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Card-based delivery date promising in high-variety manufacturing with order release control

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ABSTRACT

Card-based systems – like Kanban and Constant Work-in-Process (ConWIP) – can be simple yet effective means of controlling production. Existing systems, however, can be criticized for their limited applicability and scope. First, card-based systems have not been successful in the production environments that are arguably most in need of their help: complex job shops that produce low-volume, high-variety products. Second, while most existing systems simplify shop floor control, other planning tasks – such as the estimation of short, feasible due dates during customer enquiry management – are not supported. To overcome these limitations, a card-based version of Workload Control – known as COBACABANA (COntrol of BALance by CARd-BASEd Navigation) – was recently proposed that uses cards for both due date estimation and order release control. This unique combination makes COBACABANA a potentially important means of controlling production, particularly for small job shops with limited resources. However, the original approach had several shortcomings. This paper refines the due date estimation procedure of COBACABANA to make it more practical and consistent with the order release method applied. It then uses simulation to demonstrate – for the first time – the potential of COBACABANA as an integrated concept that combines customer enquiry management and order release control to improve job shop performance. Results also suggest that the need for processing time estimations can be simplified, further facilitating the implementation of COBACABANA in practice.

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1. Introduction

Card-based systems, such as Kanban (e.g. Sugimori et al., 1977; Shingo, 1989) and Constant Work-in-Process (ConWIP; e.g. Spearman et al., 1990; Hopp and Spearman, 1996), provide a simple, visual approach to controlling production and have helped repetitive manufacturers reduce costly buffers while maintaining short lead times. However, researchers and practitioners have reported that these card-based systems are not equally effective in job shops producing a high variety of made-to-order, customized products (e.g. Germs and Riezebos, 2010; Harrod and Kanet, 2013). Even Paired cell Overlapping Loops of Cards with Authorization (POLCA; e.g. Suri, 1998; Riezebos, 2010), which was designed to

cope with more variability than Kanban and ConWIP, still requires a certain degree of repetitiveness in order to be effective. Hence, to date, simple card-based production control systems have not been successful in complex job shops. But these shops are often small firms and, therefore, arguably in most need of card-based support since other solutions require an investment in expert knowledge and advanced technology that exceeds their resources. Moreover, existing card-based systems are restricted to controlling either the release of orders to the shop floor, e.g. ConWIP, or to controlling both order release and order progress on the shop floor, e.g. Kanban and POLCA. They do not support other planning tasks, such as due date estimations during customer enquiry management. This limits the advantage of using a simple, card-based control system and requires companies to maintain sophisticated planning and control processes to support these other tasks.

Production control in job shops that produce customized products to order is very challenging since finished goods cannot be stocked in advance of demand and detailed order specifications, e.g. processing and set-up times, are often uncertain as it may be the first time that an order has been placed. This makes many approaches to production planning and control presented in the

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literature, such as optimized scheduling approaches, unfeasible. In general, few production planning and control systems – irrespective of whether they are card-based or otherwise – have been developed that are suitable for such contexts (e.g. [Stevenson et al., 2005](#)). One exception is the originally non-card-based Workload Control concept, which has been demonstrated to improve job shop performance through simulation (e.g. [Thürer et al., 2012, 2014a; Fernandes et al. 2015](#)) and action research (e.g. [Hendry et al., 2013](#)). To use Workload Control, a manager must make complex workload calculations, which typically requires both an investment in software, to provide a decision support system, and an investment in hardware (e.g. barcode scanners) to collect data from the shop floor (see, e.g. [Stevenson and Silva, 2008; Hendry et al., 2013](#)). These complex calculations and the prerequisites for implementation affect Workload Control's suitability, particularly for small shops with limited resources. As a result, many studies have found implementing Workload Control in practice to be extremely challenging (e.g. [Stevenson, 2006; Hendry et al., 2008; Stevenson et al., 2011](#)).

In response to the need for simple, visual production control, [Land \(2009\)](#) developed COBACABANA (COntrol of BALance by CARD-Based NAVigation), which is a card-based approach for embedding the core principles of Workload Control. These principles are to: (i) stabilize the workload; and, (ii) ensure there is a short yet feasible allowance for the delivery time. COBACABANA operationalizes these principles by first controlling the release of orders to the shop floor and, second, by using the higher level customer enquiry management procedure to accept/reject orders and ensure appropriate delivery time allowances. Hence, COBACABANA is unique in that it incorporates card-based due date determinations during customer enquiry management and a card-based order release control system. Many rules for determining due dates in job shops have been presented (e.g. [Weeks, 1979; Ragatz and Mabert, 1984; Thürer et al., 2013](#) for a recent review), but effective rules typically require software support. In contrast, and to the best of our knowledge, COBACABANA represents the first card-based approach to estimating due dates. As it is card-based, COBACABANA does not require software support.

Although COBACABANA provides a potential card-based solution for small job shops with limited resources, [Land's \(2009\)](#) original approach suffers from several shortcomings, which are addressed here. More specifically, this study refines COBACABANA's customer enquiry management stage, including its due date estimation procedure. It then demonstrates the effectiveness of our refinements and – for the first time – the potential of COBACABANA as an integrated concept to improve performance in job shops using simulation.

The remainder of this paper is organized as follows. COBACABANA is first described and then refined in [Section 2](#). [Section 3](#) outlines the job shop simulation model used to examine its performance, before the results are presented and discussed in [Section 4](#). Finally, concluding remarks are made in [Section 5](#), where managerial implications and future research directions are also outlined.

2. COBACABANA – a simple card-based approach to workload control

COBACABANA is based on the Workload Control concept, which integrates two control levels: order release and customer enquiry management. These two levels will be discussed in [Sections 2.1 and 2.2](#), respectively before [Section 2.3](#) summarizes COBACABANA as a comprehensive concept.

Fig. 1. Card-based order release with loops between the central planner and stations on the shop floor.

2.1. COBACABANA: card-based order release

Workload Control stabilizes the shop floor workload using order release control to decouple the shop floor from a pre-shop-pool of orders. Orders are released from the pool onto the shop floor in time to meet their due dates while keeping the shop floor workload balanced. The order release method outlined here follows the refinements proposed by [Thürer et al. \(2014b\)](#) to [Land's \(2009\)](#) original card-based concept; being its potential to improve performance in high variety contexts recently been demonstrated in [Thürer et al. \(2014b and 2015\)](#).

COBACABANA establishes card loops between the planner performing the order release decision and each station on the shop floor, as illustrated in [Fig. 1](#). At fixed (periodic) intervals, orders in the pool are sorted according to their planned release dates. Orders are then considered for release in sequence.

Each operation in a job has one *release card* and one *operation card*. The size of the release card represents the corrected workload of the operation (as described in [Section 2.1.1](#) below). To consider an order for release, the planner places the release card that corresponds to the corrected workload of the order at each station in its routing in each station's area on the planning board. The planner then compares the station workloads with the pre-determined workload limits or norms. If, for any station in the routing of an order, the workload represented by the release cards on the planning board exceeds 100% of the workload limit, the order is retained in the pool and the order's release cards are removed from the planning board. Otherwise, the order's release cards remain on the planning board, the planner attaches the corresponding operation cards to an order guidance form that travels with an order through the shop, and the order is released. This process continues until there are no unexamined orders in the order pool. The shop floor returns each operation card to the planner as soon as the operation is completed. This closes the information loop and signals the planner can remove the release card that matches the operation card from the planning board. This process could be simplified by color coding the cards, so that each station is represented by a color, similar to POLCA ([Riezebos, 2010](#)).

[Fig. 2](#) illustrates how the planning board is used when making a release decision. In this example, a new order with two operations is considered for release: one operation at Station 1 and one at Station 3. In this example, since both operations can be loaded into their respective stations without exceeding the workload norm,

Fig. 2. Planner's planning board for order release (with an example release).

the order is released and its corresponding operation cards are sent to the shop.

In addition to the periodic release mechanism, COBACABANA incorporates a continuous workload trigger. If the direct load of any station falls to zero (i.e. a station becomes idle), the first order in the pre-shop pool that has the idle station first in its routing is released irrespective of whether this exceeds any workload norms at other stations. This avoids premature idleness (Kanet, 1988; Land and Gaalman, 1998) that can occur when strictly enforcing workload norms during periodic releases.

2.1.1. Workload measure applied: the corrected aggregate load method

Early studies on Workload Control typically compared the aggregate load of a station (i.e. the sum of all of the processing times of jobs released but not yet completed by a station) with the workload norm (Bertrand and Wortmann, 1981; Hendry and Kingsman, 1991). The aggregate load ignores the likelihood that much of this load will be indirect (i.e. it includes work still upstream of the station) and that the actual arrival of an order depends on the position of a station in the job's routing. COBACABANA uses the *corrected* aggregate load method to address this issue (Oosterman et al., 2000). This approach divides the operation processing time by the station's position in the job's routing. This recognizes that the operation card for the second operation stays on the shop floor about twice as long as the operation card for the first operation.

2.2. COBACABANA: card-based customer enquiry management

Customer enquiry management performs two functions within Workload Control. First, it stabilizes the planned workload by controlling the acceptance/rejection of orders. Second, it ensures short, feasible delivery time allowances or due dates. In fact, Thürer et al. (2014a) demonstrated that these two functions can be combined by ensuring due dates are feasible and reflect a firm's actual operational capabilities.

Order release divides the planned workload into two parts: the load in the pre-shop pool and the load on the shop floor. So, the allowance for the time the job spends in the system can be divided into an allowance for the pool waiting time and an allowance for the operation throughput times on the shop floor. COBACABANA uses order release to control the amount of work on the shop floor so only the pre-shop pool waiting time is considered to vary; the allowance for the operation throughput time is considered constant. This substantially reduces the requirements for information from the shop floor during customer enquiry management and

Fig. 3. Salesperson's display for customer enquiry management (as in Land, 2009).

allows COBACABANA to estimate due dates using cards. COBACABANA estimates the due date (d_j) of a newly arrived job j at time t by Eq. (1), where α is a variable allowance for the time that the order has to wait in the pre-shop pool prior to release; β_i is a constant to allow for the operation throughput time of each operation i in the routing R_j of the order; and, γ is an allowance for external variability between the calculated delivery time and the ultimately realized delivery time.

$$d_j = t + \alpha + \sum_{i \in R_j} \beta_i + \gamma \quad (1)$$

2.2.1. The due date estimation procedure from Land (2009)

Land (2009) introduced the first card-based system to not only control the shop floor but also support due date estimations at customer enquiry management. Land's (2009) original due date estimation procedure determined an appropriate allowance for the pool waiting time using *acceptance cards*, where each acceptance card represented a fixed amount of workload. When an order arrived, the planner drew enough acceptance cards from the salesperson's display (see Fig. 3) to reflect the workload contribution of each operation in the order's routing. Cards were attached to the order and later returned to the salesperson's display once the order was released. Hence, the total number of acceptance cards withdrawn from the display at any moment in time indicated the current pool load for each station. Following Little's Law (Little, 1961), and recognizing that the bottleneck controls the process, the expected waiting time prior to release was indicated by the total processing time units waiting in the pool to be released to the most constrained station, i.e. the station in the job's routing with the largest load in the pre-shop pool.

Land's (2009) extension of the use of cards to due date estimations made an important contribution to simple, visual production control for small job shops with limited resources. But the original due date estimation procedure has three main weaknesses:

- Multiple cards are required to represent the workload of a single operation, which means that a large number of cards travel with an order.
- It assumes that jobs can be released at any moment in time, although most releases occur periodically at fixed time intervals.
- It estimates a job's expected pool waiting time by using the long run average rate at which work is released to the shop floor and ignoring the short-term effects of the workload norm.

These shortcomings will be discussed further in Sections 2.2.2–2.2.4 below, where we also outline how we refined COBACABANA

in response. Section 2.2.5 then summarizes the resulting due date estimation procedure to be used for customer enquiry management.

2.2.2. COBACABANA refined: limiting the number of cards at customer enquiry management

Each acceptance card in Land's (2009) original due date estimation procedure represents a fixed workload amount, so an order typically requires multiple cards per operation to reflect its workload. For an order with a high workload and/or long routing length, the number of cards soon becomes impractical. The same problem existed at the order release stage until Thürer et al. (2014b) introduced cards of different sizes, where the card size indicates the workload contribution. The same principle is extended here to customer enquiry management. Since we cannot know the required card sizes in advance, the salesperson's display is inverted such that acceptance cards on the display represent the workload contribution of pool jobs rather than this being represented by the cards missing from the display. Meanwhile, as the pool load is represented by acceptance cards on the display, each card has to be duplicated to allow for feedback from the pool. The duplicate will be referred to as the "pool card". One pool card per operation (or per job if all operations are released at once) travels with the order to the pool and is fed-back to the salesperson at release.

2.2.3. COBACABANA Refined: Implications of the Periodicity of Release

Land's (2009) original due date procedure allowed planned release dates to occur anytime. But unless a station is starving (triggering COBACABANA's continuous release element), an order arriving has to wait in the pool until at least the next periodic release. This periodicity should be reflected when calculating due dates. Therefore, the scale on the display should measure the average release rate per release interval.

2.2.4. COBACABANA refined: considering short-term fluctuations

Land (2009) used the full processing time units actually waiting in the pool for the station most likely to restrict an order's release and the average output rate of a station to calculate the expected pool waiting time using Little's Law (Little, 1961). However, there may be significant differences between the short-term rate at which work is released and the average rate at which it is processed on the shop floor (the output rate). In the short term, actual order release is restricted by the workload norm measured in units of corrected processing time. Since the corrected aggregate workload responds to routing mix fluctuations, the amount of work (measured in processing time units) that can be released at each periodic release decision may vary. For example, if a station is the initial station in the routing of many jobs, then using the corrected norms may temporarily but significantly restrict the work that can be released to this station. To account for these short term fluctuations, it is argued that COBACABANA should use acceptance cards to represent the corrected workload accumulated in the pool. Consequently, the scale should represent the average release rate in corrected processing time units per release interval. While Land's (2009) approach should yield better estimates for long pool waiting times, the new approach should improve estimation accuracy for short pool waiting times.

The design of COBACABANA should also recognize that a station's cumulative workload may be below its workload norm at the end of a periodic release procedure, which would indicate the potential to release more work at the next release decision. For example, if the corrected aggregate load of a station is zero at the moment that the release decision takes place, the whole workload norm can be filled up. Thus, the release rate for the current release

Fig. 4. Card-based customer enquiry management – the salesperson's display.

interval should be adjusted in accordance with the load gap after the preceding release decision.

2.2.5. Summary of the refined due date estimation procedure

COBACABANA establishes card loops between customer enquiry management and the pre-shop pool. There is a pair of cards – one acceptance card and one pool card – per operation. The acceptance cards are used to visualize the workload waiting in the pre-shop pool. The size of each acceptance card reflects the operation's workload contribution to a particular station on the salesperson's display. Using Little's Law, the pool waiting time is estimated by the corrected workload in the pool – as represented by the acceptance cards – for the station most likely to restrict the order's release and the average release rate measured in terms of the corrected processing time per release interval, as represented by the scale. The scale is moveable to reflect the possibility of releasing more work during the current release interval if the norms were not completely filled up during the last release. This feedback can be provided with the pool cards of the released orders.

An example is shown in Fig. 4, where an order has two operations: one at Station 1 and one at Station 2. Since Station 1 has the largest corrected aggregate load waiting in the pool (including the workload contribution of the order), it becomes the basis for estimating the pool waiting time. The pool load contribution of the order falls into the third release interval, which means it can take up to three more release intervals before the order is actually released. The allowance for the pool waiting time α is then given by adding three release intervals to the time until the next release date. Once a due date has been determined, the pool card(s) are attached to an order guidance form and the order moves into the pool. When the planner has released the order, the pool card(s) come back to the salesperson and the corresponding acceptance cards are withdrawn from the salesperson's display.

2.3. COBACABANA (including refinements): a comprehensive card-based system

The overall COBACABANA system is depicted in Fig. 5. The first card loop is between customer enquiry management and the pre-shop pool. The acceptance cards for each operation represent the pool load used to calculate due dates at the salesperson's display. The corresponding pool card(s) move with the order and provide feedback information; when the order is released, the pool card(s) returns to the salesperson's display and the respective acceptance cards are removed. The second loop is from the pool to the shop floor. The release cards for each operation represent the shop floor workload, used by the planner to select jobs for release. The corresponding operation cards move with the order and provide feedback information; when an operation is completed, the corresponding operation card is returned to the planning board and

Fig. 5. Integrated COBACABANA card-based solution for complex job shops – card loops between the salesperson at customer enquiry management and order release and between the planner at order release and shop floor stations.

Table 1
Summary of the different card types used in COBACABANA.

Where used?	Customer enquiry management		Order release control	
	Acceptance card	Pool card	Release card	Operation card
For what?	Represents the workload of a station in the pool on the salesperson's display	Creates the feedback loop between customer enquiry management and order release	Represents the shop floor workload of a station on the planner's planning board	Creates the feedback loops between order release and each station on the shop floor
How many?	One per operation; card size represents the workload contribution	One per operation	One per operation; card size represents the workload contribution	One per operation

the corresponding release card is withdrawn. The four different card types and their functions are summarized in Table 1.

Cards are physically stored in an order guidance form, which accompanies an order through the whole process. This guidance form can be used to summarize basic job information and, in the absence of electronic information feedback, collect order progress information for later diagnosis (see, e.g. Soepenberg et al., 2008). For example, operators can write realized operation completion dates or quality problems on the form for subsequent analysis.

The acceptance and release cards can be cut to exactly the right size to represent the load contributions of the operations involved. Thürer et al. (2014b) recently demonstrated that the need for processing time estimations at order release can be simplified by limiting the number of card sizes such that a card size represents a certain range of load contributions, rounded to the estimated average in that range, rather than representing the exact workload. Results in Thürer et al. (2014b) suggested that applying just three card sizes to represent small, medium and large workload contributions is sufficient to achieve good performance. However, the impact of this simplification on customer enquiry management has not been evaluated.

Simulation is next used to: (i) evaluate COBACABANA as a comprehensive system that combines card-based due date setting with card-based order release; and then (ii) examine the performance impact of using a limited set of card sizes at customer enquiry management.

3. Simulation model

3.1. Overview of modeled shop and job characteristics

A simulation model of a randomly routed job shop or pure job shop (Melnik and Ragatz, 1989) has been implemented in Python[®] using the SimPy[®] module. The shop contains six stations, where each station is a single resource with constant capacity. The routing length of orders varies uniformly from one to six operations. All stations have an equal probability of being visited and a particular station is required at most once in the routing of an order. 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. 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. The arrival of orders follows a stochastic process. The inter-arrival time of orders is exponentially distributed with a mean of 0.648, which – based on the average number of stations in the routing of an order – deliberately results in a utilization level of 90%. These settings facilitate comparison with earlier studies on both Workload Control (e.g. Oosterman et al., 2000; Thürer et al., 2012, 2014a) and COBACABANA (Thürer et al., 2014b).

3.2. Customer enquiry management

A due date is determined when the order arrives. As it is rare that all due dates are either determined internally (i.e. fully under the company's control) or set externally (i.e. always specified by a customer), five due date setting scenarios are modeled to assess the effect of the mix of orders with due dates set internally and specified by the customer. The modeled ratios are as follows: 100%, 75%, 50%, and 25% of due dates set using the internal due date estimation rule; and, no due dates set internally (i.e. 100% of due dates set externally by the customer). The probability that a due date can be set internally is modeled as a Bernoulli trial.

Internally (or endogenously) set due dates are determined using COBACABANA (see Section 2.2.5), which leads to a value for the pool waiting time allowance (α). In case an order can be released directly upon arrival by the continuous release trigger, α is set to zero. The constant allowance for the operation throughput time (β) is set to 5 time units, based on the average operation throughout times realized in preliminary simulation experiments. As a reference, the original due date estimation procedure from Land (2009) has also been included in the experimental design (see Section 2.2.1). In both methods, the external allowance (γ) was set through preliminary simulation experiments such that the average of the quoted delivery lead time is 40 time units for all experiments. The quoted delivery lead time is defined as the customer due date minus the time the order was received.

Externally (or exogenously) set due dates specified by the customer are modeled by adding a random allowance factor, uniformly distributed between 30 and 50 time units, to the time when the order is received. For orders with externally set due dates, a planned release date is then calculated by backward scheduling from the production due date (i.e. the customer due date minus the external allowance).

3.3. Order release

Once the due date is determined, an order flows into the pool to await release. As in previous simulations of Workload Control and COBACABANA (e.g. Melnyk and Ragatz, 1989; Land and Gaalman, 1998; Fredendall et al., 2010; Thürer et al., 2014b, 2015), it is assumed that materials are available and all necessary information on shop floor routing, processing times, etc. is known upon the arrival of an order in the pool. 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 orders are released onto the shop floor immediately upon arrival.

3.4. Card sizes

The size of an acceptance card (at customer enquiry management) and a release card (at order release) reflects the workload

contribution of the order. In addition to the use of a fully flexible card size – and as in Thürer et al. (2014b) for order release only – we will experiment with 2, 3, 4, and 5 predetermined card sizes, where each card size represents the average of a certain range of workload contributions. We will assess the trade-off between simplifying the method and deteriorating performance caused by not accurately representing the workload contribution of jobs. To keep the experimental setting to a reasonable level, the number of different card sizes is the same for the acceptance and release cards.

Note that the workload measure applied for estimating due dates at customer enquiry management differs from Land (2009). In Land (2009), the full processing time is assigned to the corresponding stations whereas, here, the workload contribution is corrected. Table 2 summarizes the card sizes and the range of workload contributions represented by each card size for the corrected aggregate load and for the classical aggregate load used in Land (2009).

The ranges for each card size were deliberately chosen such that each range would represent an equal percentage of the load contributions. These ranges and the conditional mean in each range could be determined analytically for the load contributions which result directly from truncated 2-Erlang distributed processing times. As the corrected aggregate loads divide these processing times by the routing position resulting from another stochastic process, the ranges for the corrected aggregate load contributions have been determined numerically. Of course, in practice, ranges and card sizes will not be determined this exactly, but additional experiments have shown that our results are highly robust to the choice of range.

3.5. Priority dispatching rule for the shop floor

Dispatching follows operation due dates, i.e. the job with the earliest operation due date from the set of jobs queuing in front of a station is processed first. The operation due date d_{ji} of the i th operation of job j is determined when a job is released by distributing the available slack – i.e. the due date of job j (d_j) minus its release date (t_j^r) – over the operations in its routing in accordance with Eq. (2) below. This procedure is based on Land et al. (2014) and is especially suitable when order release control is applied as it takes deviations from the schedule caused by order release into account.

$$\text{if } (d_j - t_j^r) \geq 0; \quad d_{ji} = t_j^r + i \cdot \frac{(d_j - t_j^r)}{n_j} \quad \forall i \in R_j \quad (2)$$

$$\text{else if } (d_j - t_j^r) < 0; \quad d_{ji} = t_j^r \quad \forall i \in R_j$$

n_j = routing length (i.e. the number of operations in the routing) of job j

Table 2
Definition of different card sizes used in this study.

Card configuration ^a		Average contribution in the interval (determines card size); and range of contributions represented by each card				
Corrected aggregate 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]
"Classical" aggregate load	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]

^a Number of card sizes / percentage represented by each card size.

3.6. Experimental design factors and performance measures

The experimental factors are: (i) the 5 different percentage levels for the proportion of due dates set internally by COBACABANA (100%, 75%, 50%, 25% and 0%, i.e. all due dates set externally by the customer); (ii) the five different number of card sizes at customer enquiry management and order release (2, 3, 4 and 5 card sizes, plus a fully flexible card size); and, (iii) the eight workload norm levels at order release (from 5 to 12 time units). A full factorial design with 200 cells was used, where each cell was replicated 100 times. Results were collected over 10,000 time units following a warm-up period of 3000 time units. These parameters allowed us to obtain stable results while keeping the simulation run time to a reasonable level.

Finally, three main performance measures are considered in this study: (i) *the mean throughput time*, i.e. the mean of the completion time minus the release time across jobs; (ii) *the percentage tardy*, i.e. the percentage of jobs completed after the customer due date; and (iii) *the mean tardiness*, i.e. the mean of the tardiness $T_j = \max(0, L_j)$, with L_j being the lateness of job j (i.e. its actual delivery time minus its customer due date).

4. Results

Statistical analysis has been conducted by applying ANOVA to give a first indication of the relative impact of our three experimental factors. ANOVA is here based on a block design, where the norm level is the blocking factor. Thus, statistical analysis is restricted to the main effects of order release, as each norm level can be considered to be a different system. The results are summarized in Table 3 where all main effects and two-way interactions related to percentage tardy and mean tardiness are shown to be statistically significant. Detailed performance results will be presented next in Section 4.1 before the performance of COBACABANA's due date estimation procedure is examined more closely in Section 4.2.

4.1. Assessment of performance

Results are presented in the form of performance curves, with Fig. 6 showing the percentage tardy and mean tardiness results over the throughput time results for experiments where all due dates are determined internally by COBACABANA (Fig. 6a) and all due dates are determined externally by the customer (Fig. 6b). Each curve represents the performance obtained for a certain setting of (acceptance and release) card sizes for the whole

spectrum of workload norms. The workload norm increases step-wise by moving from left to right in each graph, with each data point representing one norm level (from 5 to 12 time units). In addition, the performance curve of Land's (2009) original COBACABANA approach (i.e. without refinement) is given by the dashed curve in Fig. 6a. Meanwhile, the results obtained when orders are released immediately – referred to as IMM (IMMediate release) – are included in Fig. 6b (see the single point “X” to the far right of the figure). IMM represents the outcome with no order release control, i.e. when control is only exercised through the shop floor dispatching rule.

Fig. 6a and b demonstrate that substantial performance improvements across all three performance measures considered here – percentage tardy, mean tardiness and throughput time – can be realized by COBACABANA compared to immediate release. This underlines the potential of COBACABANA to improve performance and should provide the necessary confidence for implementation in practice. Results in Fig. 6a further demonstrate the effectiveness of our refinements: a significant performance improvement in percentage tardy and mean tardiness can be observed over the original procedure proposed by Land (2009). Interestingly, the results in Fig. 6a suggest that using a discrete number of card sizes improves mean tardiness performance if due dates are determined internally. Discretizing the workload contributions at customer enquiry management avoids the extremes in the pool waiting time estimates, which mitigates the negative effect created by the difference between the rate at which jobs are released and the rate at which jobs are processed on the shop floor. Meanwhile, when all jobs have a due date determined externally by the customer (Fig. 6b), performance is mainly determined by COBACABANA's release mechanism, and this mechanism better balances the workload if a fully flexible card size is used (Thürer et al., 2014b). Finally, the shorter throughput times realized for the same workload norm level if fewer card sizes are used are due to an increase in the granularity of the workload contributions at release.

The same positive performance effects created by COBACABANA can be observed from Fig. 7, which depicts the remaining results for 25%, 50% and 75% of due dates determined internally by the due date setting rule. As expected from the results in Fig. 6 above, the relative performance of each setting of the number of card sizes changes gradually. If the majority of jobs have a due date determined by COBACABANA's due date estimation procedure, using a fully flexible card size results in worse performance in terms of mean tardiness and in equivalent performance in terms of percentage tardy compared to using a discrete number of card sizes. Meanwhile, when the majority of jobs have a due date

Table 3
ANOVA results.

Performance measure	Source of variance	Sum of squares	Degree of freedom	Mean squares	F-ratio	p-Value
Throughput time	% Due dates set (%DD)	486.376	4	121.594	138.126	0.000
	Card size	1285.951	4	321.488	365.198	0.000
	Norm level	110,010.890	7	15,715.841	17,852.610	0.000
	%DD × card sizes	9.640	16	0.602	0.684	0.812
	Error	17,578.042	19,968	0.880		
	Total	128,400.259	20,000			
Percentage tardy	% Due dates set (%DD)	12.578	4	3.145	8998.350	0.000
	Card size	0.063	4	0.016	44.877	0.000
	Norm level	1.673	7	0.239	684.108	0.000
	%DD × card sizes	0.034	16	0.002	6.014	0.000
	Error	6.978	19,968	0.000		
	Total	14.253	20,000			
Mean tardiness	% Due dates set (%DD)	1110.668	4	277.667	3709.200	0.000
	Card size	8.727	4	2.182	29.145	0.000
	Norm level	214.516	7	30.645	409.372	0.000
	%DD × card sizes	11.317	16	0.707	9.448	0.000
	Error	1494.784	19,968	0.075		
	Total	2339.702	20,000

Fig. 6. Performance Results for: (a) All due dates determined by COBACABANA's Due date estimation procedure; and (b) All due dates determined externally by the customer.

determined externally by the customer, the use of a fully flexible card size leads to slightly better performance in terms of the percentage tardy and mean tardiness. This explains the significant two-way interactions observed in our earlier ANOVA analysis.

4.2. Performance analysis of COBACABANA's due date estimation procedure

COBACABANA's due date estimation procedure relies on two assumptions: (i) that order release controls the direct load, which makes operation throughput times predictable and, consequently, (ii) that the pool waiting time is the only variable component of the delivery time. In this section, we will first examine the ability of COBACABANA to estimate appropriate allowances for the pool waiting time in Section 4.2.1 before we take a closer look at the assumption of controlled operation throughput times in Section 4.2.2.

4.2.1. Estimating appropriate allowances for the pool waiting time

Correcting a job's workload contribution at release – by dividing operation processing times by the routing position – means that the further downstream in the routing of orders that a station is positioned, the more work is permitted to be on its way to that station. This can be a very desirable property at release that partly avoids, for example, premature station idleness. Yet this correction introduces an additional element of variability into the due date estimation procedure as the rate at which jobs are released now not only depends on the rate at which the workload is processed on the shop floor but also on the current position of each station in the routing of the jobs present in the pool. In the long term, the release rate in terms of processing time units

released per time unit equals the output rate of the shop, indicated by the utilization; but, in the short term, significant fluctuations may occur. If, for example, the pool currently contains a large number of jobs with a certain station as the first in their routing then, in the short term, jobs will be released slower than the average output rate used by Land (2009) to estimate pool waiting times. It was this shortcoming that led us to refine COBACABANA such that pool waiting time estimates are based on the corrected load of the pool. Meanwhile, if there are currently a large number of jobs in the pool, then they will temporarily be released quicker than estimated since, in the long term, it is the average output rate of the shop that dictates the release rate. Finally, if the pool contains a large number of jobs with a certain station as the sixth in their routing then jobs will be: in the short term, released sooner than estimated by Land (2009); and, in the long term, released slower than estimated by the corrected aggregate load.

This effect can be observed from Fig. 8a and b, which depict the distribution of pool lateness across jobs, i.e. their realized minus their estimated pool waiting times, for COBACABANA (refined) with a fully flexible card size and for the original procedure outlined by Land (2009), respectively. The bars in the figures represent a class size of 1, e.g. the bar for a pool lateness of zero represents the class $(-0.5, 0.5]$. For COBACABANA, the planned release date is rounded up to the end of the next periodic release interval, which means that most pool lateness observations are multiples of the release interval (i.e. 4).

First, we compare the results for COBACABANA (Fig. 8a) with the results for the original procedure (Fig. 8b). Although visually this is complicated by the multi-mode distributions in Fig. 8a, we observe that COBACABANA reduces tardiness (e.g. 3% instead of

Fig. 7. Performance results for 75%, 50% and 25% of due dates determined internally by COBACABANA's due date estimation procedure.

10% of jobs have a pool lateness exceeding 3.5 time units at a workload norm of 7). In addition, more jobs are released exactly by their planned release date (e.g. 40% instead of 11% of jobs were released within half a time unit of their planned release date at a workload norm of 7). Second, we move from left to right in both figures. In doing so, we observe that estimation accuracy for COBACABANA in particular diminishes at tighter norms, as can be seen from the increased dispersion of the observations. As expected, the largest deviations occur when there are more jobs in the pool, i.e. when pool waiting times are longer.

4.2.2. The assumption of controlled operation throughput times

A basic assumption of COBACABANA's due date estimation procedure is that its order release mechanism controls the direct load and, consequently, operation throughput times (Land, 2009). But this assumption relies on first-come-first-served dispatching – as applied in many early studies on Workload Control – in which case, operation throughput times closely follow the direct load. In this study, we use dispatching based on operation due dates. To examine whether the assumption also holds for operation due date oriented dispatching, we recorded the distribution of realized

Fig. 8. Distribution of pool lateness (realized minus estimated pool waiting time) for: (a) COBACABANA with a fully flexible card size; and (b) the original procedure from Land (2009).

operation throughput times and of the direct load level for an arbitrary station for a norm level of 5, 7, and 9 time units and for immediate release (IMM). Results – with the workload only presented for observations greater than zero – are depicted in Fig. 9a and b, respectively for experiments where all due dates are determined by COBACABANA.

Interestingly, the mode of the distribution of realized operation throughput times (Fig. 9a) appears not to be influenced by the workload norm level. Relative to first-come-first-served dispatching (where operation throughput times would follow the direct load distribution closely), the mode is positioned close to the average processing time as it is more likely that a job is processed directly upon arrival at the station in situations where all other jobs in the queue are less urgent. If a job is released too early, it often has to wait in front of the station. Thus, it is the schedule deviation at release that causes this shape of the distribution, stretching to the right with the mode always close to the average

processing time. In general, however, it can be observed that order release improves the control of both operation throughput times and the direct load level compared to immediate release. This partly justifies the assumption of controlled operation throughput times within COBACABANA's due date determination procedure. While a substantial amount of variability remains, it is argued that accounting for this variability is beyond the scope of a simple card-based solution for estimating due dates at customer enquiry management. It can be addressed using a more sophisticated approach to Workload Control, e.g. as outlined in Thürer et al. (2014b).

5. Conclusion

Card-based systems – most notably Kanban, Constant Work-in-Process (ConWIP), and Paired cell Overlapping Loops of Cards with

Fig. 9. Distribution of: (a) Operation Throughput Times; and (b) the Direct Load at an Arbitrary Work Center with a Workload Norm of 5, 7 and 9 Time Units and Immediate Release (IMM) When All Due Dates are Determined Internally by COBACABANA.

Authorization (POLCA) – provide simple, visual approaches to controlling production and have helped repetitive manufacturers reduce costly buffers while maintaining short lead times. Yet, the applicability of card-based systems to complex job shops that produce made-to-order, customized products – as is typical of many small manufacturing companies – is limited. Moreover, all three of the established card-based systems referred to above restrict themselves to controlling the shop floor. Other planning tasks – such as the estimation of short yet feasible due dates at customer enquiry management – are not supported. This maintains a considerable degree of sophistication in the planning process and partly negates the advantage of simple, visual control. In response, this study builds on Land (2009) and Thürer et al. (2014b) by further developing COBACABANA, a card-based approach to Workload Control. Workload Control is a production planning and control concept developed for the specific needs of job shops, but its sophisticated workload calculations are reliant on hard/software investment, which arguably affects its applicability, especially to small job shops with limited resources. More specifically, the customer enquiry management stage of COBACABANA has been refined and simulation used to assess – for the first time – the performance impact of COBACABANA as an integrated concept that combines customer enquiry management with order release. Results demonstrate the effectiveness of our refinements and underline the potential of COBACABANA to improve the performance of job shops in practice.

5.1. Managerial implications

COBACABANA is, to the best of our knowledge, the first card-based production control approach that has been shown to be truly suitable for job shops. It is argued here to be of particular importance to small shops, which are in need of a simple, visual and effective control solution. Providing a visualization of the workload in the system, COBACABANA will create awareness in sales and production of the actual operational capabilities of the shop. At the same time, it will alleviate information requirements at sales: as order release controls workload levels on the shop floor, the shop floor can be treated as a “black-box” at customer enquiry management. In addition, the simulation results highlight the potential for alleviating one of the major obstacles to implementation in high-variety job shops: the assumption that accurate processing time estimates need to be obtained. Using COBACABANA, processing time estimations can be simplified by limiting the number of card sizes (or discretizing workload contributions)

not only at order release (see Thürer et al., 2014b) but also, as shown here, at customer enquiry management. Our results suggest that the choice of just a few card sizes, e.g. three to represent small, medium and large workload contributions, is enough to achieve a good level of performance or might even be favorable.

5.2. Future research directions

The key to setting short, feasible allowances for the delivery time – if order release is applied – is a good estimation of when the job will actually be released. Our analysis has revealed that this depends on at least two factors: the short-term rate at which the workload can be released from the pool and the long-term average rate at which work can be processed on the shop. For COBACABANA and Workload Control, each relates to a different measure of workload, as the workload is bounded at release based on the corrected aggregate load. Since cards can only represent one workload measure, a trade-off has to be made between estimation accuracy for long and short pool waiting times. We have prioritized short-term accuracy, arguing that long-term fluctuations are better handled in practice by capacity adjustments and/or can be more easily corrected for by the salesperson. Using a computer based-system, the physical bound of cards no longer exists and calculations can consider both the rate at which jobs are released and the rate at which jobs are processed on the shop floor. This also allows for the use of more advanced forward scheduling methods to estimate release dates. One research direction is consequently to develop more effective approaches for determining planned release dates regardless of whether they are card-based solutions or not – although, if they are not card-based, their suitability for small shops will be jeopardized. A second important direction for future research is therefore to investigate whether more advanced scheduling approaches can be executed using a card-based approach. Finally, it is important to assess the effectiveness of the theoretical advances presented in this paper in practice. Therefore, arguably the most important contribution that could be made by future research in this area would be the implementation of COBACABANA in practice.

References

- Bertrand, J.W.M., Wortmann, J.C., 1981. *Production Control and Information Systems for Component-manufacturing Shops*. Elsevier Scientific Publishing Company, Amsterdam.

- Fernandes, N.O., Silva, C., Carmo-Silva, S., 2015. Order release in the hybrid MTO–FTO production. *Int. J. Prod. Econ.* <http://dxdoi.org/10.1016/j.ijpe.2015.03.025> (in press).
- Fredendall, L.D., Ojha, D., Patterson, J.W., 2010. Concerning the theory of workload control. *Eur. J. Oper. Res.* 201 (1), 99–111.
- Gerns, R., Riezebos, J., 2010. Workload balancing capability of pull systems in MTO production. *Int. J. Prod. Res.* 48 (8), 2345–2360.
- Harrod, S., Kanet, J.J., 2013. Applying work flow control in make-to-order shops. *Int. J. Prod. Econ.* 143, 620–626.
- Hendry, L.C., Kingsman, B.G., 1991. A decision support system for job release in make to order companies. *Int. J. Oper. Prod. Manag.* 11, 6–16.
- Hendry, L.C., Huang, Y., Stevenson, M., 2013. Workload control: successful implementation taking a contingency-based view of production planning & control. *Int. J. Oper. Prod. Manag.* 33 (1), 69–103.
- Hendry, L.C., Land, M.L., Stevenson, M., Gaalman, G., 2008. Investigating implementation issues for workload control (WLC): a comparative case study analysis. *Int. J. Prod. Econ.* 112, 452–469.
- Hopp, W.J., Spearman, M.L., 1996. *Factory Physics*. Richard D. Irwin, Boston, MA.
- Kanet, J.J., 1988. Load-limited order release in job shop scheduling systems. *J. Oper. Manag.* 7 (3), 44–58.
- Land, M.J., 2009. Cobacabana (control of balance by card-based navigation): a card-based system for job shop control. *Int. J. Prod. Econ.* 117, 97–103.
- Land, M.J., Gaalman, G., 1998. The performance of workload control concepts in job shops: Improving the release method. *Int. J. Prod. Econ.* 56–57, 347–364.
- Land, M.J., Stevenson, M., Thürer, M., 2014. Integrating load-based order release and priority dispatching. *Int. J. Prod. Res.* 52 (4), 1059–1073.
- Little, J., 1961. A proof of the theorem $L = \lambda W$. *Oper. Res.* 8, 383–387.
- Melnyk, S.A., Ragatz, G.L., 1989. Order review/release: research issues and perspectives. *Int. J. Prod. Res.* 27 (7), 1081–1096.
- Oosterman, B., Land, M.L., Gaalman, G., 2000. The influence of shop characteristics on workload control. *Int. J. Prod. Econ.* 68 (1), 107–119.
- Ragatz, G.L., Mabert, V.A., 1984. A simulation analysis of due date assignment rules. *J. Oper. Manag.* 5 (1), 27–39.
- Riezebos, J., 2010. Design of POLCA material control systems. *Int. J. Prod. Res.* 48 (5), 1455–1477.
- Shingo, S., 1989. *A Study of the Toyota Production System from an Industrial Engineering Viewpoint*. Productivity Press, Cambridge, MA.
- Soepenberg, G.D., Land, M.J., Gaalman, G., 2008. The order progress diagram: A supportive tool for diagnosing delivery reliability performance in make-to-order companies. *Int. J. Prod. Econ.* 112 (1), 495–503.
- Spearman, M.L., Woodruff, D.L., Hopp, W.J., 1990. CONWIP: a pull alternative to kanban. *Int. J. Prod. Res.* 28 (5), 879–894.
- Stevenson, M., 2006. Refining a workload control (WLC) concept: a case study. *Int. J. Prod. Res.* 44 (4), 767–790.
- Stevenson, M., Silva, C., 2008. Theoretical development of a workload control methodology: Evidence from two case studies. *Int. J. Prod. Res.* 46 (11), 3107–3131.
- Stevenson, M., Hendry, L.C., Kingsman, B.G., 2005. A review of production planning and control: The applicability of key concepts to the make to order industry. *Int. J. Prod. Res.* 43 (5), 869–898.
- Stevenson, M., Huang, Y., Hendry, L.C., Soepenberg, E., 2011. The theory & practice of workload control: A research agenda & implementation strategy. *Int. J. Prod. Econ.* 131 (2), 689–700.
- Sugimori, Y., Kusunoki, K., Cho, F., Uchikawa, S., 1977. Toyota production system and Kanban system Materialization of just-in-time and respect-for-human system. *Int. J. Prod. Res.* 15 (6), 553–564.
- Suri, R., 1998. *Quick Response Manufacturing: a companywide approach to reducing lead times*. Productivity Press, Portland, OR.
- Thürer, M., Stevenson, M., Silva, C., Land, M.J., Fredendall, L.D., 2012. Workload control (WLC) and order release: a lean solution for make-to-order companies. *Prod. Oper. Manag.* 21 (5), 939–953.
- Thürer, M., Stevenson, M., Silva, C., Land, M.J., 2013. Towards an integrated workload control (WLC) concept: the performance of due date setting rules in job shops with contingent orders. *Int. J. Prod. Res.* 51 (15), 4502–4516.
- Thürer, M., Stevenson, M., Silva, C., Land, M.J., Fredendall, L.D., Melnyk, S.A., 2014a. Lean control for make-to-order companies: integrating customer enquiry management and order release. *Prod. Oper. Manag.* 23 (3), 463–476.
- Thürer, M., Land, M.J., Stevenson, M., 2014b. Card-based workload control for job shops: improving COBACABANA. *Int. J. Prod. Econ.* 147, 180–188.
- Thürer, M., Stevenson, M., Protzman, C.W., 2015. COBACABANA (control of balance by card based navigation): an alternative to *Kanban* in the pure flow shop? *Int. J. Prod. Econ.* 166, 143–151.
- Weeks, J.K., 1979. A simulation study of predictable due dates. *Manag. Sci.* 25 (4), 363–373.