Card-Based Delivery Date Promising in High-Variety Manufacturing with Order Release Control

Matthias Thürer, Martin Land, Mark Stevenson, and Lawrence Fredendall

Name:	Matthias Thürer
Institution:	Federal University of Sao Carlos
Address:	Department of Industrial Engineering Rodovia Washington Luis, km 235 13565905 - Sao Carlos - Brasil
Email:	mailboxmatthiasthurer@gmail.com

Name:	Dr. Martin J. Land
Institution:	University of Groningen
Address:	Department of Operations Faculty of Economics and Business University of Groningen 9700 AV Groningen– The Netherlands
Email:	m.j.land@rug.nl

Name:	Dr. Mark Stevenson
Institution:	Lancaster University
Address:	Department of Management Science Lancaster University Management School Lancaster University LA1 4YX - U.K.
Email:	m.stevenson@lancaster.ac.uk

Name:	Professor Lawrence D. Fredendall
Institution:	Clemson University
Address:	Department of Management 101 Sirrine Hall Clemson SC – United States
Email:	flawren@clemson.edu

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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 (<u>CO</u>ntrol of <u>BA</u>lance by <u>CA</u>rd-<u>BA</u>sed <u>Na</u>vigation) – 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.

Keywords: *Workload Control; Card-based Control; Job Shop; Customer Enquiry Management; Order Release; COBACABANA.*

1. Introduction

Card-based systems, such as Kanban (e.g. Sugimuri *et al*., 1977; Shingo, 1989) and Constant Work-in-Process (ConWIP; e.g. Spearman *et al*., 1990; Hopp & 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 & Riezebos, 2010; Harrod & Kanet, 2013). Even Paired cell Overlapping Loops of Cards with Authorization (POLCA; e.g. Suri, 1998; Rizebos, 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. These are often small firms, which are arguably the shops that are in most need of card-based support since other solutions require an investment in expert knowledge and advanced technology that exceeds the resources of small shops. 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 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 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) 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 & 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).

In response to the need for simple, visual production control, Land (2009) developed COBACABANA (<u>CO</u>ntrol of <u>BA</u>lance by <u>CA</u>rd-<u>BA</u>sed <u>NA</u>vigation), 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 & Mabert, 1984; Thürer *et al*., 2013 for a recent review), but effective rules typically 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 (e.g. Thürer *et al*. 2012, 2014a), which integrates two control levels: order release and customer enquiry management. These two levels will be discussed in Section 2.1 and 2.2, respectively before Section 2.3 summarizes COBACABANA as a comprehensive concept.

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. COBACABANA establishes card loops between the planner performing the order release decision and each station on the shop floor, as illustrated in Figure 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.

[Take in Figure 1]

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 predetermined 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).

Figure 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 (in dark gray) and one at Station 3 (in light gray). In this example, since both operations can be loaded into their respective stations without exceeding the workload norm, the order is released and its corresponding operation cards are sent to the shop.

[Take in Figure 2]

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 & 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 & Wortmann, 1981; Hendry & 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 routing card for the second operation stays on the shop floor about twice as long as the routing 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 to ensure 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 delivery time allowance 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 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 Equation (1), where β is a variable allowance for the time that the order has to wait in the pre-shop pool prior to release; α_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.

$$d_j = t + \beta + \sum_{i \in R_j} \alpha_i + \gamma \qquad (1)$$

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 Figure 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.

[Take in Figure 3]

Land's (2009) extension of the use of cards to due date estimating 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:

i. Multiple cards are required to represent the workload of a single operation, which means that a large number of cards travel with an order.
ii. It assumes that jobs can be released at any moment in time, although most releases occur periodically at fixed time intervals.
iii. 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 subsections 2.2.2 to 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 example, if an acceptance card represents 10 minutes of work then a one-hour operation requires six cards (for this one operation alone). Thus, 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 (rather than the number of cards). 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 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), as used in Land (2009). 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 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 distance between each marker on the scale represents the average release rate in terms of the amount of work that can be released during a release interval. 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 given in Figure 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 (see dark grey) 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 β 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.

[Take in Figure 4]

2.3 COBACABANA (including Refinements): A Comprehensive Card-Based System

The overall COBACABANA system is depicted in Figure 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 allow the information flow to be established. 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 allow the information flow to be established. When an operation is completed, the corresponding operation card is returned to the planning board and 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.

[Take in Figure 5 and Table 1]

Following the proposed refinements to the number of cards (see Section 2.2.2), 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 contribution. 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

The shop and job characteristics modeled in the simulations are first outlined in Section 3.1. How customer enquiry management and order release have been operationalized in the simulation is then discussed in sections 3.2 and 3.3, respectively before Section 3.4 outlines the parameters for the experiments with a limited number of card sizes. COBACABANA controls the release of orders to the shop floor; but, different from Kanban and POLCA, it does not provide a detailed schedule for the flow of orders through the shop floor. Control on the shop floor is instead exercised using a shop floor dispatching rule. The priority dispatching rule applied on the shop floor is therefore described in Section 3.5. Finally, the experimental design is outlined and the measures used to evaluate performance are presented in Section 3.6.

3.1 Overview of Modeled Shop and Job Characteristics

A simulation model of a randomly routed job shop or pure job shop (Melnyk & 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. This allows us 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 (β). In case an order can be released directly upon arrival by the continuous release trigger, β is set to zero. The constant allowance for the operation throughput time (α) 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). Here also, β is set to zero when an order can be released by the continuous release trigger directly upon arrival. In both methods, the external allowance (γ) was set through preliminarily 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 & Ragatz, 1989; Land & Gaalman, 1998; Fredendall *et al*., 2010; Thürer *et al*., 2014b), 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 to the various stations in its routing. 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 (by reducing the number of acceptance and release card sizes) 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).

[Take in Table 2]

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 used at customer enquiry management, which result directly from truncated 2-Erlang distributed processing times. As the corrected aggregate loads used at order release 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 Equation (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.

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

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

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 3,000 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 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 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.

[Take in Table 3]

4.1 Assessment of Performance

Results are presented in the form of performance curves, with Figure 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 (Figure 6a) and all due dates are determined externally by the customer (Figure 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 Figure 6a. Meanwhile, the results obtained when orders are released immediately – referred to as IMM (IMMediate release) – are included in Figure 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.

[Take in Figure 6]

Figure 6a and 6b 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 Figure 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 Figure 6a suggest that using a discrete number of card sizes improves mean tardiness performance if due dates are determined by COBACABANA. 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 (Figure 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 Figure 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 Figure 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 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.

[Take in Figure 7]

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. Premature idleness in turn can occur when the work released to a station is at its limit (i.e. filled up to the workload norm) but most of this work is still queuing or being processed at an upstream operation. 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 average 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 Figure 8a and 8b, 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).

[Take in Figure 8]

First, we compare the results for COBACABANA (Figure 8a) with the results for the original procedure (Figure 8b). Although visually this is complicated by the multi-mode distributions in Figure 8a, we observe that COBACABANA reduces tardiness (e.g. 3% instead of 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 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 Figure 9a and 9b, respectively for experiments where all due dates are determined by COBACABANA.

[Take in Figure 9]

Interestingly, the mode of the distribution of realized operation throughput times (Figure 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 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 either the shop floor or order release and 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.

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Table 1: Summary of the Different Card Types used in COBACABANA

	Acceptance Card	Pool Card	Release Card	Operation Card
Where Used?	Customer Enquiry Management		Order Release Control	
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 from the pool	Represents the shop floor workload of a work center on the planner's display	Creates the feedback loop between order release from the pool and each station
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

Table 2: Definition of Different Card Sizes used in this Study

Order Release	Card Configuration[1]	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]

[1] Number of Card Sizes / Percentage Represented by Each Card Size

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	110010.890	7	15715.841	17852.610	0.000
	%DD x Card Sizes	9.640	16	0.602	0.684	0.812
	Error	17578.042	19968	0.880		
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 x Card Sizes	0.034	16	0.002	6.014	0.000
	Error	6.978	19968	0.000		
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 x Card Sizes	11.317	16	0.707	9.448	0.000
	Error	1494.784	19968	0.075		

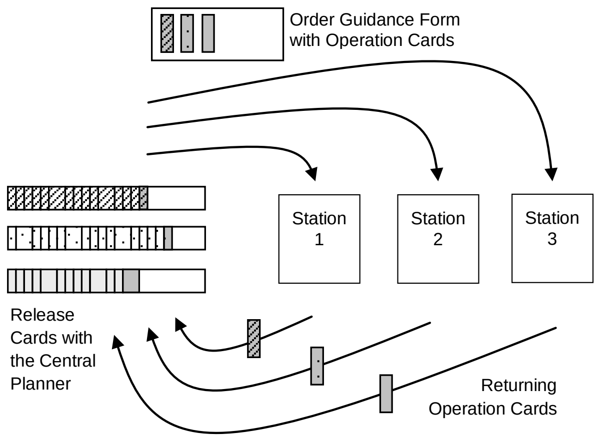


Figure 1: Card-based Order Release with Loops between the Central Planner and Stations on the Shop Floor

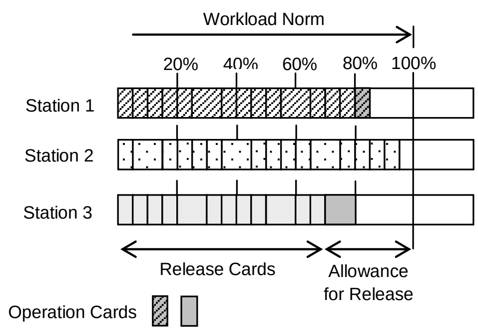


Figure 2: Planner's Planning Board for Order Release (with an Example Release)

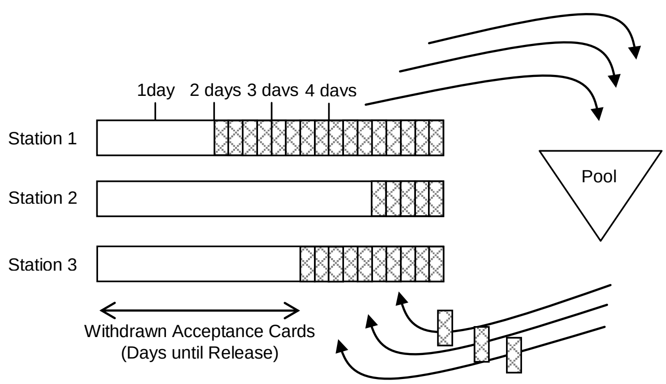


Figure 3: Salesperson's Display for Customer Enquiry Management (as in Land, 2009)

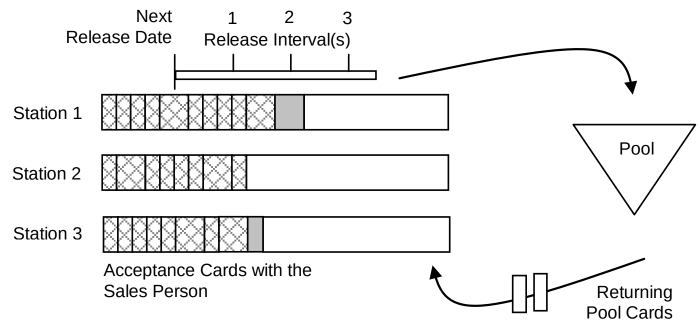


Figure 4: Card-based Customer Enquiry Management – The Salesperson's Display

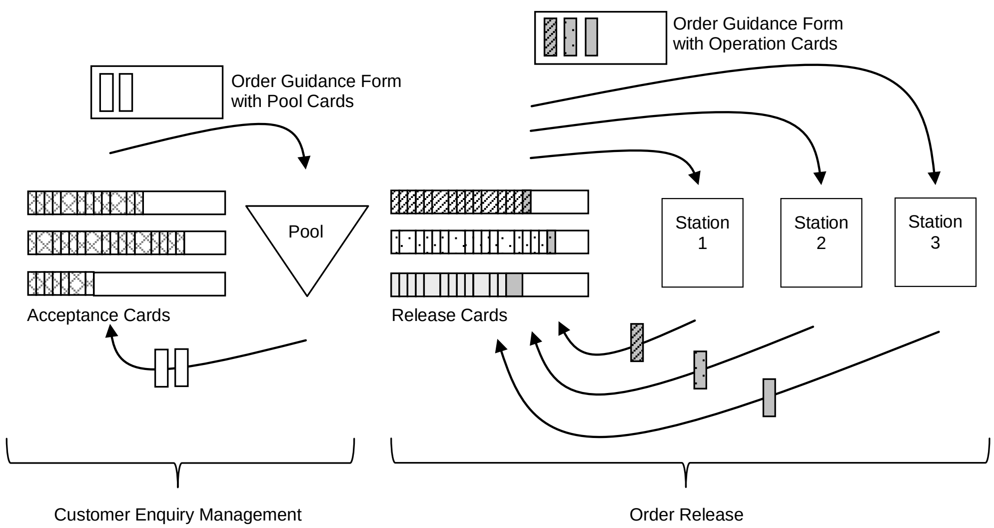
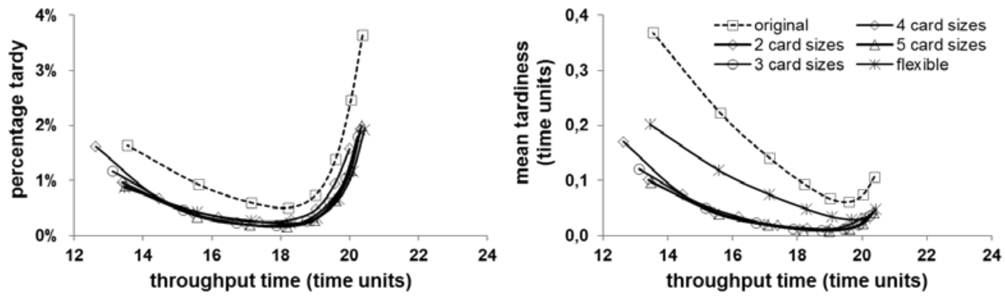
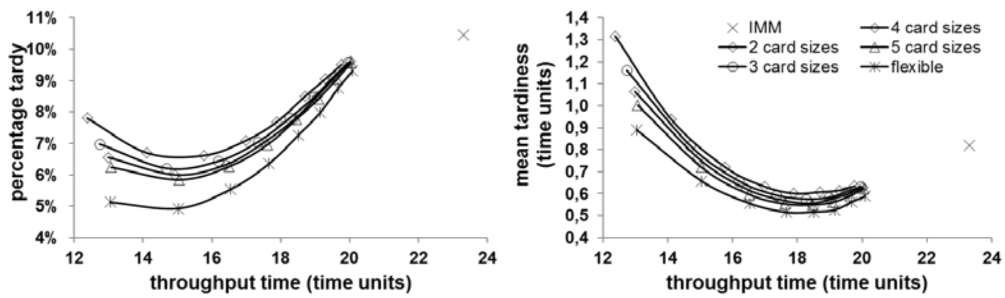


Figure 5: Integrated COBACABANA Card-Based Solution for Complex Job Shops – Card Loops between the Salesperson at Customer Enquiry Management & Order Release and between the Planner at Order Release & Shop Floor Stations

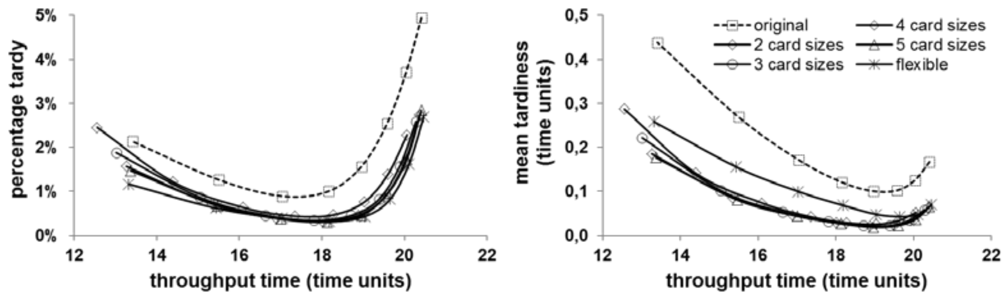


(a) All Due Dates Determined Internally by COBACABANA

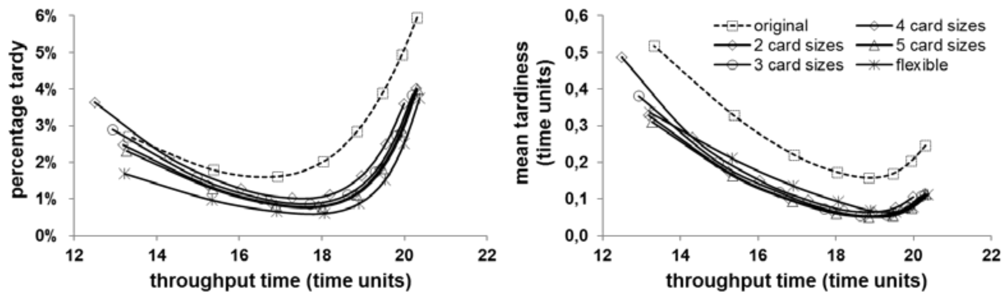


(b) All Due Dates Determined Externally by the Customer

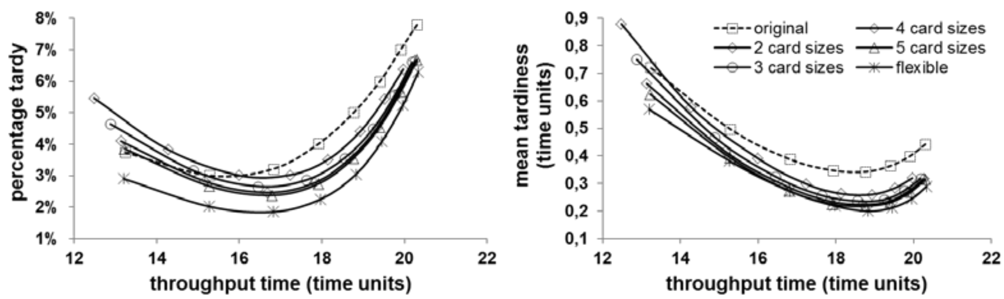
Figure 6: Performance Results for: (a) All Due Dates Determined by COBACABANA's Due Date Estimation Procedure; and (b) All Due Dates Determined Externally by the Customer



(a) 75% of Due Dates Determined Internally by COBACABANA

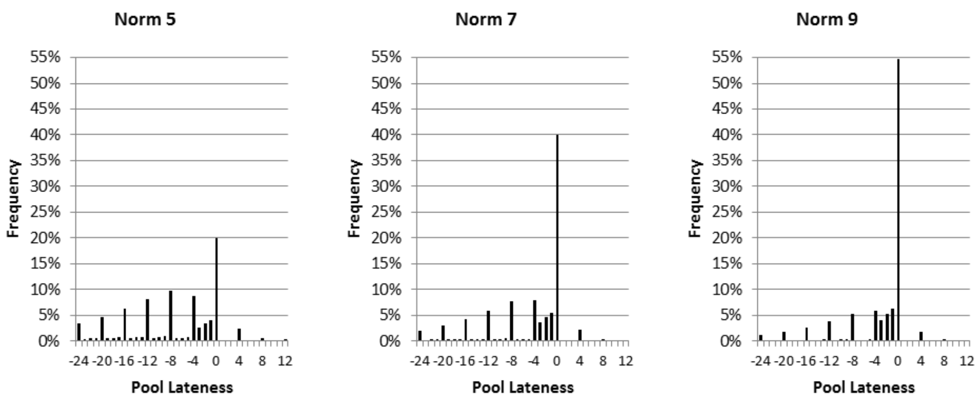


(b) 50% of Due Dates Determined Internally by COBACABANA

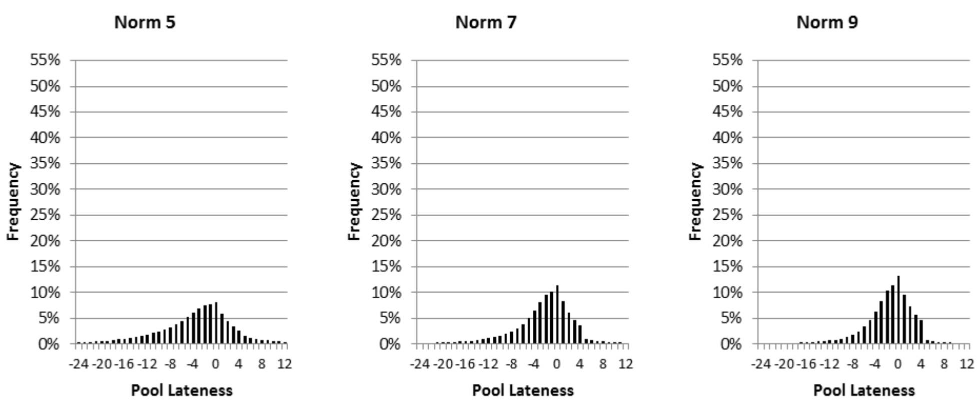


(c) 25% of Due Dates Determined Internally by COBACABANA

Figure 7: Performance Results for 75%, 50% and 25% of Due Dates Determined Internally by COBACABANA's Due Date Estimation Procedure

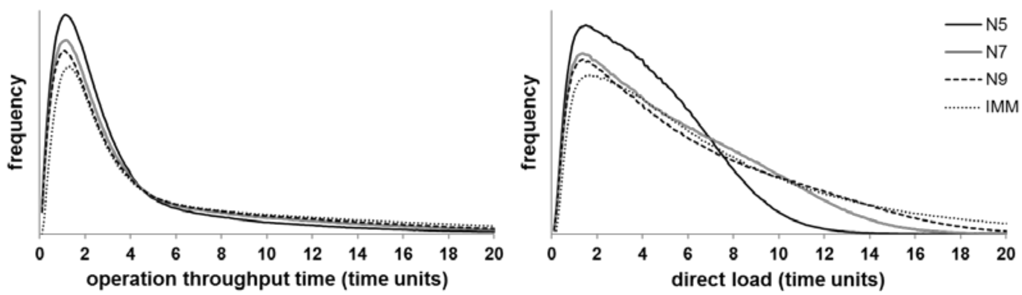


(a) COBACABANA with a Fully Flexible Card Size



(b) Original Procedure (as in Land, 2009)

Figure 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)



(a) Distribution of Realized Operation Throughput Times

(b) Distribution of the Direct Load

Figure 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