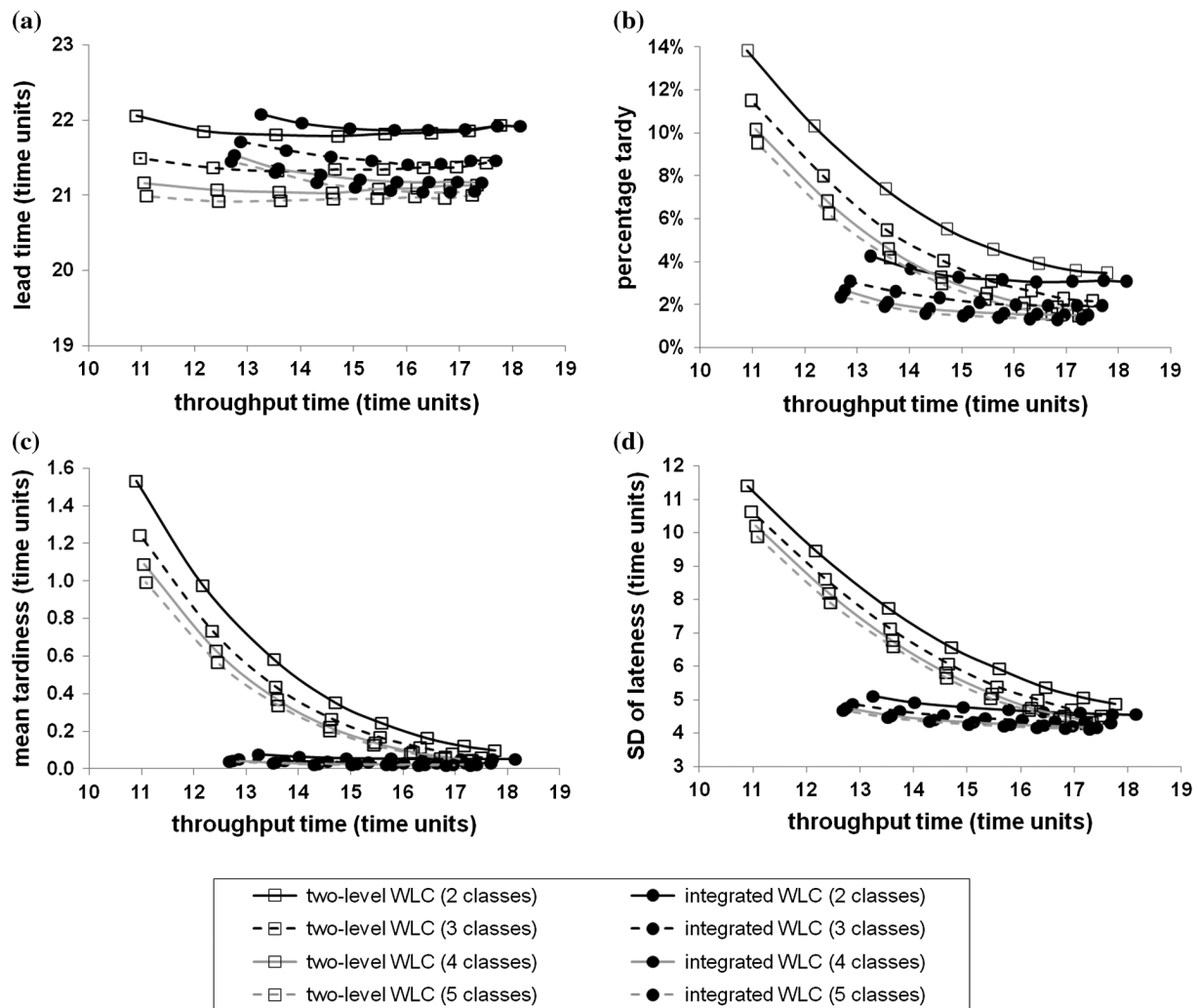


Figure 5. Performance Comparison for simplified processing time estimations (two-level WLC vs. integrated WLC): (a) lead time; (b) percentage tardy; (c) mean tardiness; and (d) standard deviation of lateness over the shop floor throughput time.

processing time have an increased risk of extreme tardiness. The correlation coefficient between pool lateness and final lateness is 0.959, 0.944 and 0.924 for N6, N8 and N10, respectively, where pool lateness is defined as the difference between the realised and planned release date. This strongly supports the argument that job lateness is due to tardy release from the pool. The same scatter plots for integrated WLC – see Figure 3(a)–3(c) – demonstrate that the extent of tardiness can be controlled if jobs are released on their planned release dates.

5.2. Robustness of results: simplifying the need for processing time estimates

From the results in Section 5.1, it can be concluded that: (i) our new approach to estimating planned release dates enhances performance compared to the existing approach from the literature (two-level WLC vs. two-level WLC Land) across all measures considered in this study; and (ii) integrated (single-level) WLC outperforms two-level WLC on tardiness performance. But both of these conclusions rest on the assumption that processing times are known during the planning process; i.e. deterministic.

This is often not realisable in practice, e.g. due to the high-variety production environment typical of job shops and/or the high investment costs required to achieve high levels of accuracy. Therefore, additional experiments have been conducted in which the need for processing time estimations is simplified by grouping processing times into classes (i.e. processing times are stochastic), as described in Section 4.1.1. Estimates represent a certain range of load contributions, rounded to the estimated average in that range, rather than representing the exact workload contribution of a job. For example, with three classes, a manager need only estimate whether a processing time is small, medium or large.

The resulting performance curves for 2, 3, 4 and 5 classes are presented in Figures 4 and 5. Figure 4 presents the results for two-level WLC and two-level WLC Land. Meanwhile, Figure 5 presents the results for two-level WLC and one-level WLC. The results show the expected decreasing marginal effect, e.g. the improvement from 4 to 5 classes is smaller than the improvement from 2 to 3 classes. Most importantly, the results confirm that the performance effects observed in Section 5.1 are robust to uncertainty in processing time estimates.

6. Conclusion

If order release is controlled, then the realised delivery time can be split at the release date into two parts: the pool waiting time prior to release; and the shop floor throughput time after release. Both parts have to be considered when setting delivery time allowances or due dates. Yet, prior literature concerned with due date setting in job shops where order release is controlled has typically assumed the immediate release of jobs or used a constant allowance for the pool waiting time. This limits the applicability of due date setting rules previously presented in the literature. In response, this study has developed a new approach to setting planned release dates for integration into WLC's due date setting procedure and demonstrated its effectiveness through simulation. Our approach to estimating planned release dates is unique in that it anticipates WLC's load-limiting order release decision as part of the due date setting procedure. This means that a second independent release decision becomes superfluous. Making the release decision an integral part of the due date setting procedure – by actually releasing all jobs on their planned release dates without further review – means that deviations between planned and realised release dates are avoided. Our analysis revealed that these deviations are a major cause of tardiness for systems with two independent control levels. As a result, for a throughput time reduction of 35% compared to immediate release, 50% fewer tardy jobs and a mean tardiness reduction of more than 90% could be observed for integrated (single-level) WLC compared to two-level WLC. These results make a compelling argument for a paradigm shift in the literature away from treating due date setting and order release control as two independent decision levels.

6.1. Limitations and future research directions

This research has demonstrated that deviations between the planned release date used to determine the delivery time allowance and the actual realised release date are a major cause of tardiness. These deviations can be avoided if the release decision is anticipated when due dates are set and jobs are released on their planned release dates. This finding questions a fundamental assumption in the literature on production planning and control, i.e. that due date setting and order release are two independent decision levels, where the former precedes the latter. As a consequence, this study calls for a paradigm shift: to recognise the potential of the release decision being an integral part of the due date setting procedure.

There are however some limitations. First, while our results were shown to be robust to uncertainty in processing times, we did not explicitly consider factors such as scrap or station breakdowns. These factors may impact throughput and thus hinder the creation of comparable experiments for our two WLC methods. This also explains why we did not consider sequence dependent set-up times. Future research is therefore required to address these issues. Second, we considered a constant station capacity. In practice, managers often use capacity adjustments to 'catch-up' with the plan. This may make performance improvements for integrated WLC less striking or may even re-balance results in favour of two-level WLC. Future research is therefore required

to assess whether integrated WLC also maintains its advantage when capacity control is exercised.

Finally, another important avenue for future research concerns Advanced Planning and Scheduling (APS) systems (see, e.g. Stadtler and Kilger 2005). One of the key features of an APS system is Finite Capacity Scheduling, a module that is designed to overcome the weaknesses of Material Requirements Planning logic. Similar to our approach, an APS system integrates decision-making, but it is intended for large-scale production environments. Our study may provide an important search direction for extending the applicability of APS systems to smaller scale, complex job shop environments.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Natural Science Foundation of China [grant number 71550110254].

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