

On the Integration of Input and Output Control: Workload Control Order Release

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Abstract

Workload Control is a production planning and control concept developed for high-variety job shops. It integrates two control mechanisms: (i) input control, to regulate the inflow of work to the system; and (ii) output control, which uses capacity adjustments to regulate the outflow of work from the system. Much Workload Control research has focused on input control, while output control has been largely neglected. Only recently has research emerged that uses Workload Control theory to guide capacity adjustments. Yet this literature focuses on capacity adjustments (output control) only – it fails to integrate it with Workload Control’s input control element. In response, this study explores the performance impact of Workload Control when input control (controlled order release) and output control (capacity adjustments) are combined. Job shop simulation results demonstrate that input and output control can and should play complementary roles. Both elements significantly enhance performance in isolation, and performance effects appear to complement each other. Further, results indicate that the choice of the workload threshold that triggers capacity adjustments has a stronger impact on performance than the actual size of the adjustment. The measure of workload used to guide the load-based order release decision is also used to determine the workload threshold that triggers the capacity adjustment. This facilitates implementation in practice. Finally, although our study is on Workload Control, the findings have important implications for other production planning and control concepts.

Keywords: *Order Release; Capacity Adjustments; Input / Output Control; Workload Control.*

1. Introduction

Workload Control is a production planning and control concept that was developed for high-variety contexts, such as small and medium-sized make-to-order companies, which often have a job shop configuration (Zäpfel & Missbauer, 1993; Stevenson *et al.*, 2005). The concept has been shown to significantly improve the performance of job shops both through simulation (e.g. Thüerer *et al.*, 2012, 2014a) and, on occasions, in practice (e.g. Wiendahl, 1992; Bechte 1994; Hendry *et al.*, 2013; Silva *et al.*, 2015). While there exists several different approaches to Workload Control (Thüerer *et al.*, 2011), a major unifying principle driving Workload Control 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). Consequently, there are two control mechanisms within the Workload Control concept (e.g. Land & Gaalman, 1996; Kingsman, 2000): (i) *input control*, which regulates the work that can enter the shop and/or shop floor; and (ii) *output control*, which uses capacity adjustments to regulate the outflow of work. While input control has received much attention in the Workload Control literature (e.g. Melnyk & Ragatz, 1989; Philipoom *et al.* 1993; Bergamaschi *et al.*, 1997; Sabuncuoglu & Karapinar, 1999; Land, 2006; Fredendall *et al.*, 2010; Thüerer *et al.*, 2012, 2015a), how output control can be effectively realized has been largely neglected. Recently, research has emerged that uses Workload Control theory to guide output control decisions – in particular, when to adjust capacity (Land *et al.*, 2015; Thüerer *et al.* 2014b, 2015b). But this recent research has neglected the input control element of Workload Control. In response, this study examines the combined impact of input control (in the form of order release) and output control within Workload Control.

Order release is one of the key mechanisms for realizing input control within Workload Control. Order release decouples the shop floor from higher level planning. Jobs are not released

onto the shop floor immediately but flow into a pre-shop pool from which they are released to meet due dates while also keeping work-in-process within limits or norms. This buffers the shop floor against variance in the incoming order stream (Melnik & Ragatz, 1989; Thürer *et al.*, 2012). Although order release can stabilize the workload on the shop floor, there remains variability in the workload accepted by a company: the planned workload. Order release does not affect the rate at which work arrives at the shop; it just controls the release rate to the shop floor. It typically shifts variability from the shop floor to the pre-shop pool. This means that the probability of temporary periods of high and low (planned) loads occurring is not, or only moderately, affected. These high load periods, i.e. periods during which more work arrives at the shop than a particular station can handle, have a direct detrimental effect on performance. The longer such a period persists, the more probable it is that congestion will increase workloads to a degree that causes the due dates of orders to be exceeded (Land *et al.* 2015).

Since the probability of high load periods is not reduced by order release control, another control mechanism is required. Thürer *et al.* (2014a) showed how influencing the probability of winning an order through the competitiveness of the bid can be used to level the planned workload over time. However, this hinges on the assumption that jobs can be rejected (and so never enter the planned workload) without affecting the average throughput rate, i.e. it is assumed that there is a competitive environment where the work available exceeds the amount of work accepted or won. An alternative approach for handling high load periods is output control on the shop floor in the form of capacity adjustments.

Land *et al.* (2015) recently demonstrated that small, timely capacity adjustments that alleviate capacity shortages in high load periods can significantly improve performance. These capacity adjustments were triggered when the workload at a station surpassed a certain workload

threshold. But although Land *et al.* (2015) used a measure of the workload that was derived from Workload Control theory, their procedure was not applied to a shop using Workload Control's input control mechanism. To the best of our knowledge, no work exists in the Workload Control literature that looks at the combined effect of input and output control. In response, this study has two objectives:

- (i) To outline how Workload Control order release (input control) and the output control procedure for capacity adjustments introduced by Land *et al.* (2015) can be combined; and,
- (ii) To use simulation to assess – for the first time – the performance impact of Workload Control as a concept that combines input control (in the form of order release) with output control (in the form of capacity adjustments).

The remainder of this paper is structured as follows. In Section 2, we review the Workload Control literature on order release (input control) and capacity adjustments (output control) to identify the methods to be applied in this study. The simulation model used to evaluate performance is then described in Section 3 before the results are presented, discussed and analyzed in Section 4. Finally, conclusions are drawn in Section 5, where managerial implications and future research directions are also outlined.

2. Literature Review

Although it is acknowledged that input control may be exercised at several points within the Workload Control concept (job entry, order release, etc.), we focus on order release since it is the most widely applied approach in the literature. In Section 2.1, we first review the Workload Control literature on order release to identify the release method to be considered in our study. Section 2.2 then reviews the Workload Control literature that focuses on output control and

outlines how input control (in the form of order release) and output control can be combined within Workload Control.

2.1 Workload Control Order Release Method (Input Control)

There are many order release methods in the Workload Control literature; for examples, see the reviews by Wisner (1995), Land & Gaalman (1996), Bergamaschi *et al.* (1997), Sabuncuoglu & Karapinar (1999) and Fredendall *et al.* (2010). In this paper, the LUMS COR (Lancaster University Management School Corrected Order Release) method is used because it was recently shown to be the best order release solution for Workload Control (Thürer *et al.*, 2012a). LUMS COR uses a *periodic* release procedure, executed at fixed intervals, to control and balance the shop floor workload. This procedure keeps the workload W_s released to a station s within a workload norm pre-established by management as follows:

- (1) All jobs in the set of jobs J in the pre-shop pool are prioritized according to a pool sequencing rule (e.g. planned release date).
- (2) The job $j \in J$ with the highest priority is considered for release first.
- (3) Take R_j to be the ordered set of operations in the routing of job j . If job j 's processing time p_{ij} at the i^{th} operation in its routing – corrected for station position i – together with the workload W_s released to station s (corresponding to operation i) and yet to be completed fits

$$\text{within the workload norm } N_s \text{ at this station, that is } \frac{p_{ij}}{i} + W_s \leq N_s \quad \forall i \in R_j, \quad (1)$$

then the job is selected for release. That means it is removed from J , and its load

$$\text{contribution is included, i.e. } W_s := W_s + \frac{p_{ij}}{i} \quad \forall i \in R_j. \quad (2)$$

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

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

A released job contributes to W_s until its operation at this station is completed. Early studies on Workload Control 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 upstream work), which is dependent on the position of a station in the routing of jobs. Therefore, the load contribution to a station in LUMS COR is calculated by dividing the processing time of the operation at a station by the station's position in the job's routing. Using this "corrected" measure of the aggregate workload (Oosterman *et al.*, 2000) recognizes that a job's contribution to a station's direct load is limited to only the proportion of time that the job is actually queuing and being processed at the station instead of the full time between release and completion at a station.

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

2.2. Workload Control and Capacity Adjustments (Output Control)

To the best of our knowledge, no study has been presented in the literature that looks at the combined effect of input control via order release and output control. The only two studies that have examined the combined effect of input and output control, presented by Hendry *et al.* (1998) and Kingsman & Hendry (2002), focused on job entry rather than order release. Both papers operationalized input control by rejecting orders that did not fit within a predetermined maximum of the planned workload (similar to, e.g. Philipoom & Fry, 1992; Moreira & Alves, 2009). Meanwhile, the authors operationalized output control by adjusting capacity so that an order may fit within the maximum workload norm.

Here, it is argued that, in general, it is unlikely that a company will reject an order – rather, a longer due date may be quoted or work subcontracted. Workload Control theory has recently been used to guide subcontracting decisions in job shops where average demand exceeds available capacity. Thürer *et al.* (2014b, 2015b) demonstrated that basing the decision concerning which jobs to subcontract and which jobs to process internally on well-established measures of the workload derived from the Workload Control literature significantly improves performance compared to alternative rules (such as those presented in Bertrand & Sridharan, 2001). However, the rules in Thürer *et al.* (2014b, 2015b), like those in Hendry *et al.* (1998) and Kingsman & Hendry (2002), focused on job entry to decide which jobs can enter the planned workload and which cannot. For integrating order release and output control, we require a method that focuses on improving performance for a given planned workload through selective capacity adjustments on the shop floor. This method has been presented by Land *et al.* (2015), as described next.

2.2.1 Integrating Input Control (Order Release) and Output Control (Capacity Adjustments)

Land *et al.* (2015) control capacity adjustments based on the planned workload to a certain station – capacity is adjusted as soon as the planned load to a station violates a predefined trigger threshold. This load is measured in units of the corrected aggregate load since this measure gives the best representation of the future expected direct load of a station based on the mix of routings actually present in the planned workload (Oosterman *et al.*, 2000). It gives the earliest possible indication that congestion is foreseen at a certain station as it includes not only the direct load but also a proportion of the work on its way to the station.

The planned load is given by the released load on the shop floor and the load currently in the pool. Both measures – the pool load and the released workload – are used at the order release stage to guide the release decision described in Section 2.1 above. Thus, Land *et al.*'s (2015) capacity adjustment procedure for output control can be integrated into Workload Control's release mechanism for input control. This is illustrated in Figure 1, which presents the graphical user interface typically used for supporting the order release decision (see, e.g. Stevenson, 2006). The grey bar gives the released workload W_s to each station s that is kept within the workload norm N_s . To obtain the planned load, which is used to guide capacity adjustments in Land *et al.* (2015), the pool load (i.e. the load contribution of all jobs waiting in the pool to be released, measured in corrected load) is simply added to the released workload.

[Take in Figure 1]

Workload Control integrates two control mechanisms: input control (order release) and output control (capacity adjustments). The above procedure presents a simple approach to operationalizing both within Workload Control thereby unlocking its full potential. This

addresses our first objective of outlining how Workload Control order release (input control) and the output control procedure for capacity adjustments introduced by Land *et al.* (2015) can be combined. Our second objective, to use simulation to assess (for the first time) the performance impact of Workload Control as a concept that combines input control with output control, will be addressed next.

3. Simulation Model

The objective of the simulation experiments is to assess the joint impact of input control (in the form of order release) and output control (capacity adjustments). A simple job shop model is used to avoid interactions that may interfere with our understanding of the effects of the experimental factors. The shop and job characteristics modeled in the simulations are first outlined in Section 3.1. The parameters set for the order release method (input control: LUMS COR), are then outlined in Section 3.2, before the parameters for controlling capacity adjustments (output control) are specified in Section 3.3. The priority dispatching rule applied for controlling the progress of orders on the shop floor is then described in Section 3.4. Finally, the experimental design is outlined and the measures used to evaluate performance are presented in Section 3.5.

3.1 Overview of Modeled Shop and Job Characteristics

A simulation model of a randomly routed job shop (Conway *et al.*, 1967) – later referred to as a pure job shop (Melnik & Ragatz, 1989) – has been implemented in the Python[®] programming language using the SimPy[®] simulation module. The shop contains six stations, where each station is a single, constant capacity resource. The routing length of jobs 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 a job. Operation processing times follow a truncated 2-Erlang distribution with a mean of 1 time unit after truncation and a maximum of 4 time units. The inter-arrival time of jobs follows an exponential distribution with a mean of 0.648, which – based on the average number of stations in the routing of a job – deliberately results in a utilization of 90%. While any individual job shop in practice will differ in many aspects from this stylized environment, it captures the typical job shop characteristics of high routing variability, processing time variability, and arrival variability. Consequently, it is widely applied in job shop research.

Due dates are set exogenously by adding a random allowance factor, uniformly distributed between 28 and 36 time units, to the job entry time. The minimum value will be sufficient to cover a minimum shop floor throughput time corresponding to the maximum processing time (4 time units) for the maximum number of possible operations (6) plus an allowance for the waiting or queuing times of 4 time units. The maximum value has been set such that the percentage of tardy jobs is 20% if jobs are released immediately upon arrival and capacity adjustments are not applied. Finally, Table 1 summarizes the simulated shop and job characteristics. These settings facilitate comparison with earlier studies on both order release (e.g. Thürer *et al.*, 2012) and output control (Land *et al.*, 2015) that have applied the same job shop model.

[Take in Table 1]

3.2 Order Release (Input Control)

As in previous simulation studies on Workload Control (e.g. Land & Gaalman, 1998; Fredendall *et al.*, 2010; Thürer *et al.*, 2012), it is assumed that all jobs are accepted, materials are available and all necessary information regarding shop floor routings, processing times, etc is known. Jobs

flow into a pre-shop pool to await release according to LUMS COR. The time interval between releases for the periodic element of LUMS COR is set to 4 time units and seven workload norms – from 4 to 10 time units – are considered. As a baseline measure, experiments without controlled order release have also been executed, i.e. where jobs are released onto the shop floor immediately upon arrival.

3.2.1 Pool Sequencing Rule

The sequence in which jobs are considered for release has, until recently, received little attention in the literature. It was implicitly assumed that this sequence is only responsible for the timely release of jobs based on some measure of urgency. However, Thürer *et al.* (2015a) showed that the pool sequencing rule should support load balancing, specifically when many jobs are at risk of becoming urgent. Thürer *et al.*'s (2015a) Modified Capacity Slack (MODCS) rule switches from a focus on urgency to speeding up jobs during periods when many jobs become urgent. Since these periods are highly correlated with periods of high load (Land *et al.*, 2015), MODCS may be considered an alternative approach to handling high load periods; it does not seek to eliminate high load periods but rather to reduce their impact in terms of percentage tardy performance. Consequently, this rule is considered in our study.

In addition to MODCS, we also consider the Planned Release Date (PRD) rule as a baseline measure. PRD sequences jobs according to planned release dates. The planned release date of a job is given by its due date minus a constant allowance for the operation throughput time for each operation in its routing. The constant allowance of the operation throughput time has been set to 5 time units since this value resulted in the best overall performance in preliminary simulation experiments.

MODCS, as introduced by Thürer *et al.* (2015a), uses: (i) a load-oriented Capacity Slack CORrected (CSCOR – as described below) element to speed up production when multiple jobs become urgent; and, (ii) a time-oriented PRD element to ensure non-urgent jobs are released so the mix of released jobs can be produced on time. MODCS can be summarized as follows:

- (i) Jobs are divided into two classes: urgent jobs, i.e. jobs with a planned release date that falls within the next release period or has already passed; and non-urgent jobs. Urgent jobs will always receive priority over non-urgent jobs.
- (ii) Within the class of urgent jobs, jobs are sequenced according to the CSCOR rule.
- (iii) Then, within the class of non-urgent jobs, jobs are sequenced according to the PRD rule.

CSCOR is a load-oriented rule that sequences jobs according to a capacity slack ratio based on corrected aggregate load measures of the workload, as given by Equation (3) below. This rule integrates three elements into one priority measure: (i) the *workload contribution* of the job (i.e. the corrected processing time); (ii) the *load gap* at a station (i.e. the remaining capacity that is available for orders in the pool to fill); and, (iii) the *routing length*, which is used to average the ratio between the load contribution and load gap elements over all operations in the routing of the job. The lower the capacity slack ratio (S_j) of job j , the higher is the priority of the job. Note that the same rule – but based on an uncorrected measure for calculating the load contribution and load gap elements – was originally proposed by Philipoom *et al.* (1993).

$$S_j = \frac{\sum_{i \in R_j} \left(\frac{P_{ij}}{N_s - W_s} \right)}{n_j} \quad (3)$$

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

Note that the other parameters in the equation are as defined in Section 2.1.

Finally, the capacity slack ratio could become negative due to the continuous starvation trigger that LUMS COR incorporates (in addition to its periodic release element). This could result in the sequencing rule prioritizing a job that contributes to the workload of an already overloaded station. Therefore, if the workload of a station is equal to or exceeds the workload norm, that is $N_s - W_s \leq 0$, then the job is positioned at the back of the queue by replacing the

component $\left(\frac{\frac{P_{ij}}{i}}{N_s - W_s} \right)$ related to this station in the priority value S_j by $\left(\frac{P_{ij}}{i} \cdot M \right)$, where M is a

sufficiently large number.

3.3 Capacity Adjustments (Output Control)

Various options exist in practice to temporarily increase capacity, for example using overtime, reallocating operators from under-loaded to high load stations, etc. However, we are not interested in the specific adjustment mechanisms used but in the performance impact of output control in combination with input control. Therefore, during a high load period, we simply decrease the operation processing times of jobs at the station with a high load by a predetermined percentage.

As in Land *et al.* (2015), capacity adjustments are guided by three parameters:

1. The size of the processing time reduction (α);
2. The load threshold that triggers the commencement of the capacity adjustment (β); and,
3. The load threshold signaling that the load has reduced sufficiently to cease the adjustment (γ).

The latter two thresholds specify which periods will be distinguished as high load periods and thus require capacity adjustments. These thresholds have been determined numerically based on preliminary simulation experiments. We recorded the cumulative frequency distribution of the planned workload (measured in terms of the corrected load) that emerges without capacity adjustment for each dispatching rule and workload norm being considered. The load threshold for each experimental setting of the dispatching rule and workload norm was then derived using a percentile of this distribution. Table 2 presents the workload threshold for the 75, 80, 85, 90 and 95th percentile.

Five levels of α , three levels of β , and three levels of γ are considered in this study. The different levels of each parameter are summarized in Table 3. Note that the percentile for γ is expressed as the number of percentage points below the trigger threshold β at which the station returns to normal capacity conditions.

[Take in Table 2 and Table 3]

Finally, none of the capacity adjustments in our experiments reduced the overall utilization by more than 0.5 percentage points. To provide an appropriate lower bound for a constant capacity that would lead to a comparable average utilization, we also include experiments with an average capacity utilization of 89.5% (rather than 90%). To realize this utilization, all processing times are reduced by multiplying them by a factor of 89.5/90.

3.4 Shop Floor Dispatching

Jobs on the shop floor are prioritized according to the earliest operation due date. The calculation of the operation due date d_{ij} for the i^{th} operation of a job j follows Equation (4) below. The

operation due date for the last operation in the routing of a job is equal to the due date d_j , while the operation due date of each preceding operation is determined by successively subtracting a constant allowance b from the operation due date of the next operation. The allowance has been set to 5 time units in this study. This value has been chosen based on preliminary simulation experiments, which indicated that it resulted in the best overall performance.

$$d_{ij} = d_j - (n_j - i) \cdot b \quad i:1..n_j \quad (4)$$

3.5 Experimental Design and Performance Measures

The experimental factors are: (i) the 7 different workload norms for LUMS COR (from 4 to 10 time units); (ii) the 2 different pool sequencing rules (PRD and MODCS); and, (iii) our three parameters that guide capacity adjustments (α – 5 levels, β – 3 levels, and γ – 3 levels; see Table 2). A full factorial design was used with 630 cells, 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 are in line with those used in previous studies that have applied similar job shop models (e.g. Land, 2006; Thürer *et al.*, 2012a) and allow us to obtain stable results while keeping the simulation run time reasonable.

The four principal performance measures considered in this study are as follows: *mean throughput time* – the mean of the completion date minus the release date across jobs; *mean lead time* – the mean of the completion date minus the pool entry date across jobs; *percentage tardy* – the percentage of jobs completed after the due date; and, *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

To obtain a first indication of the relative impact of the experimental factors, statistical analysis has been conducted by applying ANOVA. The ANOVA is here based on a block design with the workload norm as the blocking factor, i.e. the seven levels of workload norm were treated as different systems. A block design allowed the main effect of the workload norm and both the main and interaction effects of the sequencing rules and our three output control parameters to be captured. Due to space restrictions, we do not present the full results here. We discuss the results and refer the reader to an online supplement that accompanies this paper for further information.

All main effects and most two-way interactions were shown to be statistically significant. The only two-way interactions that were not shown to be significant were between the pool sequencing rule and β in terms of the throughput time and lead time; and between the pool sequencing rule and γ in terms of the throughput time. Meanwhile, except for the three-way interaction between the pool sequencing rule, α , and γ – which was shown to be significant but weak in terms of the percentage tardy – no significant three-way interactions could be observed. Finally, there was no significant four-way interaction.

Detailed performance results, to assess the individual and combined impact of Workload Control's input and output control elements, will be presented next. Section 4.1 focuses on assessing the performance impact under: (i) different levels for the pool sequencing rule used by the order release method; and, (ii) the size of the capacity adjustment α . Section 4.2 then examines the duration and frequency of capacity adjustments for these experimental settings. Finally, the sensitivity of the results to β and γ – the parameters that determine when to start and cease capacity adjustments – is explored in Section 4.3.

4.1. Performance Assessment: Input vs. Output Control

The lead time, percentage tardy and mean tardiness results are shown in Figure 2 set against the throughput time results for the PRD (Figure 2a) and MODCS (Figure 2b) pool sequencing rules. Only results for a β of 90 and γ of 5 are given; the sensitivity of the results to these two parameters will be discussed in Section 4.3. The results are presented in the form of performance curves, where the left-hand starting point of the curves represents the tightest workload norm of 4 time units. The workload norm increases step-wise by moving from left to right in each graph, with each data point representing one workload norm (from 4 to 10 time units). Loosening the norms (towards a norm of 10 time units) increases the workload on the shop floor and, as a result, the throughput times on the shop floor.

In addition, the results obtained when jobs are released immediately are also included. These results are given by the single points towards the right-hand side of each figure. They represent the outcome with no order release control, i.e. output control in isolation. Finally, the results obtained for a capacity utilization of 89.5% - which is below the utilization realized with adjusted capacities - are given by the dashed curve (or broken line) in the figures.

[Take in Figure 2]

The following can be observed from the results:

- Input control only (i.e. order release): The effect of input control in isolation can be observed from the performance curves indicated as no adjustment. Applying input control allows for improvements in all four performance measures when compared to immediate release (the corresponding single data points on the right-hand side in the graphs), as long as the workload norm is set appropriately. There is however a trade-off between percentage tardy and mean

tardiness performance since the smallest percentage tardy is achieved at a lower workload norm than the lowest mean tardiness. This trade-off has to be considered by management when setting workload norms.

- Output control only (i.e. capacity adjustments): The effect of output control in isolation can be observed from the single data points for the different alpha values towards the right-hand side of the graphs. As for input control, applying output control also allows for improvements in all four performance measures. This can be observed by comparing the results achieved with no capacity adjustments with those achieved with capacity adjustments (the different levels of α). There are however diminishing returns, i.e. the improvement achieved by increasing alpha diminishes with alpha. An alpha (α) of 20% realizes most of the performance improvements – increasing the adjustment further leads to only marginal performance gains. This indicates that it is not so much the size but rather the timeliness of the capacity adjustment that is important.
- Input and output control combined: The joint effect of input and output control can be observed from the performance curves for the different alpha values. Using input and output control together appears to create effects that largely complement each other within the Workload Control concept. In other words, if we compare the performance improvement achieved through capacity adjustments for each norm (i.e. each data point on the performance curves), performance improvements remain largely unchanged and similar to the performance improvement obtained under immediate release (i.e. output control only). The only exception is the percentage tardy performance at very tight norms. This indicates that there is no strong interaction between the control mechanisms. It further appears that input control has a stronger effect on the lead time and percentage tardy while output control affects the mean

tardiness the most. Therefore, the two mechanisms can and should play complementary roles within Workload Control.

- PRD vs. MODCS pool sequencing rule: MODCS significantly enhances performance compared to PRD pool sequencing in terms of the lead time and percentage tardy under all experimental settings. MODCS also improves mean tardiness performance compared to PRD if no capacity adjustments are applied and alpha is set to 10, 20 or 30%; however, MODCS may require higher workload norms than PRD. Finally, MODCS is outperformed by PRD in terms of the mean tardiness for an alpha of 40%.

Overall, the above results confirm that input control (in the form of the LUMS COR method, as introduced by Thürer *et al.* 2012) and output control (capacity adjustments during high load periods, as proposed by Land *et al.* 2015) should play complementary roles within Workload Control. Further, it has been shown that the performance improvement obtained by MODCS remains effective when input and output control are combined.

4.2. Sensitivity Analysis: The Duration and Frequency of Capacity Adjustments

This section explores the effect of the workload norm and pool sequencing rule on the frequency and duration of capacity adjustments. Figures 3a and 3b give the number of times a capacity adjustment was triggered per 1,000 time units over the throughput time. As in Section 4.1, the results are presented for a β of 90 and γ of 5. In addition, Table 4 provides the capacity utilization realized across stations for each experimental result presented in Figure 3. From Table 4, an increase in capacity utilization can be observed if workload norms are tightened. However, this increase does not exceed 0.06%, which is the result observed for MODCS with an alpha of 40%. For our further analysis, this can be considered not relevant. The frequency of the

adjustments still provides an indication of the duration of the adjustments since the utilization is the result of the frequency multiplied by the duration. In other words, when adjustments are less frequent, they have to be maintained for longer to realize the same utilization.

[Take in Table 4 & Figure 3]

The following can be observed from the results:

- The impact of the workload norm: A lower workload norm appears to result in less frequent (and consequently longer) capacity adjustments. But this observation has to be interpreted with care since the parameter values for β and γ result in different load thresholds for each workload norm (i.e. each marker on a curve). This was necessary to realize comparable capacity utilizations across experiments when tightening the norm. Referring back to Table 2, we can see that tighter workload norms result in higher thresholds, which may explain why there is a reduction in the frequency of the capacity adjustments. The fact that a tight norm leads to a higher threshold can also be seen from Figure 4a and 4b, which give the cumulative frequency distribution used for determining the percentiles for immediate release (IMM) and for a workload norm of four time units (the tightest workload norm in our experiments). However, the effect disappears if the load is not corrected. This can be seen from Figures 4c and 4d, which give the distribution of the planned workload when measured in terms of the uncorrected load.
- The impact of the pool sequencing rule: MODCS (Figure 3b) significantly reduces the frequency of capacity adjustments compared to PRD (Figure 3a). From Table 2, we can see that, for MODCS, high-load periods relate to higher workload thresholds than for PRD pool sequencing. This indicates that, for MODCS, there is more work on average in the system,

which may explain why there is a reduction in the frequency of capacity adjustments. The difference between MODCS and PRD is that MODCS switches to a Capacity Slack (CS) rule during high load periods. This CS element of MODCS speeds up the progress of small jobs – where “small” is defined in terms of the corrected measure of the load. This means that jobs with a small corrected workload contribution have a higher probability of being released than jobs with a large corrected workload contribution. The large jobs stay in the system longer, which increases the planned workload if measured in terms of the corrected load.

[Take in Figure 4]

The results in Section 4.1 and the analysis in Section 4.2 have only looked at different levels of the pool sequencing rule and adjustment size α . A sensitivity analysis of the effect of our two remaining parameters for guiding capacity adjustments (β and γ) will be presented next.

4.3. Sensitivity Analysis: Output Control Parameters

The presentation of results has so far only focused on one setting for β and γ , i.e. the two parameters that indicate when to start and when to cease capacity adjustments, respectively. Figure 5a and 5b now show the lead time, percentage tardy, and mean tardiness results over the throughput time results under PRD pool sequencing for a β of 85 and 95, respectively. This allows us to assess the impact of this parameter on performance. We do not present and discuss the impact of γ here due to space restrictions and since the nature of the performance impact of this parameter has been found to be similar to the impact of β . This confirms the findings in Land *et al.* (2015) who argued for a single performance frontier to which performance results obtained for the different parameter settings converge. Results for γ can be found as part of the online

supplement to this paper. The main difference between the performance impact of β and γ is that decreasing β allows for stronger performance improvements than varying γ .

[Take in Figure 5]

The following can be observed from the results under PRD pool sequencing:

- The results support our observations from Figure 2 above – output control in the form of capacity adjustments effectively enhance the performance of input control (i.e. order release in isolation). Therefore, these two control mechanisms can and should play complementary roles within Workload Control.
- Capacity adjustments have a stronger impact on mean tardiness than on the percentage tardy or lead time. For example, the mean tardiness is already significantly reduced even when β is just 95 (see Figure 5b) compared to no capacity adjustments and a utilization of 89.5%. Meanwhile, no significant performance improvement in terms of the percentage tardy and lead time can be observed for this level of β .
- Comparing the performance gain obtained by varying α from 10% to 40% with the performance gain obtained by varying β (i.e. Figure 5a compared to Figure 5b), suggests that *when* an adjustment is started has a stronger impact on performance than the actual *size* of the adjustment.

Finally, as can be seen from Figures 6a and 6b – which show the lead time, percentage tardy and mean tardiness results over the throughput time results under MODCS pool sequencing for a β of 85 and 95, respectively – the same observations made above for the PRD rule also hold for the MODCS pool sequencing rule.

[Take in Figure 6]

5. Conclusions

The Workload Control concept is a production planning and control approach specifically developed for high-variety job shops. Workload Control integrates two control mechanisms: (i) input control, e.g. in the form of order release, to regulate the inflow of work to the shop floor; and, (ii) output control in the form of capacity adjustments to regulate the outflow of work. To date, Workload Control research has largely focused on input control – the output control element has received limited attention. Only recently has research emerged that has used Workload Control theory to effectively decide when to adjust capacity (Land *et al.*, 2015). However, Land *et al.* (2015) neglected the input control component of Workload Control. Thus, the performance of a combined approach that controls the input and output of work has not been evaluated.

In response, this study set out to (i) integrate input and output control within Workload Control; and (ii) assess the performance of a Workload Control concept that combines input and output control through simulation. We first saw that output control, as recently suggested by Land *et al.* (2015), can be integrated into LUMS COR, an order release method (input control) that was recently identified as the best solution for Workload Control. Simulation results then demonstrated that both mechanisms – input and output control – can and should play complementary roles within the Workload Control concept.

5.1 Managerial Implications

While input control (in the form of order release) and output control (i.e. capacity adjustments) allow significant performance improvements to be realized in isolation, thereby confirming the

results of recent studies on input (Hendry *et al.*, 2013; Thüerer *et al.*, 2012, 2014a, 2015a) and output control (Land *et al.*, 2015), the real potential of Workload Control is unlocked when the two control mechanisms are combined. In fact, the positive effects on performance of the two types of control appear to complement each other. While input control has a stronger impact on the lead time and percentage tardy, output control has a stronger impact on the mean tardiness of jobs.

The capacity adjustment procedure used in this study (from Land *et al.*, 2015) is a simple extension of order release. This facilitates implementation in practice, e.g. a firm that has already implemented Workload Control order release can gain further performance benefits from adopting some straightforward principles for adjusting capacity. Three parameters have been used to control capacity adjustments in this study: (i) the size of the adjustment; (ii) the workload threshold that determines when to start an adjustment; and, (iii) the workload threshold that determines when to cease an adjustment. Our results indicate that:

- There are strong diminishing returns for the size of the adjustment. A capacity adjustment equivalent to a reduction in processing times of just 10-20% allowed for achieving most of the performance improvements in our simulation experiments; and,
- The workload threshold that determines when to start the adjustment has the strongest impact on performance. This means that performance is more about the timeliness of the adjustment than the size of the adjustment.

5.2 Limitations and Future Research

A first limitation of our approach to adjusting capacity is that the corrected workload contribution is independent from the actual progress of an order on the shop floor. Further performance improvement may be obtained by updating the corrected workload in accordance

with realized job progress, thereby justifying the increase in complexity that would be implied. In general, one of the advantages of the approach for guiding capacity adjustments considered here is its simplicity. But there are other approaches presented in the literature, e.g. based on finite loading (Bechte, 1994), which are worth further exploration. Another limitation is our assumption that there are no constraints on capacity adjustments. This may not always be realistic in practice (see, e.g. Stevenson & Silva, 2008) since overtime may not be applicable to all stations; or operators may not be transferable due to different training requirements or skills (e.g. Malhotra *et al.*, 1993). Capacity adjustments may also incur a delay after being triggered rather than being directly realized. Assessing the impact of these constraints is an important future research issue. Finally, a major limitation of our study is the restricted environmental setting. To keep the experimental setting reasonable, we did not assess the performance of input and output control under different shop and job characteristics. But future research could explore the impact of input and output control, for example, when routings become more directed, as in the pure flow shop.

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Table 1: Summary of Simulated Shop and Job Characteristics

Shop Characteristics	Routing Variability No. of Stations Interchange-ability of Stations Station Capacities	Random routing; no-re-entrant flows 6 No interchange-ability All equal; output control is exercised
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 ; $d \sim U[28, 36]$ Exp. Distribution; mean = 0.648

Table 2: Summary of the Corrected Planned Workload Thresholds that result for the Different Percentiles of the Frequency Distribution

Pool Sequencing Rule	Percentile	Norm 4	Norm 5	Norm 6	Norm 7	Norm 8	Norm 9	Norm 10	IMM
PRD	95 th	29.12	27.24	25.9	24.83	23.99	23.49	23.04	21.84
	90 th	23.64	22.16	21.01	20.23	19.65	19.24	18.93	18.23
	85 th	20.46	19.19	18.24	17.58	17.1	16.79	16.54	16.02
	80 th	18.19	17.07	16.23	15.66	15.25	15.01	14.8	14.4
	75 th	16.39	15.37	14.63	14.13	13.79	13.6	13.43	13.1
MODCS	95 th	30.06	29.02	28.18	27.42	26.77	26.09	25.64	21.84
	90 th	24.11	23.19	22.44	21.72	21.14	20.65	20.22	18.23
	85 th	20.73	19.88	19.16	18.55	18.04	17.62	17.29	16.02
	80 th	18.29	17.51	16.83	16.31	15.87	15.52	15.26	14.4
	75 th	16.36	15.63	15.02	14.56	14.18	13.89	13.69	13.1

Table 3: Summary of Capacity Adjustment Parameters

Parameter	Definition	Level
α	Size of the capacity adjustment, measured in terms of the percentage reduction in operation processing times at the triggering station.	0 (i.e. no capacity adjustment), 10, 20, 30 and 40%
β	Workload that triggers the start of the capacity adjustment expressed as percentile of the frequency distribution of the planned workload.	85, 90, and 95 th percentile
γ	Percentage points below the triggering threshold β at which the station returns to normal capacity conditions.	0, 5, and 10

Table 4: Average Capacity Utilization Across Stations for the Results in Figure 3

Pool Sequ. Rule	Alpha Value	Workload Norm							
		4	5	6	7	8	9	10	IMM
PRD	$\alpha = 0.1$	89.77%	89.77%	89.77%	89.77%	89.76%	89.76%	89.76%	89.75%
	$\alpha = 0.2$	89.72%	89.72%	89.71%	89.71%	89.71%	89.70%	89.70%	89.69%
	$\alpha = 0.3$	89.69%	89.69%	89.68%	89.68%	89.67%	89.67%	89.66%	89.65%
	$\alpha = 0.4$	89.67%	89.67%	89.66%	89.65%	89.65%	89.65%	89.64%	89.63%
MODCS	$\alpha = 0.1$	89.77%	89.78%	89.78%	89.77%	89.77%	89.77%	89.77%	89.75%
	$\alpha = 0.2$	89.72%	89.73%	89.73%	89.72%	89.72%	89.72%	89.72%	89.69%
	$\alpha = 0.3$	89.70%	89.70%	89.70%	89.70%	89.69%	89.69%	89.69%	89.65%
	$\alpha = 0.4$	89.69%	89.68%	89.68%	89.68%	89.68%	89.68%	89.67%	89.63%

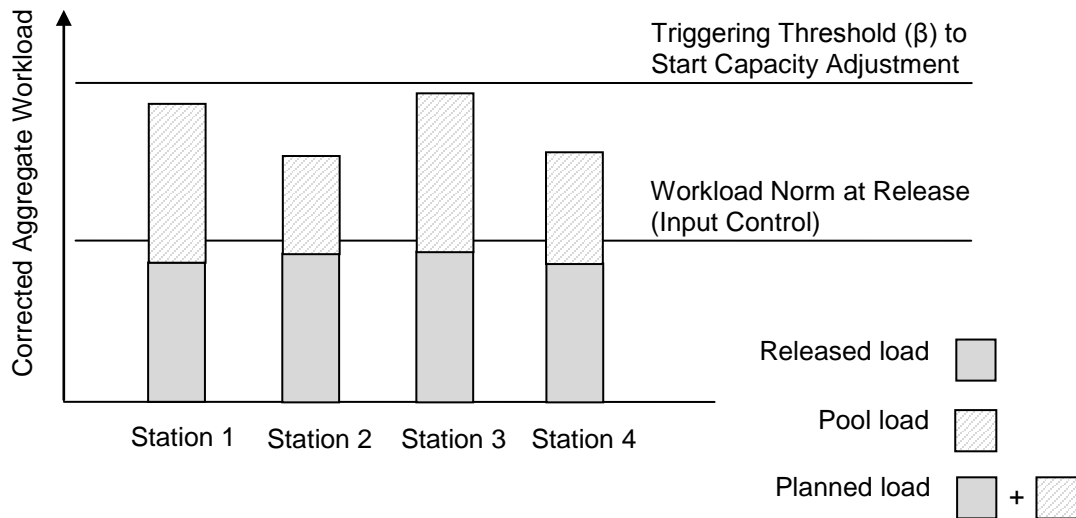
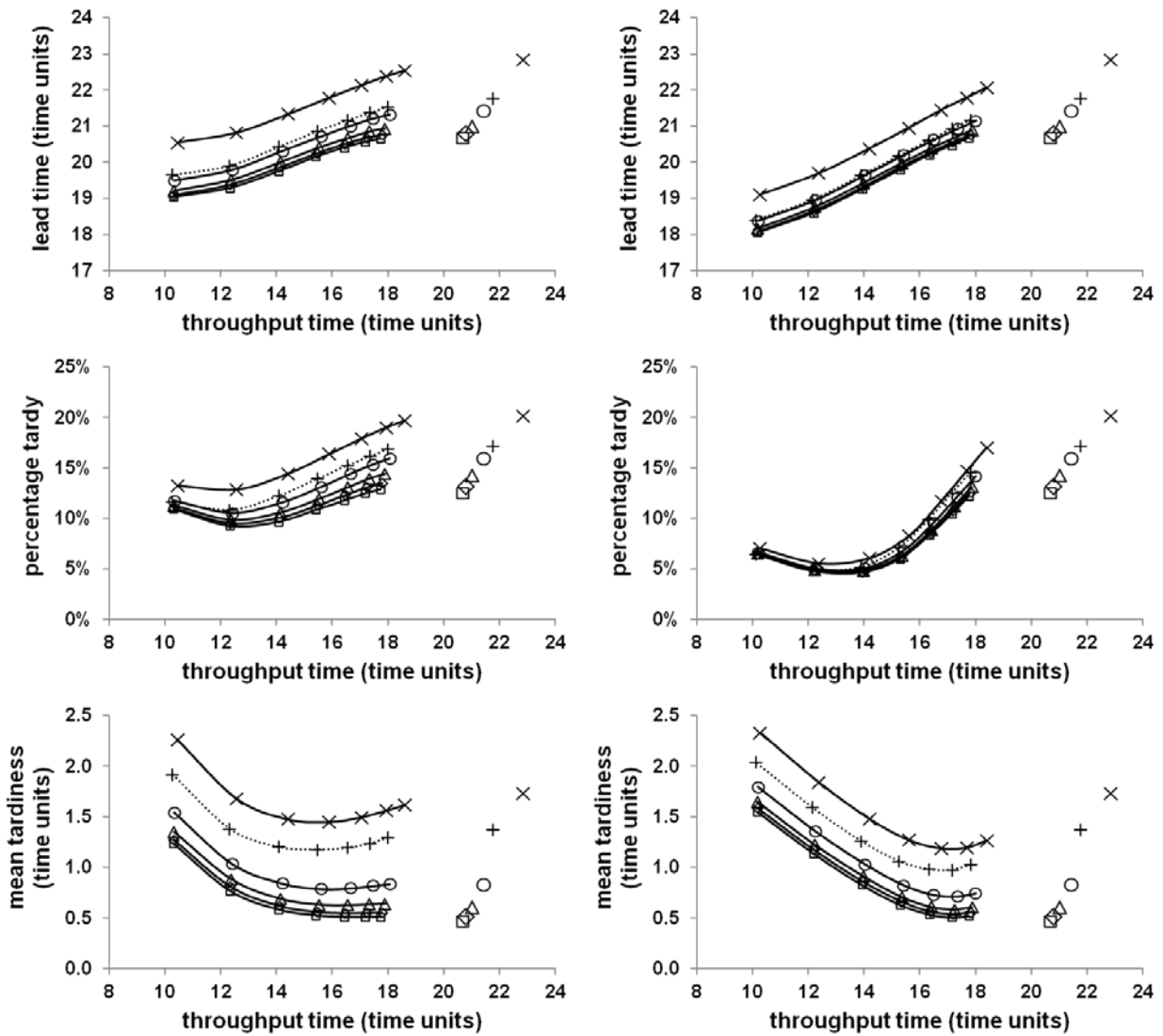


Figure 1: The Integration of Input and Output Control within Workload Control Order Release



(a) PRD Pool Sequencing

(b) MODCS Pool Sequencing

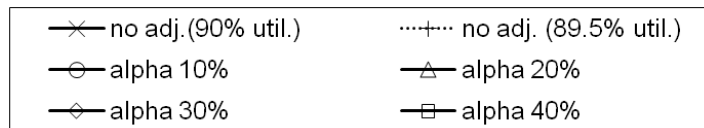
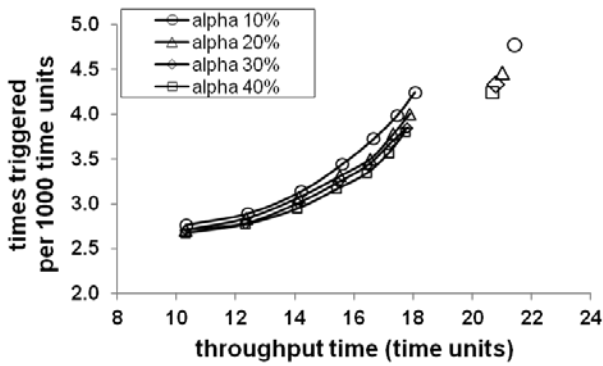
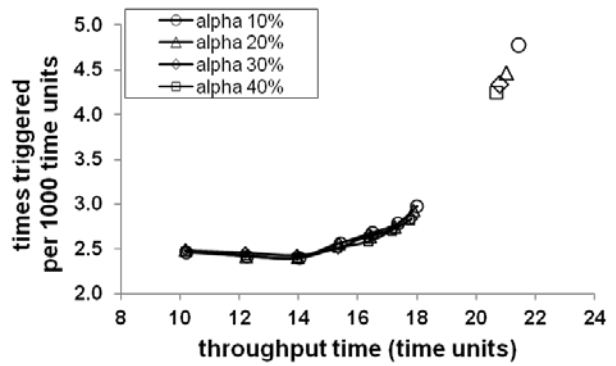


Figure 2: Performance Results for a Beta (β) of 90 to Start Capacity Adjustments and a Gamma (γ) of 5 to Stop Capacity Adjustments

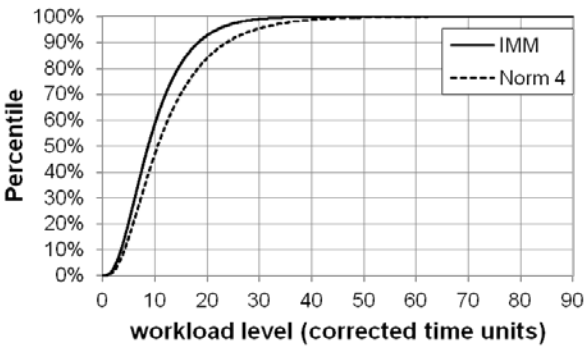


(a) PRD Pool Sequencing

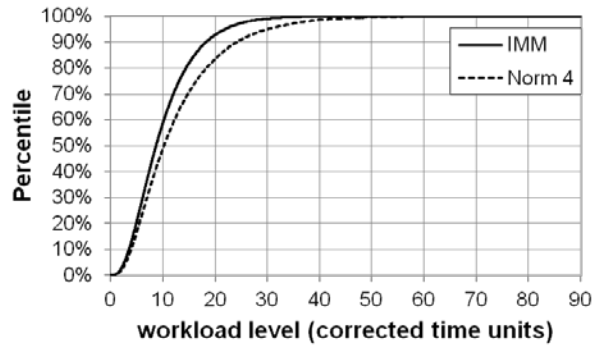


(b) MODCS Pool Sequencing

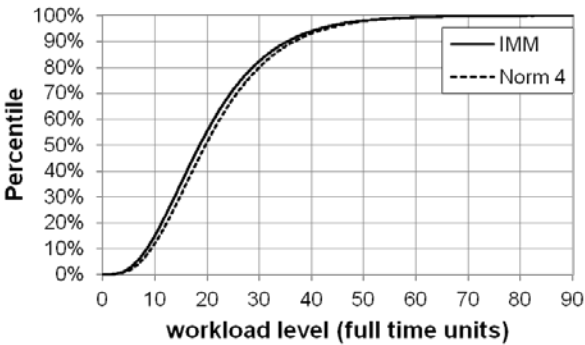
Figure 3: Analysis of the Frequency of Capacity Adjustments: Number of Times Adjustments are Triggered per 1,000 Time Units over the Throughput Time for a Beta (β) of 90 and a Gamma (γ) of 5



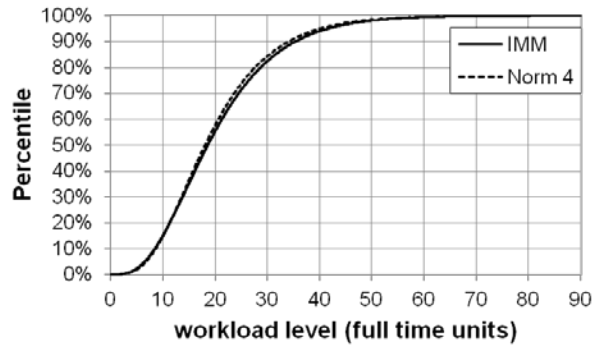
(a) PRD - Corrected Workload



(b) MODCS - Corrected Workload

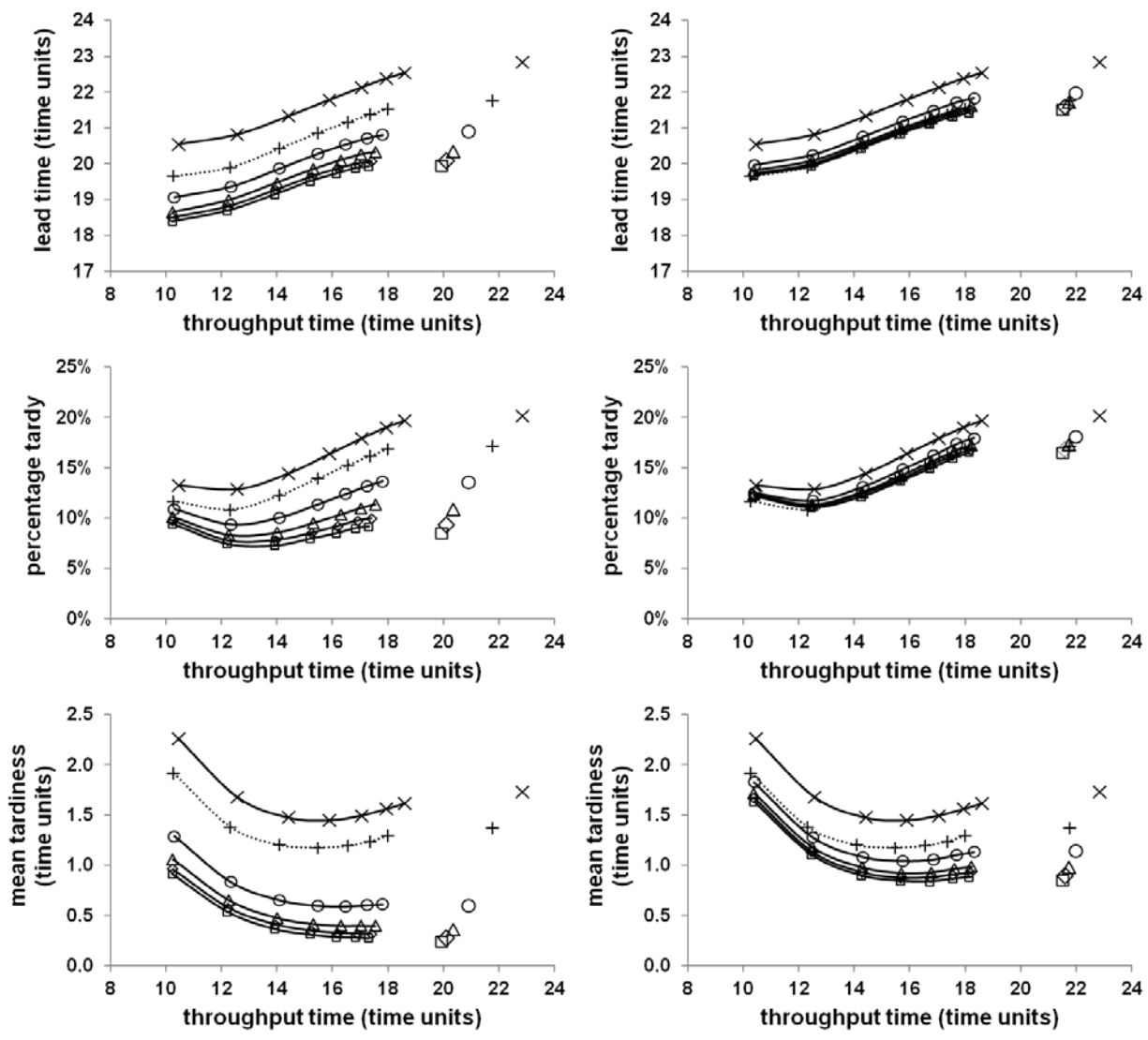


(c) PRD - Uncorrected Workload



(d) MODCS - Uncorrected Workload

Figure 4: Cumulative Frequency Distribution of the Planned Workload (No Capacity Adjustments)



(a) Beta of 85; Gamma of 5

(b) Beta of 95; Gamma of 5

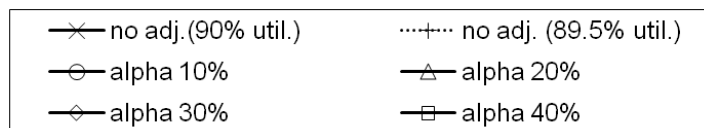
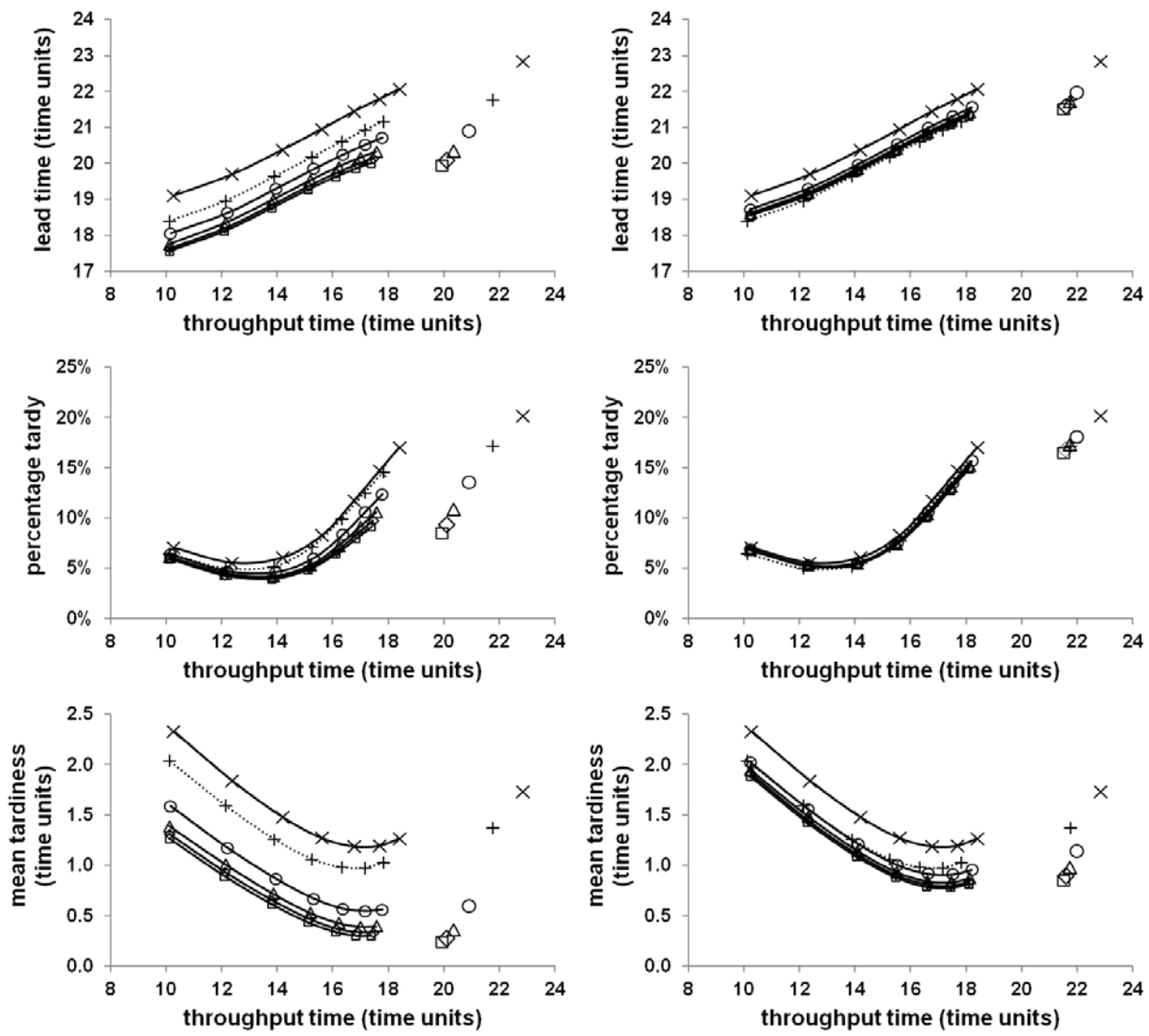


Figure 5: Performance Impact of Beta (β) with PRD Pool Sequencing



(a) Beta of 85; Gamma of 5

(b) Beta of 95; Gamma of 5

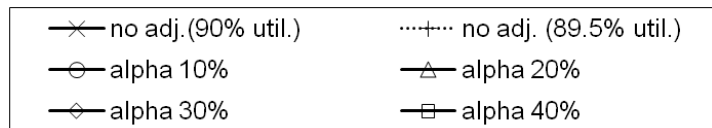


Figure 6: Performance Impact of Beta (β) with MODCS Pool Sequencing

Supplement

“On the Integration of Input and Output Control: Workload Control Order Release”

Table 1: ANOVA Results – Throughput Time

Table 2: ANOVA Results – Lead Time

Table 3: ANOVA Results – Percentage Tardy

Table 4: ANOVA Results – Mean Tardiness

Figure 1: Performance Impact of Gamma (γ) with PRD Pool Sequencing

Figure 2: Performance Impact of Gamma (γ) with MODCS Pool Sequencing

Table 1: ANOVA Results – Throughput Time

Source of Variance	Sum of Squares	Degree of Freedom	Mean Squares	F-Ratio	p-Value
Norm	427671	6	71278.5	2.00E+05	0
Pool Sequencing Rule (Pool)	294.9176	1	294.9176	823.38	0
Alpha	1326.358	4	331.5894	925.77	0
Pool x Alpha	33.37769	4	8.344423	23.3	0
Beta	102.4106	4	25.60264	71.48	0
Pool x Beta	1.361546	4	0.340386	0.95	0.4336
Alpha x Beta	28.52361	16	1.782726	4.98	0
Pool x Alpha x Beta	0.389499	16	0.024344	0.07	1
Gamma	200.6253	2	100.3126	280.06	0
Pool x Gamma	2.020591	2	1.010296	2.82	0.0596
Alpha x Gamma	57.81629	8	7.227036	20.18	0
Pool x Alpha x Gamma	0.5846	8	0.073075	0.2	0.9903
Beta x Gamma	3.325108	2	1.662554	4.64	0.0096
Pool x Beta x Gamma	0.013479	2	0.006739	0.02	0.9814
Alpha x Beta x Gamma	1.002933	8	0.125367	0.35	0.9463
Pool x Alpha x Beta x Gamma	0.011948	8	0.001493	0	1
Residuals	22530.86	62,904	0.358178		

Table 2: ANOVA Results – Lead Time

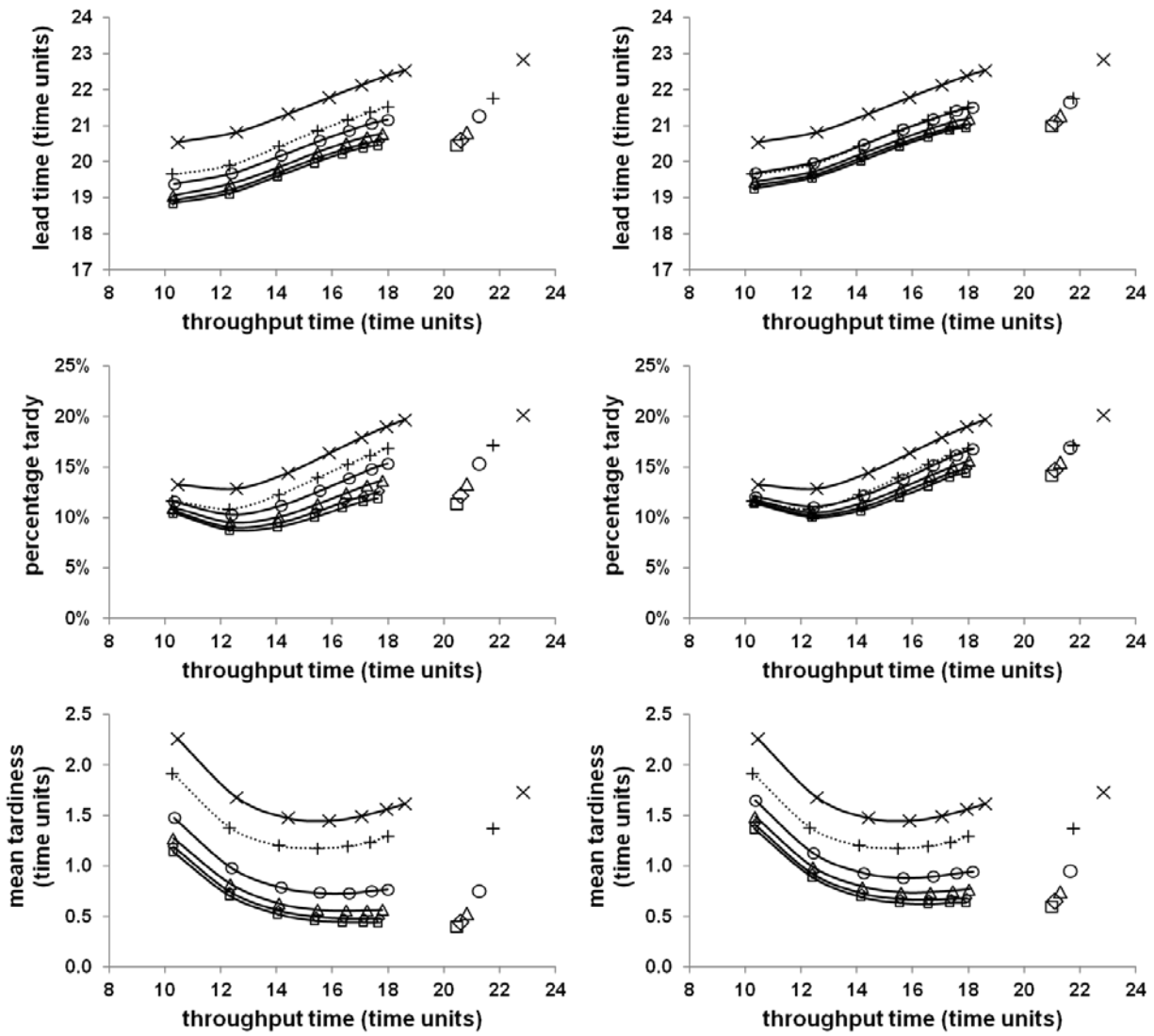
Source of Variance	Sum of Squares	Degree of Freedom	Mean Squares	F-Ratio	p-Value
Norm	39614.77	6	6602.462	4459.23	0
Pool Sequencing Rule (Pool)	4698.715	1	4698.715	3173.46	0
Alpha	15218.42	4	3804.604	2569.59	0
Pool x Alpha	385.1193	4	96.27981	65.03	0
Beta	788.4004	4	197.1001	133.12	0
Pool x Beta	14.10223	4	3.525558	2.38	0.0493
Alpha x Beta	215.6668	16	13.47918	9.1	0
Pool x Alpha x Beta	3.849476	16	0.240592	0.16	0.9999
Gamma	1818.199	2	909.0996	614	0
Pool x Gamma	20.4136	2	10.2068	6.89	0.001
Alpha x Gamma	503.1146	8	62.88932	42.47	0
Pool x Alpha x Gamma	5.57854	8	0.697317	0.47	0.8774
Beta x Gamma	24.04363	2	12.02182	8.12	0.0003
Pool x Beta x Gamma	0.152445	2	0.076223	0.05	0.9498
Alpha x Beta x Gamma	6.8899	8	0.861237	0.58	0.7939
Pool x Alpha x Beta x Gamma	0.072636	8	0.009079	0.01	1
Residuals	93137.35	62,904	1.480627		

Table 3: ANOVA Results – Percentage Tardy

Source of Variance	Sum of Squares	Degree of Freedom	Mean Squares	F-Ratio	p-Value
Norm	37.13552	6	6.189253	5782.37	0
Pool Sequencing Rule (Pool)	30.35923	1	30.35923	28363.4	0
Alpha	10.82092	4	2.70523	2527.39	0
Pool x Alpha	1.173385	4	0.293346	274.06	0
Beta	0.802449	4	0.200612	187.42	0
Pool x Beta	0.096115	4	0.024029	22.45	0
Alpha x Beta	0.22891	16	0.014307	13.37	0
Pool x Alpha x Beta	0.0291	16	0.001819	1.7	0.0395
Gamma	1.901904	2	0.950952	888.44	0
Pool x Gamma	0.157341	2	0.07867	73.5	0
Alpha x Gamma	0.553697	8	0.069212	64.66	0
Pool x Alpha x Gamma	0.046944	8	0.005868	5.48	0
Beta x Gamma	0.02809	2	0.014045	13.12	0
Pool x Beta x Gamma	0.002514	2	0.001257	1.17	0.3091
Alpha x Beta x Gamma	0.008453	8	0.001057	0.99	0.4435
Pool x Alpha x Beta x Gamma	0.000806	8	0.000101	0.09	0.9994
Residuals	67.33034	62,904	0.00107		

Table 4: ANOVA Results – Mean Tardiness

Source of Variance	Sum of Squares	Degree of Freedom	Mean Squares	F-Ratio	p-Value
Norm	5984.129	6	997.3548	6586.57	0
Pool Sequencing Rule (Pool)	44.07431	1	44.07431	291.07	0
Alpha	5047.272	4	1261.818	8333.1	0
Pool x Alpha	145.2561	4	36.31402	239.82	0
Beta	163.8835	4	40.97088	270.57	0
Pool x Beta	2.683881	4	0.67097	4.43	0.0014
Alpha x Beta	42.71488	16	2.66968	17.63	0
Pool x Alpha x Beta	0.788607	16	0.049288	0.33	0.9946
Gamma	433.8083	2	216.9042	1432.44	0
Pool x Gamma	4.075708	2	2.037854	13.46	0
Alpha x Gamma	113.935	8	14.24187	94.05	0
Pool x Alpha x Gamma	1.06156	8	0.132695	0.88	0.5355
Beta x Gamma	4.126883	2	2.063441	13.63	0
Pool x Beta x Gamma	0.016375	2	0.008187	0.05	0.9474
Alpha x Beta x Gamma	1.084469	8	0.135559	0.9	0.5193
Pool x Alpha x Beta x Gamma	0.011175	8	0.001397	0.01	1
Residuals	9525.078	62,904	0.151422		



(a) Beta of 90; Gamma of 10

(b) Beta of 90; Gamma of 0

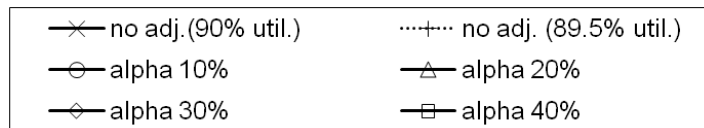
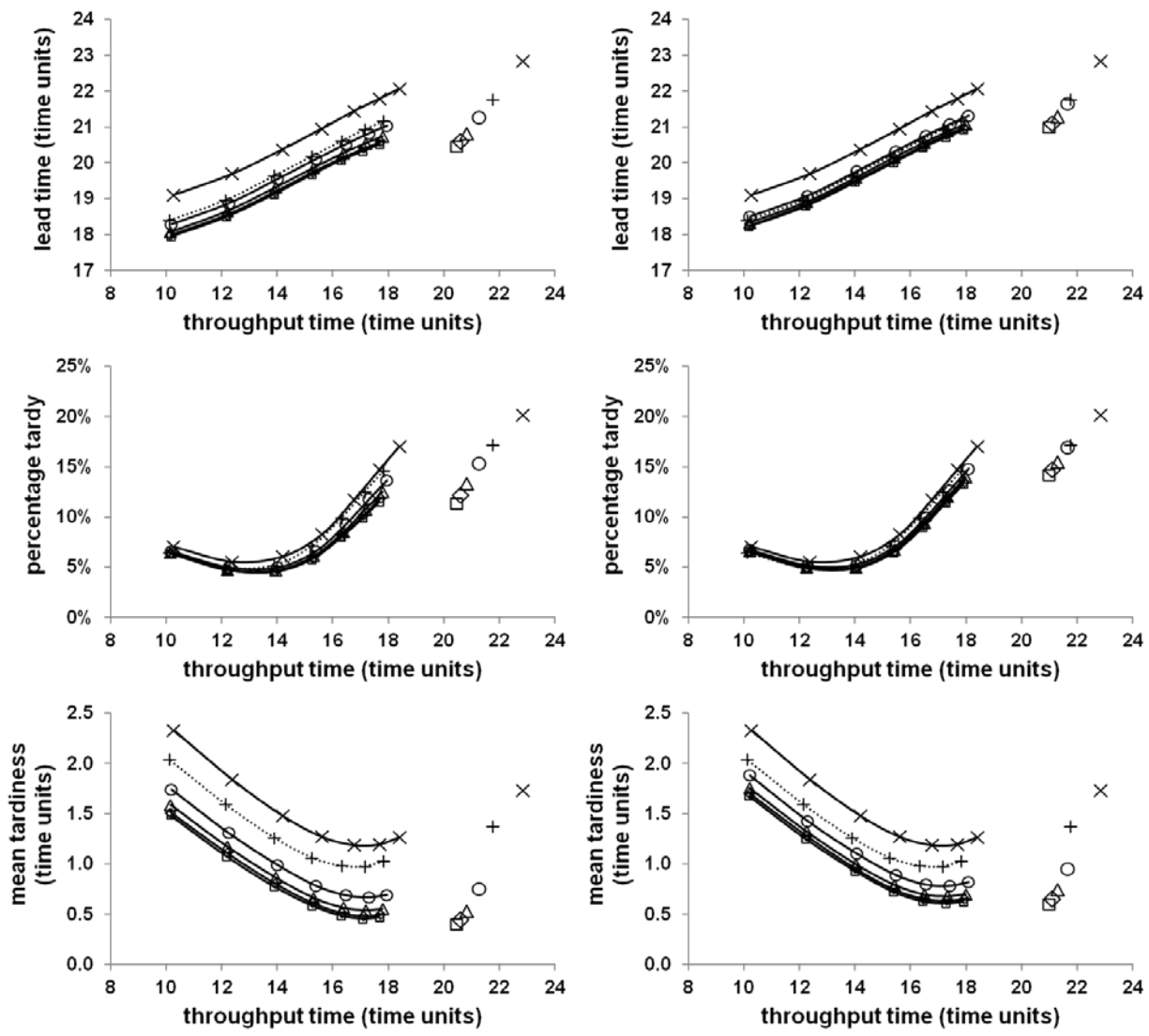


Figure 1: Performance Impact of Gamma (γ) with PRD Pool Sequencing



(a) Beta of 90; Gamma of 10

(b) Beta of 90; Gamma of 0

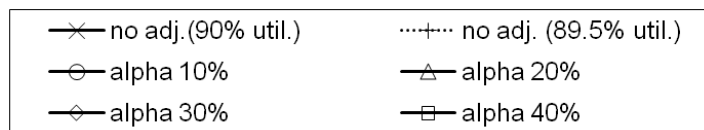


Figure 2: Performance Impact of Gamma (γ) with MODCS Pool Sequencing