Material Flow Control in High-Variety Make-to-Order Shops: Combining COBACABANA and POLCA

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Abstract: Material flow control mechanisms determine: (i) whether an order should be released onto the shop floor; and, (ii) whether a station should be authorized to produce. Well-known approaches include Kanban, Drum-Buffer-Rope (DBR), Constant Work-in-Process (ConWIP), Paired-cell Overlapping Loops of Cards with Authorization (POLCA), Workload Control (WLC), and Control of Balance by Card based Navigation (COBACABANA). The literature typically treats these approaches as competing, meaning studies argue for the superiority of one over another. However, a closer look reveals that existing mechanisms either focus on order release (ConWIP, DBR, WLC, and COBACABANA) or production authorization (Kanban and POLCA). This study therefore calls for a paradigm shift and argues that the different mechanisms may play complementary rather than competing roles. Using simulation, we assess the performance of COBACABANA and POLCA in a high-variety make-to-order shop, a type of shop arguably in most need of material flow control given the importance of throughput times and delivery time adherence. Results demonstrate that COBACABANA outperforms POLCA, but the simultaneous adoption of both control mechanisms outperforms the use of either one in isolation. More specifically, adding POLCA production authorization to COBACABANA order release enables the superfluous direct load to be further reduced, resulting in shop floor throughput time reductions of between 15% and 26% while further reducing the percentage tardy and mean tardiness by up to 14%. Compared to no material flow control, the new combined mechanism realizes a reduction of almost 50% in the percentage tardy and more than 30% in mean tardiness.

Keywords: *Material Flow Control; COBACABANA; POLCA; Workload Control.*

1. Introduction

This study argues for a paradigm shift in Material Flow Control (MFC) whereby different approaches to MFC are viewed as being complementary rather than competing with each other. To support this argument, we first combine two well-known MFC mechanisms for high-variety make-to-order shops – Control of Balance by Card Based Navigation (COBACABANA) and Paired-cell Overlapping Loops of Cards with Authorization (POLCA) – before using simulation to assess the performance of the new, combined mechanism that is referred to as COBA-POLCA. Our focus is on shops that produce a high variety of products, such as small and medium sized make-to-order companies (e.g. Muda & Hendry, 2003; Hines *et al*., 2004; Stevenson *et al*., 2005). These companies often have to juggle an array of diverse order specifications and need to respond to the demands of both one-off and repeat customers at short notice (Amaro *et al*., 1999) since highly customized orders may not be repeated and thus cannot be kept in stock (Teo *et al*., 2012). A key challenge that these companies face is in striking a balance between the input rate of orders and their capacity (i.e. the output rate) to ensure that the shop and each station remains busy while simultaneously delivering confirmed orders in a timely fashion (Kingsman *et al*., 1989; Thürer *et al*., 2014a).

In this context, MFC mechanisms address two important problems: (i) whether a job should be released onto the shop floor; and, (ii) whether a station should be authorized to produce (Graves *et al*. 1995). Well-known pull approaches to MFC include: Kanban (e.g. Sugimuri *et al*., 1977; Ohno, 1988; Shingo, 1989; Berkley, 1992; Monden, 2011); Drum-Buffer-Rope (DBR, e.g. Goldratt & Cox, 1984; Simons & Simpson, 1997; Watson *et al*., 2007); Constant Work-in-Process (ConWIP, e.g. Spearman *et al*., 1990; Hopp & Spearman, 2004); POLCA (e.g. Suri, 1998;

Vandaele *et al.*, 2008; Riezebos, 2010); WorkLoad Control (WLC, e.g. Land & Gaalman, 1996; Thürer *et al.*, 2012, 2014a); and, COBACABANA (e.g. Land, 2009; Thürer *et al.*, 2014b).

The literature typically views these different MFC mechanisms as competing. This means that contributions seek to highlight the superiority of one mechanism over another (Spearman *et al.*, 1990; Fredendall *et al.*, 2010; Harrod & Kanet, 2013) or to assess which mechanism to choose in a given context (Zäpfel & Missbauer, 1993; Graves *et al.*, 1995; Stevenson *et al.*, 2005). While studies do exist on combined approaches, they typically focus on hybrid push and pull systems that combine Material Requirements Planning (MRP) and Kanban (Graves *et al.*, 1995; Lage Junior & Godinho Filho, 2010). In addition, POLCA is commonly combined with MRP to calculate earliest release dates (Suri, 1998). But MRP is prone to MRP nervousness (Whybark & Williams, 1976), which limits its applicability to high-variety make-to-order shops that are arguably in the most need of MFC support. A major shortcoming of MRP systems in high-variety contexts is the assumption that production orders can be combined, as in repetitive contexts, and that predetermined lead times can be used when determining release dates. In high-variety contexts, the planned lead time should consider the current workload situation (Teo *et al.*, 2012; Missbauer, 2020) while phenomena such as order crossovers (Riezebos & Zhu, 2015) should be taken into account. Meanwhile, the few studies that combine two pull systems, such as the MFC mechanisms listed above, focus on ConWIP and Kanban. For example, Bonvik *et al.* (1997) extended ConWIP, which only controls the total system load, to incorporate Kanban loops to gain control over individual station loads. Taking this hybrid system as a starting point, we ask: how can two MFC mechanisms, which are typically viewed as being competing alternatives (Spearman *et al.*, 1990), be combined?

If we take a closer look at existing MFC mechanisms then we can observe that they tend to only address one of the two problems of MFC. For example, ConWIP, DBR, WLC, and COBACABANA focus on the problem of *whether* a job should be released into a manufacturing system. They use a pool of work or a backlog (Spearman *et al*., 1990) that precedes the manufacturing system. Jobs are only released into the system from the backlog if certain system characteristics or prerequisites, such as work-in-process levels, are satisfied. All four approaches – ConWIP, DBR, WLC, and COBACABANA – neglect the second problem of whether a station on the shop floor should be authorized to produce. In contrast, Kanban and POLCA focus on the problem of production authorization at shop floor stations. This means they answer the question concerning *whether* any job should be produced at a station; but they neglect the problem of whether a job should be released to the manufacturing system. Rather, jobs directly enter the shop floor and proceed to the queue in front of the first station in their routing where they are subjected to the production authorization decision. Both MFC decisions are typically accompanied by the decision regarding *which* job should be produced next. In the context of order release, this is typically referred to as backlog (or pool) sequencing (Thürer *et al*. 2015, 2017a) and, in the context of station authorization, this is typically referred to as dispatching (Blackstone *et al*., 1982).

Thus, while a broad set of MFC mechanisms exist, an integrative approach to MFC that combines both – the problem of whether to release jobs into a manufacturing system and the problem of whether a station should be authorized to produce – is still largely missing. The only exception is the hybrid mechanism presented by Bonvik *et al*. (1997), which combines ConWIP and Kanban. But this mechanism was developed for repetitive production contexts. Both ConWIP and Kanban were shown to be outperformed by mechanisms such as COBACABANA in high-variety contexts (Thürer *et al*. 2012, 2019a). Moreover, ConWIP does not control the load queuing at each station. The question therefore remains concerning whether combining an MFC mechanism that focuses on order release with an MFC mechanism that focusses on production authorization can also improve performance in a high-variety context, especially if the release mechanism already controls each station load – as is the case for COBACABANA.

In response, this study combines COBACABANA with POLCA into a new MFC mechanism referred to as COBA-POLCA. We focus on COBACABANA and POLCA since: (a) COBACABANA is the card-based equivalent of the WLC mechanism that was specifically developed for high-variety contexts, such as make-to-order companies (Zäpfel & Missbauer, 1993; Stevenson *et al*., 2005; Thürer *et al*., 2014a); and, (b) POLCA has been argued to be an alternative to Kanban systems specifically for companies that produce a high variety of products on a make-to-order basis (e.g. Krishnamurthy & Suri 2009; Riezebos, 2010). Discrete event simulation of a make-to-order job shop will be used to evaluate the performance of this integrative approach to MFC. In doing so, new insights into the different roles of order release and production authorization will be gained that support researchers and practitioners in designing more effective MFC mechanisms.

2. Background

COBACABANA is first introduced in Section 2.1 before POLCA is explained in Section 2.2. A discussion is then presented in Section 2.3 where we also outline our new COBA-POLCA system.

2.1 COBACABANA

2.1.1 Mechanisms Underpinning COBACABANA

COBACABANA is an order release mechanism. Orders are not released directly onto the shop floor but remain in a backlog from where they are released to meet certain performance targets.

COBACABANA, as presented here, follows the refinements proposed by Thürer *et al.* (2014a) to Land's (2009) original card-based concept. This means that two types of cards, not one, are used: (i) operation cards, which travel with a job and signal when an operation is complete; and, (ii) release cards, which visualize the shop floor's workload situation on a centralized planning board, as will be described further below. Using the framework proposed in Liberopoulos & Dallery (2000), COBACABANA is illustrated in Figure 1 for a shop producing jobs that move from Station 1 to Station 2 to Station 3.

[Take in Figure 1]

Since we assume that there is no output queue, there are only three elements. First, queue A_i^{COBA} contains the COBACABANA cards for station i with $i = 1 \ldots n$ where n is the number of stations in the system. Second, queue P_0 is the queue of newly created jobs that are to enter the system, i.e. the backlog. This queue reflects the job arrival rate (or demand rate) λ. And third, queue PA_i contains the jobs finished at the preceding station. There is one feedback loop of operation cards between each station and the release function. This release function keeps the workload released to each station within a certain limit or norm. It can be summarized as follows.

First, jobs in the backlog P_0 are sorted according to some priority value, e.g. planned release dates. The subset of jobs to be released from the backlog is then determined by considering all orders in the backlog for release once, beginning with the first job in the sequence. For each operation in the routing of the job there is a release card, where the size of the card represents its workload. To consider a job for release, the planner places the release card(s) at each stations' area on a planning board (see Figure 2). The planner then compares the workload of each station with the predetermined workload limits. If, for any station in the routing of a job, the workload represented by the release cards on the planning board (the existing workload plus the new order's workload) exceeds its workload limit, the job is retained in the backlog and the job's release cards are removed from the planning board. Otherwise, the job's release cards remain on the planning board, the planner attaches the corresponding operation cards to the job guidance form that travels with a job through the shop floor, and the job is released. This release process continues until all jobs in the backlog have been considered for release once. The shop floor returns each operation card to the planner as soon as an operation has been completed. This closes the information loop and signals to the planner to remove the release card that matches the operation card from the planning board.

Figure 2 illustrates how the planning board is used when making a release decision. In this example, a new job with an operation at each station is considered for release. Since the operation at Station 2 cannot be loaded without exceeding the workload limit, the job is not released.

[Take in Figure 2]

Finally, the load contribution to a station in COBACABANA is calculated using the *corrected* aggregate load method. A released job contributes to a station's released workload until its operation at the station has been completed. Early studies on WLC typically focused on limiting the aggregate of the full processing times to a station, but this ignored variance in the indirect workload (i.e. the amount of work released but still upstream of a station), which is dependent on the position of a station in the routing of jobs. To estimate the input to the direct load queuing or processing at each station over time, the indirect load can be converted by dividing the processing time of the operation at a station by the station's position in a job's routing. This "corrected" aggregate load method gives the best representation of the future expected direct load of a station based on the mix of routings actually present on the shop floor (Oosterman *et al*., 2000).

2.1.2 Background to COBACABANA

COBACABANA was originally developed by Land (2009). It is the card-based equivalent of WLC, an MFC mechanism that groups together several streams of research which seek to control workloads: Order Review and Release (ORR) methods, largely developed in North America (e.g. Melnyk & Ragatz, 1989; Ahmed & Fisher, 1992); workload controlling methods building on input/output control, largely developed in the UK at Lancaster University (e.g. Kingsman *et al*., 1989; Hendry & Kingsman 1991); and, Load Oriented Manufacturing Control (LOMC), largely developed at Hanover University in Germany (e.g. Bechte, 1988; Wiendahl *et al*., 1992; Bechte, 1994). While several different approaches to WLC exist (Thürer *et al*., 2011), a major unifying principle driving WLC is input/output control, i.e. that the input rate to a shop should be equal to the output rate (e.g. Wight, 1970; Plossl & Wight, 1971). A detailed review of the WLC literature can be found in Thürer *et al*. (2011).

In the original COBACABANA system, Land (2009) used just one set of cards, where the (operation) cards *missing* from the planning board represented the released workload (rather than using explicit release cards). To allow the workload to be represented by the size of the cards, Thürer *et al*. (2014) doubled the number of cards according to function: one card (the release card) to represent the workload; and one card (the operation card) to provide feedback. Using simulation, it was shown that just three card sizes – e.g. for small, medium, and large operations – realizes most of the performance benefits of COBACABANA (Thürer *et al*., 2014). This allows processing time estimations to be greatly simplified.

In terms of WLC implementations, Bechte (1994) reported a total throughput time reduction from 14 to 9 weeks, Wiendahl *et al*. (1992) reported a 25% reduction in the total throughput time, Hendry *et al*. (2013) reported a shop floor throughput time reduction from 3 to 1-2 weeks, with the total shop floor throughput time being reduced from 45 to 40 weeks, and Hutter *et al*. (2018) reported a 40% decrease in the total throughput time. Wiendahl *et al*. (1992) further reported a reduction in lateness from 7 to 1.5 weeks. Meanwhile, Hendry *et al*. (2013) also reported a strong reduction in mean tardiness (from 12.8 to 9.4 days), but there was less of an impact in terms of the percentage tardy. The latter can be explained by the shorter due dates quoted by the company involved in the research after the implementation of WLC. All of these studies reported an improvement in production coordination as a result of WLC implementation.

2.2 POLCA

2.2.1 Mechanisms Underpinning a POLCA System

POLCA links the different stations in the routings of jobs using card loops between pairs of stations. Each pair of consecutive stations in the routing of a job has a POLCA card that identifies the two stations. These POLCA cards are job anonymous, i.e. they are assigned to station pairs and not jobs as is the case in Kanban systems (Riezebos *et al*., 2009; Ziengs *et al*., 2012). For example, a POLCA 1-2 card is used between Station 1 and Station 2. Which specific job to work on next is determined, for example, by earliest job release dates that are calculated by the MRP system for each station (Thürer *et al*., 2019b).

The card-based element of POLCA is illustrated in Figure 3 for the same shop as for COBACABANA in Figure 1 above, i.e. the shop produces jobs that move from Station 1 to Station 2 to Station 3. Since there is no output queue, there are only three elements. Queue A_i^{POLCA} contains the POLCA cards for station i with $i = 1 \ldots n$ where n is the number of stations in the system.

Queue P_0 is equivalent to queue PA_1, which consequently directly reflects the job arrival rate (or demand rate) λ. Finally, queue PA_i contains the jobs completed at the preceding station and to which a POLCA card from the preceding station is still attached.

When a customer places an order, a new job is created and enters queue PA_1 (P_0). The job waits in queue PA_1 (P_0) until a POLCA 1-2 card is available in queue A_1. Once this card is available, the job is processed and moves to the queue PA_2 of the next station with the POLCA 1-2 card still attached. The job waits in queue PA_2 until a POLCA 2-3 card is available in queue A_2. Once this card is available, the job is processed. After processing, the POLCA 1-2 card is freed and moves back to queue A_1 and the job moves to the queue of the next station PA_3 with the POLCA 2-3 card attached. Thus, card loops are overlapping since the POLCA 1-2 card is only released after the operation at Station 2 has been completed.

[Take in Figure 3]

2.2.2 Background to POLCA

Suri (1998) was the first to present POLCA as an alternative to Kanban specifically for the context of Quick Response Manufacturing or for achieving time-based competition. POLCA has remained largely unchanged since its introduction (Riezebos, 2010). One of the few improvements reported has been the introduction of color-coded cards by Pieffers & Riezebos (2006, cited in Riezebos, 2010) whereby stations are given a specific color, meaning each POLCA card (e.g. the POLCA 1-2 card) consists of two colors. Meanwhile, Vandaele *et al*. (2008) presented an approach for setting the number of POLCA cards in accordance with expected demand in the context of an electronic POLCA system. More recently, Thürer *et al*., (2017b) demonstrated that performance gains can be obtained via the use of a simple starvation avoidance mechanism and the use of different rules for card allocation and dispatching other than the earliest release date rule typically applied in POLCA studies. While no explicit review paper on the POLCA literature exists, an extensive overview is provided within the work of Riezebos (2010) and Suri (2018).

In terms of POLCA implementations, Krishnamurthy & Suri (2009) reported that in one company the total throughput time was reduced across different products by between 22% and 68% and in another company by an average of 25%. Meanwhile, Riezebos (2010) reported a total throughput time reduction of more than 70%. In all implementations, like WLC, POLCA improved production coordination.

2.3. Discussion: The New COBA-POLCA System

WLC, the MFC mechanism underlying COBACABANA, has been under development for more than 40 years. Meanwhile, POLCA has been developed for more than 20 years. Both research streams have evolved independently and the two MFC mechanisms are considered to be competing with each other for adoption. In other words, the question is typically whether COBACABANA *or* POLCA should be applied. However, the description of the card-based elements of COBACABANA and POLCA in Figure 1 and Figure 3, respectively, highlights the limited overlap in the control spheres of these MFC mechanisms. While POLCA controls the material flow on the shop floor, the queue PA_1 at the first station in the routing of a job is equivalent to the backlog P_0 and consequently directly reflects the job arrival rate (or demand rate) λ. It is not controlled. In contrast, COBACABANA controls the job arrival rate to the shop and thus the queue PA_1; in fact, buffering the manufacturing system from variability in the job arrival rate to the shop was seen as one of the main benefits of order release (Melnyk & Ragatz, 1989). However, order release does not control the flow of material on the shop floor. All feedback loops connect stations to the centralized release function and no further control actions are possible once a job has been released.

In response, we will integrate COBACABANA *and* POLCA, thereby addressing both MFC control problems: (i) the problem of whether a job should be released onto the shop floor; and, (ii) the problem of whether a station should be authorized to produce. COBACABANA is used to control the release of jobs to the shop floor, i.e. the release from the backlog P_0 to the queue of the first station in the routing of a job PA_1. POLCA is then used to control the release of jobs from each queue PA_i to the corresponding station, thereby controlling production authorization. The structure of COBA-POLCA's card-loops is illustrated in Figure 4, with COBACABANA loops given by a dashed line and POLCA loops given by a dotted line.

[Take in Figure 4]

Discrete event simulation will be used next to evaluate the performance impact of the integrated MFC mechanism.

3. Simulation Method

3.1 Overview of Simulated Shop and Job Characteristics

A simulation model of a general flow shop has been implemented using ARENA simulation software. Make-to-order companies that produce a high variety of products often use a functional layout and operate as some form of job shop. Enns (1995, p.2804) further argued that '*routeing in most real job shops lies somewhere between the pure job shop and pure flow shop extremes.*' This 'in-sequence with bypassing flow' is characteristic of the general flow shop (Aneke & Carrie, 1986), which is the environment that is considered in our study. Our model is stochastic, whereby job routings, processing times, inter-arrival times and due dates are stochastic (random) variables. The shop contains six stations, where each station is a single constant capacity resource. The routing length varies uniformly from one to six operations. All stations have an equal probability of being visited and a station is required at most once in the routing of a job. The resulting routing vector (i.e. the sequence in which stations are visited) is sorted.

Operation processing times follow a truncated 2-Erlang distribution with a maximum of 4 time units and a mean of 1 time unit before truncation. Set-up times are considered as part of the operation processing time. Meanwhile, the inter-arrival time of orders follows an exponential distribution with a mean of 0.642, which deliberately results in a utilization level of 90%. As in most previous simulation studies on COBACABANA and POLCA, due dates are set exogenously by adding a random allowance factor to the job entry time. This factor is uniformly distributed and arbitrarily set between 30 and 50 time units. Additional experiments were conducted using the total work content of jobs for setting the due date allowance, since this may be more relevant for practice. These results are given in the online Appendix A. The results are not presented in the main body of the paper since the type of allowance did not affect our qualitative conclusions in terms of the material flow control mechanism.

Finally, Table 1 summarizes the simulated shop and job characteristics. While any individual high-variety shop in practice will certainly differ from our stylized model, our model captures the high routing variability, processing time variability, and arrival variability that defines this context in practice.

[Take in Table 1]

3.2 Manufacturing Flow Control (MFC)

As in previous simulation studies on COBACABANA (e.g. Thürer *et al*., 2014, 2019a) and POLCA (Lödding *et al*. 2003; Fernandes & Carmo-Silva, 2006; Germs & Riezebos 2010; Harrod

& Kanet, 2013; Thürer *et al*., 2017b), it is assumed that materials are available and all necessary information regarding shop floor routing and processing times is known upon the arrival of an order (job) to the shop. Once a job has arrived at the shop, it flows into the backlog to await release according to COBACABANA.

3.2.1 COBACABANA

COBACABANA is realized as a continuous release mechanism, i.e. the release decision can be taken at any moment in time, as for POLCA. Jobs are sequenced according to planned release dates, which are equivalent to the earliest release date at the first station in the routing of a job, as calculated by POLCA (and described below). Seven workload limit levels are considered. The lowest limit level was set to 5 time units to allow for the release of jobs with the maximum processing time. The limit is increased stepwise by multiplying the previous level by 1.25 and rounding it to one decimal place. This results in the following seven levels: 5, 6.3, 7.8, 9.8, 12.2, and 15.3 time units. Finally, as a baseline measure, experiments with an infinite limit have also been executed. This is equivalent to immediate release and allows the performance impact of POLCA, which will be described next, to be isolated.

3.2.2 POLCA

Once a job is released, it enters the shop floor and awaits production authorization according to POLCA. POLCA loops reflect every possible routing step for a job. Four levels for the number of cards per loop are considered: 3, 4, 6, and 10 cards per loop. The same number of cards is used within each loop in each experiment, which is justified by the balanced shop considered in our study. As a baseline measure, experiments with an infinite number of POLCA cards have also been executed. This allows the performance impact of COBACABANA to be isolated, as was described above.

Meanwhile, POLCA uses starvation avoidance cards, as proposed in Thürer *et al*. (2017b). On some occasions, a station may be starving although there is work in the queue, e.g. when all available POLCA cards that authorize production at that station are at the succeeding station. This form of premature idleness (Kanet, 1988; Land & Gaalman, 1998) can be resolved by attaching a starvation avoidance card to a job, thereby allowing it to be processed at the starving station. Using a starvation avoidance card means that the work-in-process cap or limit will be exceeded. In order to restore the limit, POLCA cards do not become available after being detached from jobs as long as starvation avoidance cards are in use on the shop floor. Only after all starvation avoidance cards have been returned can POLCA cards be used again.

Finally, the card allocation and dispatching rule advocated in POLCA is the earliest release date rule, where the earliest release date is calculated by backward scheduling from the job due date based on throughput time allowances for each operation in the routing of a job. As suggested for POLCA (Riezebos, 2010), we use a constant allowance for the planned operation throughput time that is offset at each level. This allowance is based on preliminary simulation experiments.

3.3 Experimental Design and Performance Measures

The experimental factors are: (i) the seven different limit levels for COBACABANA; and, (ii) the five levels for the number of cards for POLCA. A full factorial design was used with 35 (7x5) scenarios, where each scenario was replicated 100 times. Results were collected over 13,000 time units following a warm-up period of 3,000 time units. These simulation conditions are in line with those used in previous studies that applied similar job shop models (e.g. Land, 2006; Thürer *et al.*,

2012) and allow us to obtain stable results while keeping the simulation run time to a reasonable level.

Our focus is on assessing the performance of MFC in a make-to-order context. The on-time delivery adherence of jobs is therefore considered the major performance criterion (Teo *et al.*, 2012). The four principal performance measures considered in this study are as follows: *the mean shop floor throughput time* – the mean of the completion date minus the authorization date (i.e. the date on which the job received a POLCA card at the first station in its routing) across jobs; *the mean total throughput time* – the mean of the completion date minus the backlog entry date across jobs; *the percentage tardy* – the percentage of jobs completed after the due date; and, *the mean tardiness* – the conditional lateness, that is $T_j = \max(0, L_j)$, with L_j being the lateness of job *j* (i.e. the actual delivery date minus the due date of job *j*).

4. Results

Statistical analysis of our results was conducted using an ANOVA (An͟alysis o͟f V͟ariance). The results presented in Table 2 give a first indication of the relative performance effects of our two MFC mechanisms. The main effect of both the limit level for COBACABANA and the setting for the number of cards for POLCA were shown to be statistically significant; both are used to model the strength of control exercised by each MFC mechanism. Meanwhile, the main effect of COBACABANA appears to be stronger, specifically in terms of the percentage tardy and the mean tardiness results. Interestingly, two-way interactions for total throughput times, the percentage tardy, and mean tardiness were not found to be statistically significant. This suggests that the performance effects of COBACABANA and POLCA are independent, i.e. that the performance of one does not significantly affect the performance of the other. There are two possible explanations for this: (i) there is no performance effect; and/or, (ii) the performance effects of COBACABANA and POLCA within COBA-POLCA are complementary. Detailed performance results will be presented next.

[Take in Table 2]

4.1 Assessment of Results

Detailed performance results are given in Table 3 together with the 95% confidence intervals. The different levels of the workload limit are given in the rows while the different settings for the number of POLCA cards are given in the columns.

[Take in Table 3]

The following can be observed from the results:

- *COBACABANA*: The results for COBACABANA in isolation are given in the last column (which is marked using grey color), i.e. the number of POLCA cards is infinite and only simple dispatching is applied on the shop floor. As expected from previous literature (e.g. Thürer *et al.*, 2014b), COBACABANA enables performance to be improved significantly across all performance measures considered in this study compared to the results for immediate release (marked black). When workload limits are tightened, less work is released to the shop floor and shop floor throughput times decrease. But this does not necessarily mean that total throughput times decrease (Germs & Riezebos, 2010) since the unreleased work is still in the backlog. The decrease in total throughput times observed highlights that COBACABANA effectively balances the workload. Meanwhile, when limits are tightened, large jobs may find it harder to fit within the workload limit. This explains the increase in terms of the mean tardiness if the limits are too tight. For the best-performing limit level in terms of the mean tardiness (9.8), a mean tardiness reduction of about 27% and a percentage tardy reduction of about 43% can be observed when compared to immediate release. For this scenario, the reduction in shop floor throughput time is approximately 14%, whilst total throughput times are reduced by approximately 5%.

- *POLCA*: The rows marked grey give the results for POLCA in isolation, i.e. COBACABANA's workload limit is infinite and jobs are released immediately to the shop floor. As expected from previous literature (e.g. Thürer *et al.*, 2017b), POLCA allows performance to be improved significantly across all performance measures considered in this study compared to not using POLCA, which is given by the last column (i.e. an infinite number of POLCA cards) marked black. POLCA, as implemented here, neglects the actual work content of a job. Thus, the probability of receiving a POLCA card is the same for small and large jobs. As a consequence, mean tardiness performance is less sensitive to the setting of the number of POLCA cards. For the best-performing level of number of POLCA cards (which is 4), a mean tardiness and a percentage tardy reduction of about 13% can be observed when compared to not using POLCA. For this scenario, the shop floor throughput time reduction is about 22% and the total throughput time reduction is about 8%.
- *COBA-POLCA*: The remaining cells reveal the combined effect of COBACABANA and POLCA. If we focus on these results, we can observe that incorporating POLCA into COBACABANA allows shop floor throughput times to be reduced, i.e. for each setting of COBACABANA's workload limit (each row) the shop floor throughput time reduces if we move from right to left (within each row). This improvement is between 15% and 26%. As somewhat expected, the size of the improvement reduces with tighter COBACABANA limits.

The reduction of shop floor throughput times is accompanied by a reduction in the total throughput time of between 6% and 9%. Meanwhile, the percentage tardy reduction when POLCA is incorporated into COBACABANA is between 1% and 14%, and the mean tardiness reduction is between 6% and 14%. Note that these performance improvements are in addition to the performance improvements realized by COBACABANA, which was argued to be the best-performing material flow control mechanism for the production context under study. If we compare the best-performing parameter setting of COBA-POLCA in terms of the mean tardiness (a workload limit of 9.8 and 4 POLCA cards) with not using material flow control (the cells marked black), we can observe a percentage tardy reduction of almost 50% (from 11.32% to 5.81%), a mean tardiness reduction of about 34% (from 1 to 0.66 time units), a total throughput time reduction of more than 10% (from 23.62 to 20.84 time units), and a shop floor throughput time reduction of almost 30% (from 23.62 to 16.85 time units). Meanwhile, if a 20% reduction in mean tardiness is accepted (a workload limit of 7.8 and 4 POLCA cards) then the percentage tardy can be reduced by almost 70% (from 11.32 to 3.57), whilst realizing further reductions in shop floor and total throughput times.

4.2 Discussion of Results

The results in Table 3 above highlight that: (i) the performance impacts of COBACABANA and POLCA are independent of one another; and (ii) the performance impacts complement each other. The former is also supported by our previous argument that COBACABANA and POLCA focus on different aspects of MFC control: order release and production authorization, respectively. Nonetheless, this somewhat comes as a surprise. It is known that order release reduces the number of jobs on the shop floor, which negatively impacts the performance of shop floor dispatching rules since selection possibilities are reduced (Ragatz & Mabert, 1988). A similar effect would therefore have been expected for POLCA, i.e. less of a performance impact at tighter norms. However, dispatching determines *which* job should be produced next at a station, while an MFC mechanism such as POLCA decides *whether* any job should be produced in the first place (Graves *et al*., 1995). While the former focusses on the production sequence, the latter allows for workload limiting. Reducing the number of jobs, and thus the selection possibilities, has a direct effect on sequencing permutations and thus dispatching. However, it does not affect the load limiting capabilities of an MFC mechanism such as POLCA, which explains the results that we have obtained.

In terms of our three MFC mechanisms – COBACABANA, POLCA, and COBA-POLCA – the following insights were gained:

- *COBACABANA*: The main objective of COBACABANA is the control of the direct load queuing at each station. The direct load should be kept at a small and stable level to act as an efficient buffer (Thürer *et al*., 2012). However, order release mechanisms such as DBR, ConWIP, WLC, and COBACABANA do not control the direct load at a station. This is because there is a time delay between the control decision (order release) and the occurrence of the effect (the arrival of the job at the station), which leads to indirect load, i.e. workload that is released but still upstream of the station. Although different methods exist to predict when a job's workload will actually materialize at a station (see, e.g. Bechte, 1988; Oosterman *et al*., 2000), the direct load in a job shop will inevitably fluctuate (Land & Gaalman, 1998). Thus, there will be superfluous direct load, which provides POLCA with scope to create improvement.
- *POLCA*: POLCA is typically considered an order release system and compared, for example, to ConWIP. But our study highlights that POLCA gains the majority of its performance impact

on the shop floor with order release executed and the number of jobs under POLCA control limited by another, higher level release mechanism. In other words, POLCA improves performance by authorizing the processing of an order based on the available capacity at the next station in the routing of an order (Germs & Riezebos, 2010), rather than through order release control.

- *COBA-POLCA*: COBACABANA ensures that the set of jobs on the shop floor creates a balanced workload made up of the most urgent orders. It efficiently combines load balancing and timing considerations (Thürer *et al*., 2015). However, there is still superfluous direct load, as can be observed from Figure 5, which depicts the frequency distribution of the direct load for each station for the different POLCA card levels and a COBACABANA limit of 7.8 time units. The direct load at Station 1 does not violate this limit due to the directed routing, i.e. there is no indirect load at Station 1. Since COBACABANA constantly seeks to fill the limit, the peak of the distribution if POLCA is not applied (i.e. when there is an infinite number of POLCA cards) is on the right-hand side close to the limit. In other words, there is a high superfluous direct load. If POLCA is applied then the distribution is shifted to the left and the superfluous direct load is reduced. Further reducing the superfluous direct load leads to additional performance gains (Land & Gaalman, 1998). At the same time, starvation avoidance cards ensure that the tighter control of the direct load does not lead to premature station idleness (Kanet, 1988; Land & Gaalman, 1998), i.e. that a station starves due to the workload limit that is applied at an upstream station. If we move downstream from Station 1 to Station 6 in Figure 5, a strong reduction in the control that can be exercised by COBACABANA can be observed from the results for an infinite number of POLCA cards. As is known from the WLC literature, a tighter degree of control can be exercised at upstream stations (Thürer *et al.*, 2012). In contrast, the control of the direct load exercised by POLCA appears to be less affected. The decrease in control observed for POLCA when moving downstream is directly related to the probability that a station is the last in the routing of orders, and thus not contained in a POLCA loop (Vandaele *et al*. 2008). This also explains why there is no impact at Station 6 – in a general flow shop, this is necessarily the last routing step for jobs that must visit this station.

[Take in Figure 5]

5. Conclusions

Many competing MFC mechanisms have been presented in the literature. They include Kanban, DBR, ConWIP, POLCA, WLC, and COBACABANA. Existing literature on these MFC mechanisms typically argues for the superiority of one mechanism over the other. The question typically considered is, for example, whether COBACABANA *or* POLCA should be applied. However, the literature overlooks the fact that these systems only focus on one of the two MFC problems. They either determine whether a job should be released onto the shop floor (DBR, ConWIP, WLC, and COBACABANA) or whether a shop floor station should be authorized to produce (Kanban and POLCA). We have therefore called for a paradigm shift and argued that the above MFC mechanisms should not play competing but rather complementary roles. To support this argument, we have combined two well-known MFC mechanisms in high-variety make-to-order shops – COBACABANA *and* POLCA – into a new COBA-POLCA mechanism. Using simulation, we have demonstrated how COBA-POLCA improves performance compared to the use of either COBACABANA or POLCA in isolation, with important implications for practice and research.

5.1 Managerial Implications

We have demonstrated that the spheres of control of both systems do not overlap. Thus, existing implementations of either system can simply be extended and further performance gains can be obtained. In general, a stepwise implementation starting with one MFC mechanism is in fact recommended. Results suggest that there is no interaction in terms of parameter setting. This means that the settings for the workload limit in COBACABANA or the number of cards in POLCA that are currently used can be maintained. The newly introduced MFC mechanism should be implemented gradually by starting with a large limit or a large number of cards. Control can then be tightened to realize performance improvements until the point where performance starts to deteriorate is reached. Finally, the system outlined here is a card-based system; hence, no investment in technology is needed. The system can of course also be implemented as a partially or fully computerized system using WLC instead of COBACABANA and using an electronic version of POLCA, as in Vandaele *et al*. (2008).

5.2 Limitations and Future Research

A main limitation of our study is the limited environmental setting. For example, we used only one setting for the routing characteristic (i.e. the general flow shop), the degree of processing time variability, and the due date tightness. We also considered all due dates to be set exogenously and independently from job characteristics. In practice a company may have some control over the due dates, and due dates may depend on job or shop characteristics. Future research could therefore explore the link between the MFC mechanism(s) and due date setting rule. Future research could also seek to develop new comprehensive MFC mechanisms. A significant amount of literature seeks to establish the prevalence of one MFC mechanism over another. But this literature typically overlooks the fact that existing mechanisms only focus on one of the two MFC control problems.

So future research should seek to learn from the different MFC mechanisms to develop new mechanisms that address both control problems together.

Hopp & Spearman (2004) argued that it is the work-in-process cap that explains the majority of the success of pull systems such as Kanban since it leads to less congestion (Spearman & Zazanis, 1992) and more stable throughput times. Consequently, the work-in-process cap may appear to be a good starting point for the development of new MFC mechanisms. However, the work-in-process cap represents an upper bound only. It was developed to curb overproduction (Ohno, 1988); it does not ensure a small and stable direct load in front of each station. Our study has emphasized two important design principles for effective MFC. First, that the prevention of superfluous direct load at each station should be the basis of any MFC mechanism for high-variety shops. And second, that any limits on the workload should not be rigid to avoid premature station idleness. This supports earlier findings in Land & Gaalman (1998) and significantly changes the way in which MFC mechanisms should be designed.

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Table 1: Summary of Simulated Shop and Job Characteristics

Shop Characteristics	Routing Variability No. of Stations Station Capacities Station Utilization Rate	Random routing; directed, no re-entrant flows 6 All equal 90%
Job Characteristics	No. of Operations per Job Operation Processing Times Due Date Determination Procedure Inter-Arrival Times	Discrete Uniform[1, 6] Truncated 2–Erlang; (mean ≈ 1; max = 4) Due Date = Entry Time + *d*; *d* U ~ [30, 50] Exp. Distribution; mean = 0.642

Table 2: ANOVA Results

	Source of Variance	Sum of Squares	Degrees of freedom	Mean Squares	F-Ratio	p-Value
Shop Floor Throughput Time	COBACABANA (COBA)	19048.24	6	3174.71	2845.20	0.00
	POLCA	10021.38	4	2505.34	2245.31	0.00
	COBA x POLCA	960.85	24	40.04	35.88	0.00
	Error	3866.29	3465	1.12		
Total Throughput Time	COBACABANA (COBA)	3947.71	6	657.95	268.72	0.00
	POLCA	1810.11	4	452.53	184.82	0.00
	COBA x POLCA	45.59	24	1.90	0.78	0.77
	Error	8484.07	3465	2.45		
Percentage Tardy	COBACABANA (COBA)	28900.16	6	4816.69	597.15	0.00
	POLCA	277.10	4	69.28	8.59	0.00
	COBA x POLCA	158.85	24	6.62	0.82	0.71
	Error	27949.01	3465	8.07		
Mean Tardiness	COBACABANA (COBA)	405.81	6	67.64	306.69	0.00
	POLCA	4.26	4	1.06	4.82	0.00
	COBA x POLCA	1.47	24	0.06	0.28	1.00
	Error	764.14	3465	0.22		

Table 3: Simulation Results for COBACABANA, POLCA, and COBA-POLCA

	COBACABANA Limits	**POLCA Cards**				
		3	4	6	10	Infinite
Shop Floor Throughput Time (time units)	5	12.09±0.07	12.86±0.07	13.86±0.08	14.26±0.09	14.28±0.09
	6.3	13.55±0.10	14.45±0.10	15.79±0.12	16.56±0.13	16.64±0.14
	7.8	14.76±0.13	15.73±0.14	17.27±0.15	18.43±0.18	18.65±0.19
	9.8	15.79±0.17	16.85±0.17	18.52±0.19	20.00±0.22	20.47±0.24
	12.2	16.48±0.20	17.58±0.21	19.33±0.23	21.04±0.27	21.80±0.30
	15.3	16.90±0.22	18.03±0.23	19.87±0.25	21.67±0.29	22.72±0.34
	Infinite	17.24±0.25	18.41±0.26	20.29±0.28	22.18±0.33	23.62±0.41
Total Throughput Time (time units)	5	18.71±0.25	18.99±0.25	19.59±0.26	19.96±027	19.99±0.27
	6.3	19.24±0.26	19.52±0.26	20.22±0.27	20.75±0.28	20.82±0.28
	7.8	19.89±0.27	20.19±0.27	20.90±0.29	21.53±0.30	21.69±0.31
	9.8	20.49±0.29	20.84±0.30	21.55±0.31	22.21±0.33	22.46±0.34
	12.2	20.93±0.32	21.26±0.32	21.97±0.33	22.67±0.35	23.00±0.37
	15.3	21.20±0.33	21.53±0.33	22.27±0.34	22.94±0.36	23.36±0.38
	Infinite	21.45±0.35	21.77±0.35	22.51±0.36	23.18±0.38	23.62±0.41
Percentage of Tardy Jobs (%)	5	3.49±0.14	3.48±0.14	3.46±0.13	3.50±0.14	3.50±0.14
	6.3	3.06±0.19	2.90±0.18	2.87±0.18	2.92±0.18	2.96±0.18
	7.8	4.17±0.35	3.57±0.32	3.51±0.32	3.76±0.33	3.85±0.34
	9.8	6.56±0.56	5.81±0.53	5.72±0.53	6.13±0.57	6.42±0.59
	12.2	8.60±0.70	7.78±0.67	7.72±0.70	8.38±0.75	8.79±0.78
	15.3	9.74±0.74	8.88±0.73	9.10±0.75	9.70±0.79	10.29±0.83
	Infinite	10.66±0.81	9.86±0.79	10.08±0.81	10.72±0.86	11.32±0.90
Mean Tardines (time units)	5	1.73±0.11	1.69±0.10	1.73±0.10	1.78±0.10	1.79±0.10
	6.3	1.13±0.08	1.11±0.08	1.14±0.08	1.18±0.09	1.19±0.08
	7.8	0.83±0.07	0.80±0.07	0.82±0.07	0.86±0.07	0.87±0.07
	9.8	0.72±0.08	0.66±0.07	0.67±0.07	0.70±0.08	0.73±0.08
	12.2	0.78±0.09	0.69±0.09	0.68±0.09	0.73±0.09	0.76±0.09
	15.3	0.87±0.10	0.75±0.10	0.75±0.10	0.80±0.11	0.87±0.11
	Infinite	1.01±0.12	0.87±0.11	0.87±0.12	0.93±0.12	1.00±0.13

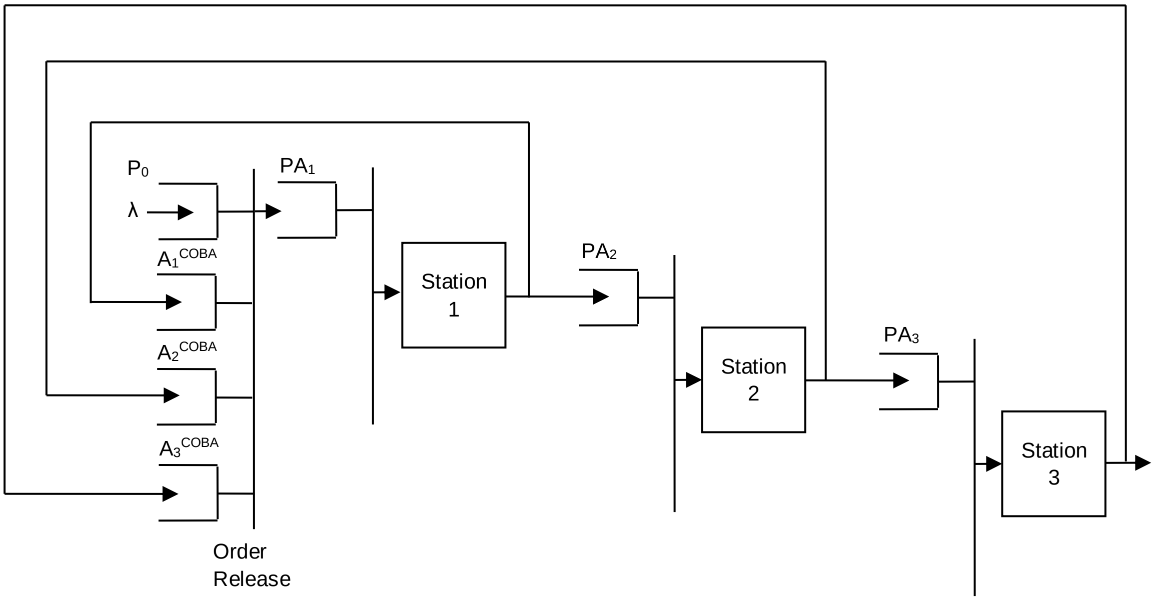

Figure 1: COBACABANA's Card-Based Control Loops

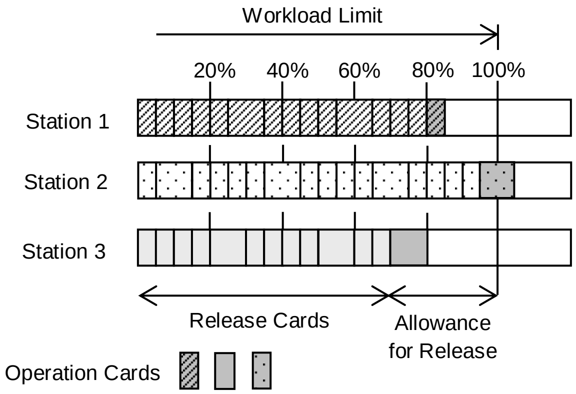

Figure 2: The Planner's Planning Board for COBACABANA Order Release (with an Example Release Decision)

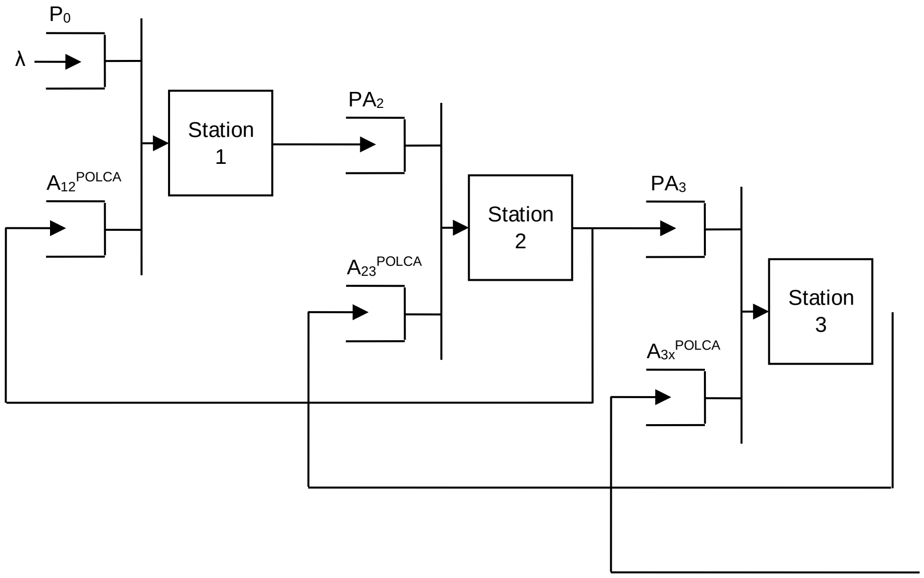

Figure 3: POLCA's Card-Based Control Loops

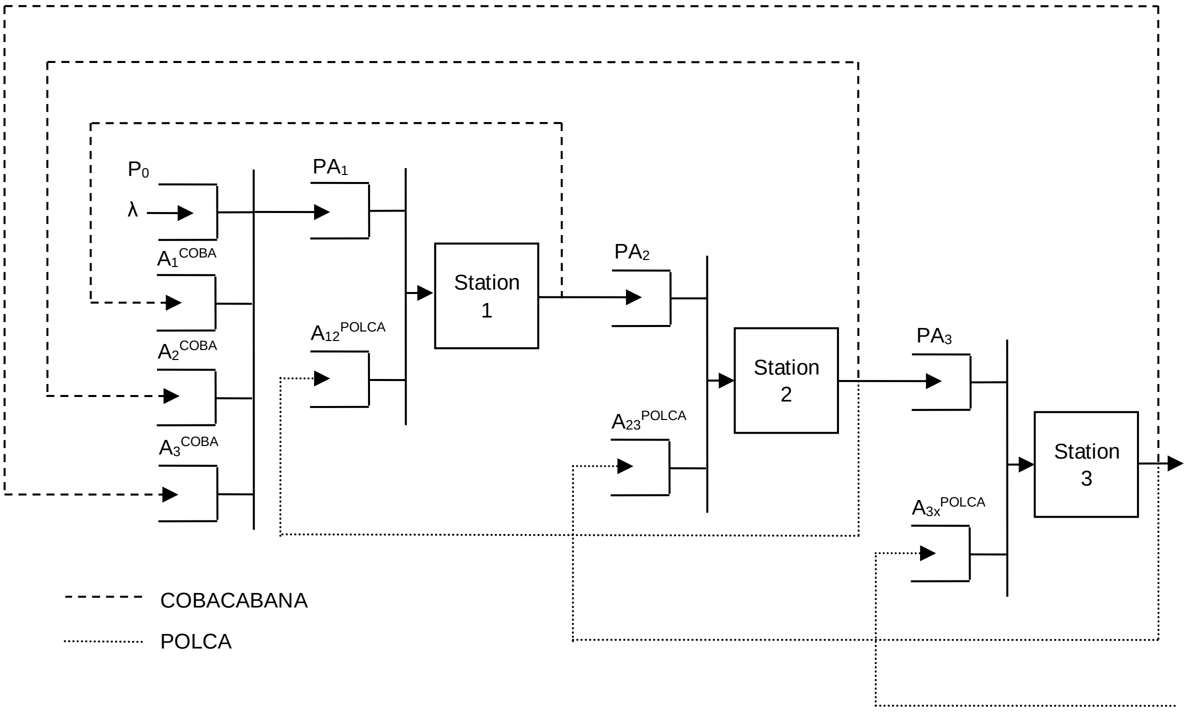

Figure 4: COBA-POLCA's Card-Based Control Loops

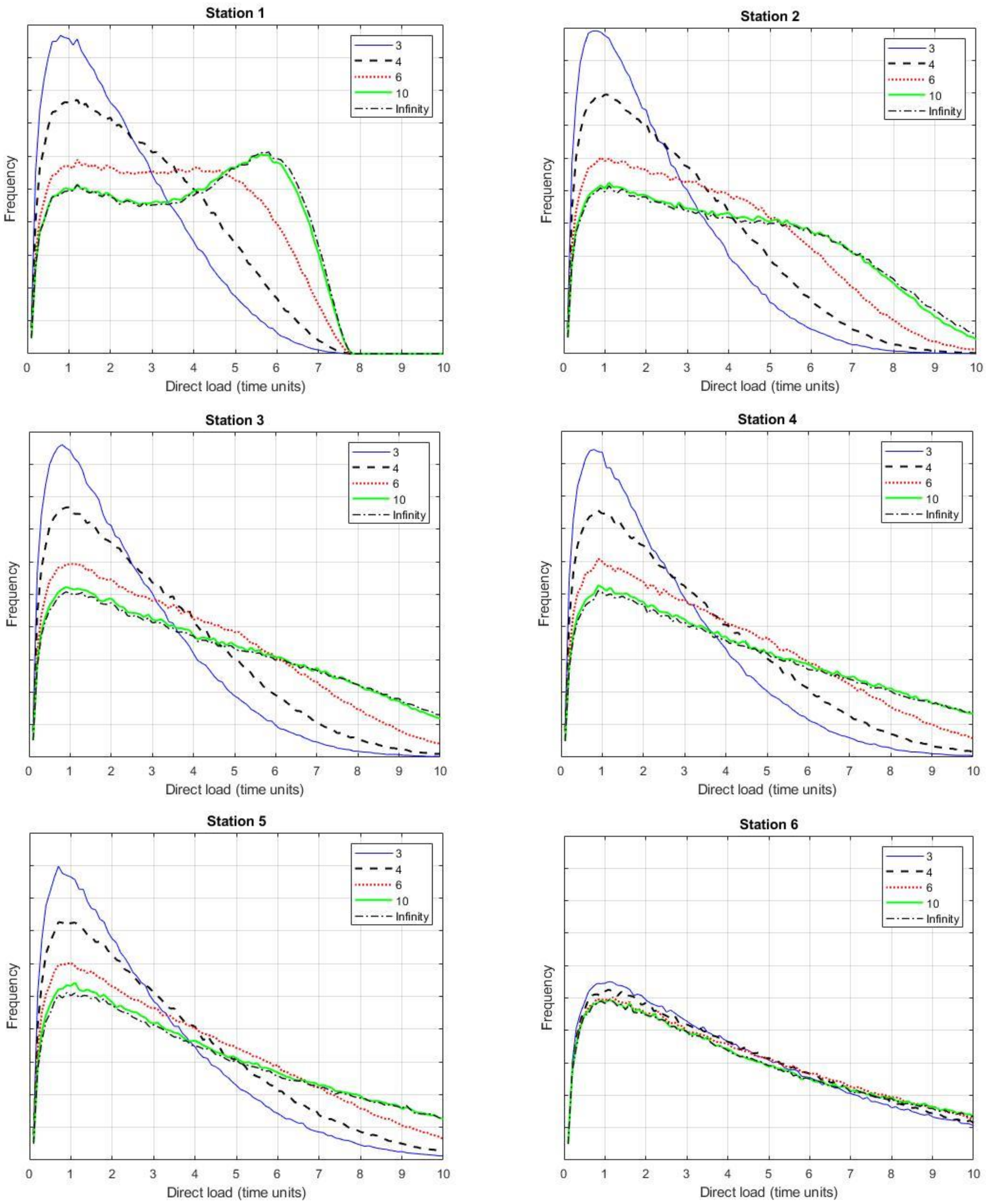

Figure 5: COBA-POLCA – Analyzing the Impact of POLCA on the Direct Load at Each Station (with a COBACABANA Workload Limit of 7.8 Time Units)