Lot Synchronization in Make-to-Order Shops with Order Release Control: An Assessment by Simulation

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Abstract

Lot splitting is an important strategy for avoiding the starvation of workstations, for accelerating the progress of jobs, and ultimately for improving overall due date performance. While lot splitting has received much attention in the extant literature, the use of alternative lot transfer policies that determine how the flow of lots through the production system is synchronized has been largely neglected. This study uses simulation to assess the performance of different lot synchronization policies at release and different lot transfer policies on the shop floor in a ConWIP (Constant Work-In-Process) controlled job shop. The results suggest that different approaches should be applied at the release and shop floor levels. While lots should be synchronized in some form at order release, their progress on the shop floor should not be synchronized. Instead, lot coordination should be executed by dispatching in accordance with *repetitive lots* logic. The results further highlight that if lot progress is synchronized in systems that limit the workload, then lot release should also be synchronized. Otherwise, blocking may occur if lot progress on the shop floor depends on the release of lots, which in turn depends on lot progress. These findings have important implications for research and practice.

Keywords: *Lot Splitting; Lot Release Policy; Lot Transfer Policy; ConWIP; Make-to-Order*.

1. Introduction

Lot splitting is an important manufacturing strategy for improving order progress and making better use of capacity, not only when orders are released to the shop floor immediately (e.g. Wagner & Ragatz, 1994; Litchfield & Narasimhan, 2000), but also when their release is controlled (e.g. Russell & Fry 1997; Aglan & Durmusoglu, 2015; Fernandes *et al.,* 2016; Thürer *et al*., 2018). More specifically, lot splitting avoids starvation at downstream stations (Calleja & Pastor, 2014), allows job progress to be accelerated, and improves delivery performance (Jacobs & Bragg, 1988; Wagner & Ragatz, 1994). As a result, there is a broad literature on lot splitting (Smunt *et al*., 1996; Jeong *et al*., 1999; Chang & Chiu, 2005; Buscher & Shen, 2009; Azzi *et al*., 2012; Cheng *et al*., 2013; Lalitha *et al*., 2017). This body of work pays attention to some important aspects such as lot sizing, but it pays insufficient attention to others, most notably lot transfer policies. This is partly explained by a focus in much of the extant literature on deterministic scheduling. In this context, lot synchronization is part of the scheduling problem. Deterministic scheduling however assumes the absence of uncertainty, which is not the case in real systems. Scheduling in stochastic environments usually requires buffering in time and quantity (Gaalman & Perona, 2002). In this context, the lot transfer policy determines when a lot can proceed to the next station, and therefore also defines how the flow of lots (that make up a job) is synchronized through the production system. While there exists some literature on lot splitting in make-to-order contexts (e.g. Jacobs & Bragg, 1988; Wagner & Ragatz, 1994, Smunt *et al.,* 1996; Azzi *et al.*, 2012; Fernandes *et al.,* 2016), most studies do not specify how lot transfers are managed; hence, this remains an important gap in the extant literature that is worthy of further research.

To the best of our knowledge, only two studies have explicitly taken the impact of the lot transfer policy into account: Kher *et al*. (2000) and Thürer *et al*. (2018). Kher *et al*. (2000) introduced a policy that synchronizes lots at each routing step. This policy only allows a lot to progress to the next station if all of the lots that make up the job have been completed. The only exception to this is if a downstream station is starving. Where a downstream station is starving, a lot can be pulled forward to avoid wasted capacity downstream. Based on a simulation of a pure flow shop, Kher *et al*. (2000) observed no significant performance improvements in terms of the throughput time or tardiness, but there were significant gains in terms of the number of lot transfers and lot integrity compared to allowing lots to progress freely through the system. Kher *et al*. (2000) defined lot integrity as the extent to which the lots that comprise a job physically stay together, i.e. the integrity of a lot is preserved when all of the transfer lots are moved together. Meanwhile, Thürer *et al*. (2018) showed that not synchronizing lots improves performance when compared to various lot transfer policies in high-variety shops, but the authors did not consider the policy proposed in Kher *et al*. (2000). Kher *et al*.'s (2000) study however was conducted in the context of a pure flow shop, where all jobs visit all stations in the same sequence. Moreover, order release was not controlled, i.e. all jobs could be released immediately onto the shop floor. In contrast, make-to-order shops, which are arguably in most need of lead time improvement, typically exhibit much higher degrees of routing complexity and benefit from the use of order release control. It therefore follows that there is a need to build on these two studies, determining how transfer policies perform in high-variety make-to-order environments, and how they interact with controlled order release.

If order release control is applied, then jobs are not directly released onto the shop floor but retained in a pre-shop pool (e.g. Land *et al.,* 2014; Cransberg *et al.,* 2016; Fernandes *et al*., 2016). Fernandes *et al*. (2016) recently showed that when order release control is applied, then enforcing synchronization at release, i.e. releasing all of the lots that make up a job together into the system, is a better policy than releasing lots individually at different release times. The authors did not however consider different lot transfer policies to coordinate lots on the shop floor. Instead, they allowed lots to progress independently through the shop. In general, and to the best of our knowledge, there has been no prior research on the interplay between the synchronization policy at release and the lot transfer policy on the shop floor.

This study seeks to provide guidance on which synchronization policy to apply at order release and on which transfer policy to apply on the shop floor. Simulation is employed to evaluate their use in a pure job shop to identify how best to take advantage of lot splitting in these contexts.

The remainder of this paper is structured as follows. In Section 2, we review the relevant literature before the simulation model used to evaluate performance is described in Section 3. The results are presented, analyzed, and discussed in Section 4 before conclusions are presented in Section 5.

2. Background

It is not our objective to comprehensively review the literature on lot splitting; for this, the reader is referred to Chang & Chiu (2005) and Cheng *et al*. (2013). Rather, Section 2.1 briefly reviews the main studies relevant to the context of our research. Section 2.2 then discusses transfer policies from the literature and introduces the research questions that motivate our paper.

2.1 Literature Review: Lot-Splitting

It has long since been demonstrated that lot splitting allows job progress to be accelerated and job due date performance to be improved (Jacobs & Bragg, 1988; Wagner & Ragatz, 1994). This effect however is dependent on a variety of factors. For example, Karmarkar *et al*. (1985) argued that an increase in set-up times may outweigh any reduction in throughput times obtained from lot splitting. Lockwood *et al*. (2000) however concluded that additional set-ups before the bottleneck may improve due date performance without affecting the average throughput time of jobs. Meanwhile, several heuristic procedures have been proposed and applied to determine the most appropriate lot size (see, e.g. Jeong *et al*., 1999; Buscher & Shen, 2009; Azzi *et al*., 2012). Kropp & Smunt (1990) concluded however that simply using equal-sized lots works well in many situations. Moreover, Smunt *et al*. (1996) investigated various lot splitting policies in both stochastic job shop and flow shop environments finding that the number of lot splits is more important than the exact form of lot splitting.

Another research stream has focused on lot splitting in the context of controlled job release (see, e.g. Russell & Fry, 1997; Aglan & Durmusoglu, 2015; Fernandes *et al*., 2016; Thürer *et al.*, 2018). Russell & Fry (1997) assessed the impact of lot splitting in a Drum-Buffer-Rope (DBR) controlled V-plant. Meanwhile, Aglan & Durmusoglu (2015) sought to identify optimum sublot sizes in a ConWIP controlled cellular production layout, where cellular and functional layouts are combined. Finally, Fernandes *et al*. (2016) and Thürer *et al*. (2018) highlighted the potential of lot splitting to improve performance in the context of Workload Control and the POLCA system (Paired Overlapping Loops of Cards with Authorization), respectively.

To the best of our knowledge, most of these studies did not specify the transfer policy applied. In contrast, the studies by Kher *et al*. (2000) and Thürer *et al*. (2018) focused explicitly on the transfer policy and lot integrity. These two studies will be further discussed next.

2.2 Discussion of Transfer Policies from the Literature

At the extremes, a lot transfer policy may either consider or not consider lot synchronization. When it is considered, there are two different views on synchronization (Chankov *et al.*, 2016, 2018): (1) the flow-focused perspective, which originated in the manufacturing and logistics research domain and refers to the coupling of work systems that are linked by material flows; and, (2) the system-focused perspective, which originated in the natural sciences domain and refers to the rhythm and repetitive behaviour of production processes in a manufacturing system. In our study, the focus is on the flow of job lots between work systems (or stations) and therefore our definition of synchronization is aligned with the former view. That is, synchronization occurs when all lots of the same job are provided to the subsequent production step just-in-time. Consequently, if lot synchronization is enforced, then a lot must wait until all lots of the job are complete before it, together with all the others, can proceed to the next station. If lot synchronization is not enforced, then any lot can proceed freely after completion at a given station. A third, intermediate option that partially synchronizes lot transfers between stations was presented by Kher *et al*. (2000). The authors did not use full synchronization. Instead, they adopted a 'pull' approach that allows a lot to proceed to the next station – even if all lots of the job are not yet completed and thus fully synchronized – if the next station is starving. Thus, in total, three transfer policies can be identified:

- *Transfer Policy 1 (synchronization)*: each lot that makes up a job must wait until all lots of the job are completed at a station before proceeding to the next station in the routing, and finally to the customer;
- *Transfer Policy 2 (synchronization plus starvation avoidance)*: as for Policy 1, but a lot may proceed to the next station even if all lots of the job have not yet been completed if the next station is starving; and,
- *Transfer Policy 3 (no synchronization)*: each lot of a job can proceed independently through the shop floor, but it must wait until all lots of a job have been completed before it can be delivered to the customer.

Policy 2 is inspired by the pull approach of Kher *et al*. (2000) and detailed in Section 3.2. In the context of the pure flow shop, where all jobs visit all stations in the same sequence, Kher *et al*. (2000) showed that the pull approach performs statistically equivalent in terms of throughput time and tardiness to Policy 3; however, the former leads to higher lot integrity. Meanwhile, Thürer *et al*. (2018) showed that when jobs have random routings, directed from upstream to downstream stations, as in general flow shops, Policy 3 is a better option than Policy 1. However, Thürer *et al*. (2018) did not consider Policy 2, while Kher *et al*. (2000) only evaluated the pull approach in a pure flow shop. The latter is a major shortcoming given that many of the shops that require lead time reduction are make-to-order shops characterized by high routing complexity. Our first research question therefore asks:

RQ1: What is the impact on performance of the alternative lot transfer policies in the context of high routing complexity?

The transfer policy controls lot progress on the shop floor, but if order release control is applied then managers must decide how the release of individual lots that make up a job should be synchronized – the reduction of work-in-process itself does not create logistic synchronization (Chankov *et al*., 2018). Fernandes *et al*. (2016) recently showed that if order release control is applied then enforcing synchronization at release, i.e. releasing all of the lots that make up a job onto the shop floor together, is a better policy than releasing lots individually at different release times. This finding however seems to contradict the results in Thürer *et al*. (2018) on the lot transfer policy, which suggest that different approaches may be needed at release and on the shop floor. Fernandes *et al*. (2016) however did not consider different transfer policies on the shop floor, while Thürer *et al*. (2018) did not consider different synchronization policies at order release. There is thus a need to combine the insights from the two studies. Our second (and final) research question therefore asks:

RQ2: Should the release of lots be synchronized in addition to synchronizing their progress on the shop floor?

Controlled simulation experiments will be used to address our two research questions. The following section outlines the simulation model used in the study.

3. Simulation

A stylized standard model of a pure job shop is used in this study to avoid interactions that may otherwise interfere with our understanding of the main experimental factors. This kind of model is widely applied in the literature (e.g. Melnyk & Ragatz, 1989; Land, 2006; Land *et al*., 2015; Fernandes *et al*., 2017; Thürer *et al*., 2018) allowing for the validation of our simulation model. While any individual shop in practice will differ from our stylized environment, the model used in this study capture the job and shop characteristics of high variety make-to-order shops, i.e. high routing variability, high processing time variability and high arrival time variability. The shop and job characteristics will be introduced in Section 3.1. Section 3.2 then summarizes the different lot transfer policies and the dispatching rule applied on the shop floor before Section 3.3 introduces the order release method. Finally, the experimental design and performance measures are outlined in Section 3.4.

3.1 Overview of Modelled Shop and Job Characteristics

A simulation model of a pure job shop has been implemented in ARENA® software. We chose the pure job shop since it exhibits low logistic synchronization (Chankov *et al*., 2018) and thus mostly relies on effective lot synchronization. We have kept our shop relatively small since this allows causal factors to be identified more easily. Small systems provide a better insight into the role of operating variables and, in practice, large systems can often be decomposed into several smaller systems (Bokhorst *et al*., 2004). At the same time, we selected a size that allows for comparison with previous studies that have investigated order release in job shop contexts. Thus, the shop contains six stations, where each is a constant and equal capacity resource.

Routings in the *pure job shop* are undirected and the routing length of jobs varies uniformly from one to six operations. The routing length is first determined before the routing sequence is generated randomly without replacement. The operation times of jobs follow a truncated 2-Erlang distribution with a mean of 1 time unit and a maximum of 4 time units. Set-up times have been considered as part of the operation time and tested at two levels, namely at zero and five percent of the operation time. Set-up times are modelled by reducing the operation time by the set-up factor (0% or 5%) if a lot from the job currently being processed is processed next at the same station.

Smunt *et al*. (1996) found that the number of lot splits is more important than the exact form of lot splitting. Therefore, we focus on this characteristic of lot splitting, considering three different splits: (i) all jobs consist of 2 lots; (ii) all jobs consist of 3 lots; and, (iii) all jobs consist of 4 lots. The lots that make up a job are of equal size, which is motivated by Kropp & Smunt's (1990) finding that using equal-sized lots works well in many situations. This means that, for example, a job with an operation time of 3 time units has 1.5 time units per lot if the lot is split into two and 1 time unit per lot if the lot is split into three. Meanwhile, a scenario without splitting jobs was not considered since the focus of the study is on lot transfer policies.

The inter-arrival time of jobs follows an exponential distribution with a mean of 0.648 time units. This deliberately result in a utilization level of 89.2% at all stations when the set-up factor is 0%, which has been the benchmark in many simulation studies (e.g. Land, 2006; Fernandes *et al*., 2016, 2017; Thürer *et al*., 2017, 2019). Due dates are set exogenously by adding a random allowance to the job entry time. This allowance is uniformly distributed between 30 and 50 time units. The lowest value of the allowance will be enough to cover a minimum shop floor throughput time corresponding to the maximum processing time of 4 time units for the maximum number of possible operations (i.e. six) plus an allowance for the waiting or queuing time. The maximum value was set arbitrarily such that the percentage tardy under immediate release is approximately 10%.

3.2 Workflow Control on the Shop Floor

The flow of work on the shop floor is controlled by a priority dispatching rule and a lot transfer policy. In this study, the *repetitive lots* logic of Jacobs & Bragg (1988) is used for shop floor dispatching. According to this logic, whenever a station becomes available a lot of the same job as the one that has just been processed is selected from the queue directly feeding it. In the case that a lot of the same job is not available, the *first-in-system-first-served* (FIFS) rule proposed by Spearman *et al*. (1990) and Hopp & Spearman (2001) is used to select the next lot. Lot progress is further restricted by the lot transfer policy (see Section 2.2 above for the three alternative policies). In the case of Transfer Policy 2 (synchronization plus starvation avoidance), the station attempts to pull a transfer lot from a feeding station whenever it becomes idle, i.e. when, after processing a lot, there are no more lots in the queue directly feeding the station. If there are multiple feeding stations, then the lot is pulled from the station with the longest queue. The FIFS rule is used as a 'tie-breaker' to select the lot to be pulled.

3.3 Job Release Control

We will use Constant Work-in-Process (ConWIP; e.g. Spearman *et al*., 1990; Hopp & Spearman, 2001; Jaegler *et al*., 2018) to control order release. ConWIP is an order release system that can be used to supplement an MRP system (e.g. Zäpfel & Missbauer 1993; Hopp & Spearman, 2001) and has been widely applied in practice (e.g. Slomp *et al*., 2009; Prakash & Chin, 2014; Crop *et al*., 2015; Leonardo *et al.*, 2017; Olaitan *et al.*, 2019). Under ConWIP, jobs are only permitted to enter the shop floor if a limit on the shop work-in-process (WIP) is not violated; otherwise, they must wait in the pre-shop pool until some of the jobs on the shop floor have been completed. ConWIP can be unit-based or load-based (Thürer *et al*., 2019), depending on whether feedback on the shop WIP represents the physical inventory or the level of workload on the shop floor. Therefore, two WIP measures are considered in the study, as follows:

- *The number of lots*: which is in accordance with the original ConWIP system; and
- *The shop load*: which represents the total workload in time units of all lots on the shop floor.

As in previous simulation studies on ConWIP (e.g. Hopp & Spearman, 1991; Bonvik *et al*., 1997; Herer & Masin, 1997; Jodlbauer & Huber, 2008; Thürer *et al*., 2017), it is assumed that materials are available and all necessary information regarding the shop floor routing, e.g. operations times, is known upon the arrival of a job in the pool. On arrival, jobs directly enter the pool and await release according to ConWIP.

Jobs in the pool are sequenced according to a capacity slack rule, as given by Equation (1), which was chosen based on its good performance in Thürer *et al*. (2017). The lower the capacity slack ratio CS_j of job j, the higher the priority of the job.

$$CS_j = \frac{\sum_{s \in S_j} \left(\frac{\frac{p_{js}}{i}}{N_s^c - W_s^c} \right)}{n_j} \tag{1}$$

The capacity slack ratio integrates three elements into one priority measure: the workload contribution of a job to a station, $\frac{p_{js}}{i}$; the load gap (N_s^c-W_s^c) at a station s processing operation i of job j; and the routing length n_j (i.e., the number of operations in the routing of the job), which is used to average the ratio between the load contribution and the load gap elements over all operations in the routing of the job.

Previous literature considered two parameters for ConWIP, a limit on the WIP and a work-ahead window (Jodlbauer & Huber, 2008; Hübl *et al*., 2011). In this study, an infinite work-ahead window will be applied, which means that all jobs in the backlog are eligible for release. This is justified by the negative performance impact – in terms of throughput time and tardiness – that has been observed from using a work-ahead window in previous research set in similar contexts to our research (e.g. Land, 2006). Meanwhile, five limit levels are applied: 30, 36, 42, 48, and 54. These limits are multiplied by the number of lots per job for the scenarios where the number of lots in the system is limited (the original ConWIP system), and by the mean operation time per job for the scenarios where the shop load, in time units, is limited. In addition, experiments with no limit on the shop WIP are also executed, referring to no order release control.

Three synchronization policies are applied for order release control, namely:

- *Release Policy 1 (synchronization)*: where all lots of a job must be released together; and,
- *Release Policy 2 (synchronization plus starvation avoidance)*: as for Policy 1, but a job may be pulled and released to the shop floor if the first station in the routing of the job is starving, even if the work-in-process limit is violated.
- *Release Policy 3 (no synchronization):* where each lot that makes up a job can be released independently.

3.4 Experimental Design and Performance Measures

The experimental factors are summarized in Table 1. A full factorial design was used with 432 (2x2x6x2x3x3) scenarios. Each scenario was replicated 100 times and all results were collected over 13,000 time units following a warm-up period of 3,000 time units. These parameters allow us to obtain stable results while keeping the simulation run time to an acceptable level.

[Take in Table 1]

Since we focus on a high-variety make-to-order environment, our main performance indicator will be delivery performance, as is widely adopted in the related literature, e.g. Melnyk & Ragatz (1989), Land (2006), Ziengs *et al.* (2012), Land *et al.*, (2015), Fernandes *et al.* (2017), and Thürer *et al.* (2018). As for most make-to-order contexts in practice, there is no penalty on earliness. Delivery performance is therefore measured based on the percentage tardy, i.e. the percentage of jobs completed after the due date; and the mean tardiness, that is $T_j = \max(0, L_j)$, with L_j being the lateness of job j. We also measure the mean *total throughput time*, i.e. the mean of the completion date minus the pool entry date, across jobs. The mean lateness can be derived directly from this measure by subtracting the mean of the due date allowance from the mean total throughput time. Finally, in addition to the three main tardiness related performance measures, we also measure the average *shop floor throughput time* (i.e. the time that a job spends in the system after it has been released) and the average *machine utilization rate*.

4. Results

To assess performance differences between control polices, Section 4.1 below presents detailed performance results for the scenario where ConWIP measures WIP in terms of the number of lots, and the set-up factor is zero. The impact of the WIP measure applied at order release, and the impact of set-up times, is then explored in Section 4.2 to assess the robustness of our results. Finally, a discussion of the results is presented in Section 4.3.

The significance of the performance differences between the outcomes of individual experiments were verified by paired t-tests, which comply with the use of common random number streams to reduce variation across experiments. Whenever we discuss a difference in outcomes between two experiments, the significance can be proven by a paired t-test at a level of 95%.

4.1 Performance Assessment: WIP Measured in Lots

To aid interpretation, the simulation results are presented in the form of performance curves, while more detailed simulation results are also provided in an online supplement (see Appendix A). The left-hand starting point in each performance curve represents the tightest limit on the shop WIP. This limit increases stepwise by moving from left to right in each graph, with each data point representing one limit level. Increasing the limit level raises the shop WIP and, as a result, increases shop floor throughput times.

Figure 1 shows the total throughput time, the percentage tardy, and mean tardiness over the shop floor throughput time for the scenarios where jobs are split into 2 lots, into 3 lots, and into 4 lots. Only results for the situation where the set-up time factor is zero and using the number of lots as the WIP measure (as in the original ConWIP system) are shown in the figure. The impact of these two factors is assessed in our robustness analysis in Section 4.2.

[Take in Figure 1]

The following can be observed from the results:

- *ConWIP control*: ConWIP has the potential to improve performance compared to no order release control in terms of the total throughput time and percentage tardy whilst simultaneously reducing WIP and shop floor throughput times. However, the limit on the number of lots allowed on the shop floor must be set appropriately. This is because a tighter limit restricts the WIP and thus leads to shorter shop throughput times, as can be observed from Figure 1. Once the total throughput time is equal to the shop floor throughput time plus the pool time, a tighter limit also leads to a shorter total throughput time. However, if the limit on the number of lots is set excessively tight, waiting times in the pre-shop pool are not compensated for by the shorter throughput times on the shop floor, and thus the total throughput time increases. The limit level at which performance starts to deteriorate will depended on the workload balancing capabilities of the control strategy adopted.
- *Release Policy*: Release Policy 2 (synchronization *plus starvation avoidance*) maintains or improves performance compared to Release Policy 1 (synchronization), specifically at tighter limits on the number of lots allowed on the shop, through its starvation avoidance mechanism. At the tightest limit for the number of lots on the shop floor, the performance improvement for the percentage tardy is 9.2%, 2.7% and 3.5% when the number of lots per job is set to 2, 3, and 4, respectively and the transfer of lots on the shop floor is based on Policy 3. When the transfer of lots is based on Policy 2, these values are 9.9%, 2.2%, and

3.1%, respectively; and when based on Policy 1, these values are 10.5%, 4.3%, and 4.9%, respectively. Performance differences between these experiments, based on a paired t-test, for the tightest limit level are presented in Table 2. Meanwhile, results for Release Policy 3 are equivalent to those for Release Policy 1. This will be discussed further in Section 4.3 below.

- *Lot Transfer Policy*: Transfer Policy 3 (no synchronization) outperforms Transfer Policy 1 (synchronization) and Transfer Policy 2 (synchronization plus starvation avoidance). For example, at the tightest setting for the limit on the number of lots in the shop, the performance improvement over Transfer Policy 1 for the percentage tardy is 19.1%, 25.1%, and 26.4% when the number of lots per job is set to 2, 3, and 4, respectively and release is based on Policy 2. Under the same conditions, the performance improvement over Transfer Policy 2 is 16.1%, 21.7%, and 22.2%, respectively. Performance differences between these experiments, based on a paired t-test, for the tightest limit level are presented in Table 2. This finding can mainly be attributed to much shorter shop floor throughput times – as can be observed from the total throughput times – that result from the overlapping of operations between successive stations in the routing of jobs.
- *Lot Splitting*: Increasing the number of lots per jobs allows for performance improvements in terms of all three performance measures considered in this study. This is in line with previous studies, e.g. Altendorfer *et al*. (2013). Most performance gains however are already realized with three lots per job, hence there are only marginal gains to be had from increasing the number of lots per job to four.

[Take in Table 2]

4.2 Robustness Analysis

4.2.1 WIP Measure

To assess the impact of the *Work-In-Process* (WIP) measure applied, Figure 2 present the same performance measures as in Figure 1 but for the scenarios where the shop load rather than the number of lots is limited.

[Take in Figure 2]

Limiting the workload leads to a general performance improvement in terms of the percentage tardy since jobs with shorter operation times have a higher probability of being released to the shop floor than large jobs. This is because they better fit the limit on the workload imposed, i.e. a shortest operation time effect is created. Compared to Figure 1, the following can be observed:

- *ConWIP Control*: ConWIP again has the potential to improve performance compared to no order release control whilst reducing work-in-process and shop floor throughput times. The results however are much more sensitive to the workload limit applied when the workload is used as the measure of the shop WIP. The use of the workload measure facilitates the release of small jobs and hinders the release of large jobs compared to the original ConWIP system (that controls the number of lots). This leads to a shortest operation time effect, and thus to a higher mean tardiness.
- *Release Policy*: While Release Policy 2 (synchronization plus starvation avoidance) retains its performance gains in terms of the total throughput time and mean tardiness, compared to Release Policy 1 (synchronization), it is outperformed by Release Policy 1 in terms of the percentage tardy when WIP is measured by the shop workload. Meanwhile, Release Policy 3 has the potential to outperform Release Policy 2 but leads to unstable results at tighter workload limits, particularly under Transfer Policy 1. Therefore, performance curves for Release Policy 3 do not contain markers for the tightest workload limit. Unstable results mean that a steady state is not reached since, at a certain moment in the simulation, jobs are no longer processed but accumulate in the pre-shop pool. This will be explained further in Section 4.3 below.
- *Lot Transfer Policy*: Transfer Policy 3 (no synchronization) outperforms Transfer Policy 1 (synchronization) and Transfer Policy 2 (synchronization plus starvation avoidance). While this can again be mainly attributed to shorter shop floor throughput times, there is also an increase in pool waiting times for transfer policies 1 and 2 at tight load limits.
- *Lot Splitting*: The positive performance effect observed when increasing the number of lots per job from two to four is less pronounced than the effect shown in Figure 1.

4.2.2 Set-up Times

Similar conclusions on the relative performance of experimental factors to those in the scenario with a set-up factor of zero can be drawn from the results for the scenario with a set-up factor of five percent. This can be observed from Figure 3 and Figure 4, which depict the results for the scenarios when the shop WIP is measured by the number of lots and by the shop load, respectively. The main difference is a general performance improvement in terms of time and tardiness related performance measures, particularly when splitting jobs into more lots, which can be explained by the lower utilization level realized. This can be seen from Table 3, which summarizes the realized utilization levels. If we compare the average utilization across transfer policies, then we observe slightly lower utilization levels for transfer policies 1 and 2. This is because enforcing synchronization while using *repetitive lots* logic necessarily minimizes set-ups. The lower utilization of these transfer policies however is not enough to outweigh the improved performance of Transfer Policy 3. While there is no synchronization in terms of lot transfer for Transfer Policy 3 (i.e. the movement from one queue to another), there is synchronization in terms of which job from the queue to process next, i.e. dispatching. The *repetitive lots* logic used at dispatching realizes a higher degree of lot synchronization in periods of high load for Transfer Policy 3 since lots wait longer in the queue, which increases the probability that lots of the same type accumulate in the same queue. Thus, additional capacity gains through set-up time reduction for Transfer Policy 1 and Transfer Policy 2 are lower in the periods when it is most important (Land *et al*., 2015). This may explain why previous studies indicated that the benefits of lot splitting are persistent even when faced with long set-ups (Kher *et al*., 2000).

[Take in Figure 3 & Figure 4 & in Table 3]

4.3 Discussion of Results

The research presented in this paper has been mainly motivated by three prior contributions to the literature: Kher *et al*. (2000), Fernandes *et al*. (2016), and Thürer *et al*. (2018). Kher *et al*. (2000) showed that, for the pure flow shop, only allowing individual lots to proceed to the next station if the downstream station is starving performs statistically equivalent to allowing lots to proceed independently through the shop floor. But rather than confirming Kher *et al.* (2000), our findings support and extend Thürer *et al*. (2018), which showed that allowing lots to proceed independently through the shop floor (Transfer Policy 3) is a better option than synchronizing their progress (Transfer Policy 1). Transfer Policy 3 led to the best results across all performance measures and all modelled scenarios.

A main explanatory variable is that in Transfer Policy 2 idle stations just pull a single transfer lot from a feeding station. The remaining lots of the job are not immediately transferred as they are processed at the feeding station. Instead, they are synchronized and transferred all together; the only exception to this is if the starving station remains idle after processing and therefore pulls another lot. While this may restrict the number of transfers incurred when compared to Policy 3, it leads to higher job throughput times as the transferred lot must wait for the remaining lots of the job to proceed to a further downstream station, with other jobs being processed in-between. This is emphasized by the routing configuration of the pure job shop that has a low level of logistic synchronization. In contrast, the pure flow shop, as used in Kher *et al*., (2000), has a high level of logistic synchronization (Chankov *et al.* 2018) since all jobs follow the same sequence, which explains the results in Kher *et al*. (2000).

Another important finding from our study is that, if some form of synchronization is enforced on the shop floor at stations, or only after all of the transfer lots belonging to a job have been processed, then synchronization at release is also required when a release mechanism that limits the shop WIP (such as ConWIP in our study) is applied. Release Policy 3 led to blocking under tight limits on the number of lots in the shop or to results that are equivalent to Release Policy 1 when the shop load, rather than the number of lots, is restricted. In our experiments, the number of ConWIP cards released back to the pool once a job has been completed is equal to the number of ConWIP cards needed to release all of the lots of a new job. Since the lots of a job share the same capacity slack value, all of the lots of a job are released together, even if no synchronization is applied. Hence, the results of Release Policy 3 are equivalent to those of Release Policy 1, i.e. full synchronization. If the number of lots per job was different across jobs and their release was not synchronized, then some of the lots that make up a job could potentially be released while others were left to remain in the pool. Similarly, if a workload limit is applied, then the workload released when one job is completed is not necessarily equal to the workload required by the lots of a job waiting in the pool. Hence, some of the lots of a job may be released, while others would continue to wait. If synchronization is applied on the shop floor, then lot progress depends on the lots in the pool also being released. Yet, at the same time, the release of lots from the pool is dependent on the progression of lots through the shop floor if the number of lots in the system is to continue to be controlled. As a consequence, blocking occurs. The risk and severity of this blocking phenomenon increases with the tightness of the WIP limit. This extends the findings in Fernandes *et al*. (2016), which recently showed that if order release control is applied then enforcing full synchronization at workload control release, i.e. releasing all of the lots that make up a job into the system together, is a better policy than releasing lots individually at different release times.

Enforcing some form of synchronization at order release is necessary to avoid blocking if some form of lot synchronization is applied on the shop floor. Synchronization plus starvation avoidance appears however to be a better solution at release than full synchronization in shops with random routings. It avoids the blocking effect that occurs with no synchronization whilst also avoiding premature station idleness, which is a characteristic of load-limiting order release methods (Kanet, 1988; Land & Gaalman, 1998).

5. Conclusions

Lot splitting is an important strategy to avoid starvation at downstream stations, to accelerate job progress, and to improve overall job due date performance. Consequently, a broad literature on lot splitting exists. The impact of the lot transfer policy that determines how the flow of lots that make up a job is synchronized through the production system has however received only limited attention. Moreover, in this limited literature, there is a lack of consensus. For example, while some studies have argued for lot synchronization on the shop floor, others have argued that not synchronizing lot progression is in fact a better strategy. One factor that may explain these apparently contradictory results is the routing characteristics underpinning the shop models.

In response to the above, we have asked two research questions. First: What is the impact on performance of the alternative lot transfer policies in the context of high routing complexity? Using simulation, we have shown that not synchronizing lot progress is the best solution if dispatching based on the *repetitive lots* logic is applied on the shop floor and that performance differences across lot synchronization policies are robust to set-up time considerations. Second: Should the release of lots be synchronized in addition to synchronizing the progress of lots on the shop floor? We have found that some form of synchronization is required at order release if lot progression is synchronized on the shop floor. Without synchronization at release, blocking may occur. This extends the results presented in the extant literature, which demonstrated that full synchronization at release outperforms no synchronization. However, our results also show that synchronization plus starvation avoidance of jobs has the potential to improve performance since it avoids premature station idleness.

5.1 Managerial Implications

The main managerial implication of our paper is that different approaches should be followed at order release and on the shop floor. While the release of lots to the shop floor should be synchronized in some form, the progress of lots once released to the shop floor should not be synchronized. Instead, a dispatching rule that ensures synchronization, such as based on repetitive lots logic, should be applied. Our study also further highlights the positive performance effects of ConWIP compared to no order release control. Yet, although limiting the workload instead of the number of lots improves performance, it also introduces a shortest operation time effect. Thus, managers must trade off percent tardy gains against losses in terms of the mean tardiness of jobs.

5.2 Limitations and Future Research

A main limitation of our study is that we have only considered one release method: ConWIP. While this is justified by ConWIP's simplicity and the need to keep our study focussed, future research is required to confirm our findings under different release methods. For example, we have shown that synchronization combined with the pull release of jobs to the shop floor for starvation avoidance has the potential to outperform synchronization without pull release (as advocated by Fernandes *et al*. (2016), but this has not been tested in the context of more sophisticated approaches, such as Workload Control. More complex manufacturing environments and other shop configurations must also be investigated.

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References

Aglan, C. and Durmusoglu, M.B., 2015, Lot-splitting approach of a hybrid manufacturing system under CONWIP production control: a mathematical model, *International Journal of Production Research*, 53, 5, 1561–1583.

Altendorfer, K., Felberbauer, T., Gruber, D., Hübl, A., (2013) Application of a generic simulation model to optimize production and workforce planning at an automotive supplier, In Proceedings of the 2013 Winter Simulation Conference: Simulation: Making Decisions in a Complex World (WSC '13). IEEE Press, Piscataway, NJ, USA, 2689-2697.

Azzi, A., Maurizio, F., and Persona, A., 2012, Lot Splitting Scheduling Procedure for Makespan Reduction and Machine Capacity Increase in a Hybrid Flow Shop with Batch Production, *International Journal of Advanced Manufacturing Technology*, 59, 5, 775–786.

Bokhorst, J.C.A., Slomp, J., and Gaalman G.J.C., 2004, On the who-rule in Dual Resource Constrained (DRC) manufacturing systems, *International Journal of Production Research*, 42, 23, 5049-5074.

Bonvik, A.M., Couch, C.E. and Gershwin, S.B., 1997, A comparison of production-line control mechanisms, *International Journal of Production Research*, 35, 3, 789- 804.

Buscher, U., and Shen, L., 2009, An Integrated Tabu Search Algorithm for the Lot Streaming Problem in Job Shops, *European Journal of Operational Research*, 199, 2, 385–399.

Calleja, G., and Pastor, R., 2014, A dispatching algorithm for flexible job-shop scheduling with transfer batches: an industrial application, *Production Planning & Control*, 25, 2, 93-109.

Chang, J.H., and Chiu, H.N., 2005, A Comprehensive Review of Lot Streaming, *International Journal of Production Research*, 43, 8, 1515–1536.

Chankov, S.M., Huett, M. and Bendul, J., 2018, Influencing Factors of Synchronization in Manufacturing Systems, *International Journal of Production Research*, 56, 14, 4781–4801.

Chankov, S.M., Huett, M., and Bendul J.,2016, Synchronization in Manufacturing Systems: Quantification and Relation to Logistics Performance, *International Journal of Production Research*, 54, 20, 6033–6051.

Cheng, M., Mukherjee, N.J., and Sarin, S.C., 2013, A Review of Lot Streaming, *International Journal of Production Research*, 51, 23–24, 7023–7046.

Cransberg, V., Land M., Hicks, C. and Stevenson, M., 2016, Handling the complexities of real-life job shops when implementing workload control: A decision framework and case study, *International Journal of Production Research*, 54, 4, 1094–1109.

Crop, F., Lacornerie, T., Mirabel, X. and Lartigau, E., 2015 Workflow Optimization for Robotic Stereotactic Radiotherapy Treatments: Application of Constant Work in Progress Workflow, *Operations Research for Health Care*, 6, 1, 18–22.

Fernandes, N.O., Land, M.J., and Carmo-Silva, S., 2016, Aligning workload control theory and practice: lot splitting and operation overlapping issues, *International Journal of Production Research*, 54, 10, 2965-2975.

Fernandes, N.O., Thürer, M., Silva, C., Carmo-Silva, S., 2017, Improving workload control order release: Incorporating a starvation avoidance trigger into continuous release, *International Journal of Production Economics*, 194, 1, 181–189.

Gaalman, G.J.C. and Perona, M., 2002, Workload control in job shops: an introduction to the special issue, *Production Planning & Control*, 2002, 13, 7, 565-567.

Herer Y. T. and Masin M., 1997, Mathematical programming formulation of CONWIP based production lines; and relationships to MRP, *International Journal of Production Research*, 35, 4, 1067-1076.

Hopp, W.J. and Spearman M.L., 1991, Throughput of a constant working process manufacturing line subject to fails, *International Journal of Production Research*, 29, 3, 635- 655.

Hopp, W.J. and Spearman M.L., 2001, *Factory Physics: Foundations of Manufacturing Management*, Irwin/McGraw-Hill.

Hübl, A., Altendorfer, K., Jodlbauer, H., Gansterer, M., Hartl, R.F., 2011, Flexible model for analyzing production systems with discrete event simulation, In Proceedings of the Winter Simulation Conference (WSC '11), S. Jain, R. Creasey, J. Himmelspach, K. P. White, and M. C. Fu (Eds.). Winter Simulation Conference 1559-1570.

Jacobs, F.R., and Bragg, D.J., 1988, Repetitive Lots: Flow-time Reductions Through Sequencing and Dynamic Batch Sizing, *Decision Sciences*, 19, 281–294.

Jaegler, Y., Jaegler, A., Burlat, P., Lamouri, S., & Trentesaux, D., 2018, The ConWip production control system: a systematic review and classification, *International Journal of Production Research*, 56, 17, 5736-5757.

Jeong, H., Park, J., and Leachman, R.C., 1999, A Batch Splitting Method for a Job Shop Scheduling Problem in an MRP Environment, *International Journal of Production Research*, 37,15, 3583–3598.

Jodlbauer, H. and Huber, A., 2008, Service-level performance of MRP, kanban, CONWIP and DBR due to parameter stability and environmental robustness, *International Journal of Production Research*, 46, 8, 2179–2195.

Kanet, J.J., 1988, Load-limited order release in job shop scheduling systems, *Journal of Operations Management*, 7, 3, 44 – 58.

Karmarkar, U.S., Kekre, S., Kekre, S., and S. Freeman, 1985, Lot-sizing and Lead-time Performance in a Manufacturing Cell, *Interfaces*, 15, 2, 1–9.

Kher, H.V., Malhorta., M.K., and Steele, D.S., 2000, The effect of push and pull lot splitting approaches on lot traceability and material handling costs in stochastic flow shop environments, *International Journal of Production Research*, 38, 1, 141-160.

Kropp, D.H., and Smunt, T.L., 1990, Optimal and Heuristic Models for Lot Splitting in a Flow Shop, *Decision Sciences*, 21, 4, 691–709.

Lalitha, J.L., Mohan, N., and Pillai V.M., 2017, Lot streaming in [N-1](1)+N(m) hybrid flow shop, *Journal of Manufacturing Systems*, 44, 12-21.

Land, M., Stevenson, M. and Thürer, M., 2014, Integrating load-based order release and priority dispatching, *International Journal of Production Research*, 52, 4, 1059-1073.

Land, M.J., 2006, Parameters and Sensitivity in Workload Control, *International Journal of Production Economics*, 104, 2, 625-638.

Land, M.J., and Gaalman, G.J.C., 1998, The performance of workload control concepts in job shops: Improving the release method, *International Journal of Production Economics*, 56 – 57, 347 – 364.

Land, M.J., Stevenson, M., Thürer, M., Gaalman, G.J.C., 2015, Job shop control: In search of the key to delivery improvements, *International Journal of Production Economics,* 168, 1, 257–266.

Leonardo, D.G., Sereno, B., Silva, D., Sampaio, M., Massote A. and Simões, J., 2017, Implementation of hybrid Kanban-CONWIP system: A case study, *Journal of Manufacturing Technology Management* 28(6) 714-736.

Litchfield, J. and Narasimhan, R., 2000, Improving job shop performance throughout process queue management under transfer batching, *Production and Operations Management*, 9, 4, 336-348.

Lockwood, W. T., Mahmoodi, F., Ruben, R.A., and Mosier, C.T. 2000, Scheduling Unbalanced Cellular Manufacturing Systems with Lot Splitting, *International Journal of Production Research*, 38,4, 951–965.

Melnyk, S.A., and Ragatz, G.L., 1989, Order review/release: research issues and perspectives, *International Journal of Production Research*, 27, 7, 1081-1096.

Olaitan, O., Alfnes, E., Vatn, J. and Strandhagen, J.O., 2019, CONWIP implementation in a system with cross-trained teams, *International Journal of Production Research*, Online.

Prakash, J. and Chin, J.F., 2014, Implementation of hybrid parallel kanban-CONWIP system: A case study, *Cogent Engineering* 1, 1, 1-15.

Russell, G.R., and Fry, T.D., 1997, Order Review/Release and Lot Splitting in Drum-buffer-rope, *International Journal of Production Research*, 35, 3, 827–845.

Slomp, J.J., Bokhorst, A.C., and Germs, R., 2009, A Lean Production Control System for High-Variety/Low-Volume Environments: A Case Study Implementation, *Production Planning & Control*, 20, 7, 586–595.

Smunt, T.L., Buss, A.H., and Kropp, D.H., 1996, Lot Splitting in Stochastic Flow Shop and Job Shop Environments, *Decision Sciences*, 27, 2, 215–238.

Spearman, M.L., Woodruff, D.L., and Hopp, W.J., 1990, CONWIP: a pull alternative to kanban, *International Journal of Production Research*, 28, 5, 879-894.

Thürer, M., Fernandes, N.O., Ziengs, N., Stevenson, M., and Qu, T., 2019; On the Meaning of ConWIP Cards: An Assessment by Simulation, *Journal of Industrial and Production Engineering*, Forthcoming.

Thürer, M., Fernandes, N.O., Carmo-Silva, S., and Stevenson, M., 2018, Lot Splitting under Load-limiting Order Release in High-Variety Shops: An Assessment by Simulation, *Journal of Manufacturing Systems*, 48, 63-72.

Thürer, M., Fernandes, N.O., Stevenson, M., and Qu, T., 2017, On the Backlog-sequencing Decision for Extending the Applicability of ConWIP to High-Variety Contexts: An Assessment by Simulation, *International Journal of Production Research*, 55, 16, 4695-4711.

Wagner, B. J., and Ragatz, G. L., 1994, The Impact of Lot Splitting on Due Date Performance, *Journal of Operations Management*, 12, 1, 13–25.

Zäpfel, G. and Missbauer, H., 1993, New concepts for production planning and control, *European Journal of Operational Research*, 67, 297 – 320.

Ziengs, N., Riezebos, J. and Germs, R., 2012, Placement of effective work-in-progress limits in route-specific unit-based pull systems, *International Journal of Production Research*, 50, 16, 4358-4371.

Table 1: Summary of Experimental Factors

Release Policy *(RP)* at Job Release	• *Release Policy 1 (synchronization)*: all lots of a job must be released together; • *Release Policy 2 (synchronization plus starvation avoidance)*: as for Policy 1, but a job may be released if the first station in the routing is starving; and, • *Release Policy 3 (no synchronization plus starvation avoidance)*: each lot that makes up a job can be released independently.
Transfer Policy (TP) on the Shop Floor	• *Transfer Policy 1 (synchronization)*: each lot of a job must wait until all lots of the job are completed at each station in its routing before proceeding to the next station and finally to the customer; • *Transfer Policy 2 (synchronization plus starvation avoidance)*: as for Policy 1, but a lot may proceed to the next station even if not all lots of the job are completed if the next station is starving; and, • *Transfer Policy 3 (no synchronization)*: each lot that makes up a job can proceed independently through the shop floor, but each lot must wait until all lots of the job are completed before being delivered to the customer.
Number of ConWIP Cards	30, 36, 42, 48, 54 times the number of lots per job, and an infinite number of cards
WIP Measure	• *Number of Lots*: the number of lots in the system; and, • *Workload*: the total workload in the system.
Set-up Factor (Environmental Factor)	• Zero; and • Five percent of the operation time
Number of lots (Environmental Factor)	2, 3 and 4

Table 2: Paired t-test Comparison of Means for the Percentage Tardy at a 0.05 Level.

Number of Lots	Control Policies	Total Throughput Time		Percent Tardy		Tardiness	
		Estimated mean difference	0.95 CI half-with	Estimated mean difference	0.95 CI half-with	Estimated mean difference	0.95 CI half-with
2	TP1RP2 - TP1RP1	-1.550	0.152	-0,745	0.0928	-1.07	0.129
3	TP1RP2 - TP1RP1	-0.365	0.0382	-0.239	0.0519	-0.204	0.0229
4	TP1RP2 - TP1RP1	-0.395	0.0419	-0.265	0.0453	-0.237	0.0274
2	TP2RP2 - TP2RP1	-1.41	0.146	-0.658	0.0915	-0.965	0.122
3	TP2RP2 - TP2RP1	-0.281	0.0380	-0,112	0,0532	-0.166	0.0241
4	TP2RP2 - TP2RP1	-0.266	0.0413	-0.142	0.0558	-0.161	0.0242
2	TP3RP2 - TP3RP1	-1.02	0.108	-0.517	0.0699	-0.648	0.0836
3	TP3RP2 - TP3RP1	-0.185	0.0304	-0.109	0.0435	-0.0884	0.0163
4	TP3RP2 - TP3RP1	-0.182	0.0315	-0.137	0.0382	-0.0923	0.0176
2	TP3RP1 - TP1RP1	-1.800	0.0956	-1.440	0.0856	-0.738	0.0821
3	TP3RP1 - TP1RP1	-1.630	0.0364	-1.460	0.0554	-0.402	0.0256
4	TP3RP1 - TP1RP1	-1.830	0.0418	-1.48	0.0611	-0.482	0.0314
2	TP3RP1 - TP2RP1	-1.350	0.0780	-1.12	0.0759	-0.559	0.0639
3	TP3RP1 - TP2RP1	-1.240	0.0363	-1.10	0.0581	-0.302	0.0243
4	TP3RP1 - TP2RP1	-1.330	0.0324	-1.08	0.0540	--0335	0.0210
2	TP3RP2 - TP1RP2	-1.270	0.0612	-1.210	0.0662	-0.362	0.0414
3	TP3RP2 - TP1RP2	-1.450	0.0303	-1.330	0.0624	-0.287	0.0194
4	TP3RP2 - TP1RP2	-1.610	0.0372	-1.350	0.0600	-0.337	0.0228
2	TP3RP2 - TP2RP2	-0.962	0.0559	-0.983	0.0672	-0.242	0.0338
3	TP3RP2 - TP2RP2	-1.140	0.0316	-1.100	0.0555	-0.224	0.0176
4	TP3RP2 - TP2RP2	-1.250	0.0361	-1.080	0.0550	-0.267	0.0194

Table 3: Utilization Results for a Set-up Factor of Five Percent of the Operation Time.

	Number of Lots	Release Policy 1	Release Policy 2	Release Policy 3
Transfer Policy 1	2	86.97%	86.97%	86.99%
	3	86.23%	86.23%	86.24%
	4	85.86%	85.86%	85.87%
Transfer Policy 2	2	86.98%	86.98%	87.00%
	3	86.24%	86.24%	86.26%
	4	85.87%	85.87%	85.89%
Transfer Policy 3	2	87.12%	87.12%	87.15%
	3	86.38%	86.38%	86.40%
	4	85.99%	85.99%	86.01%

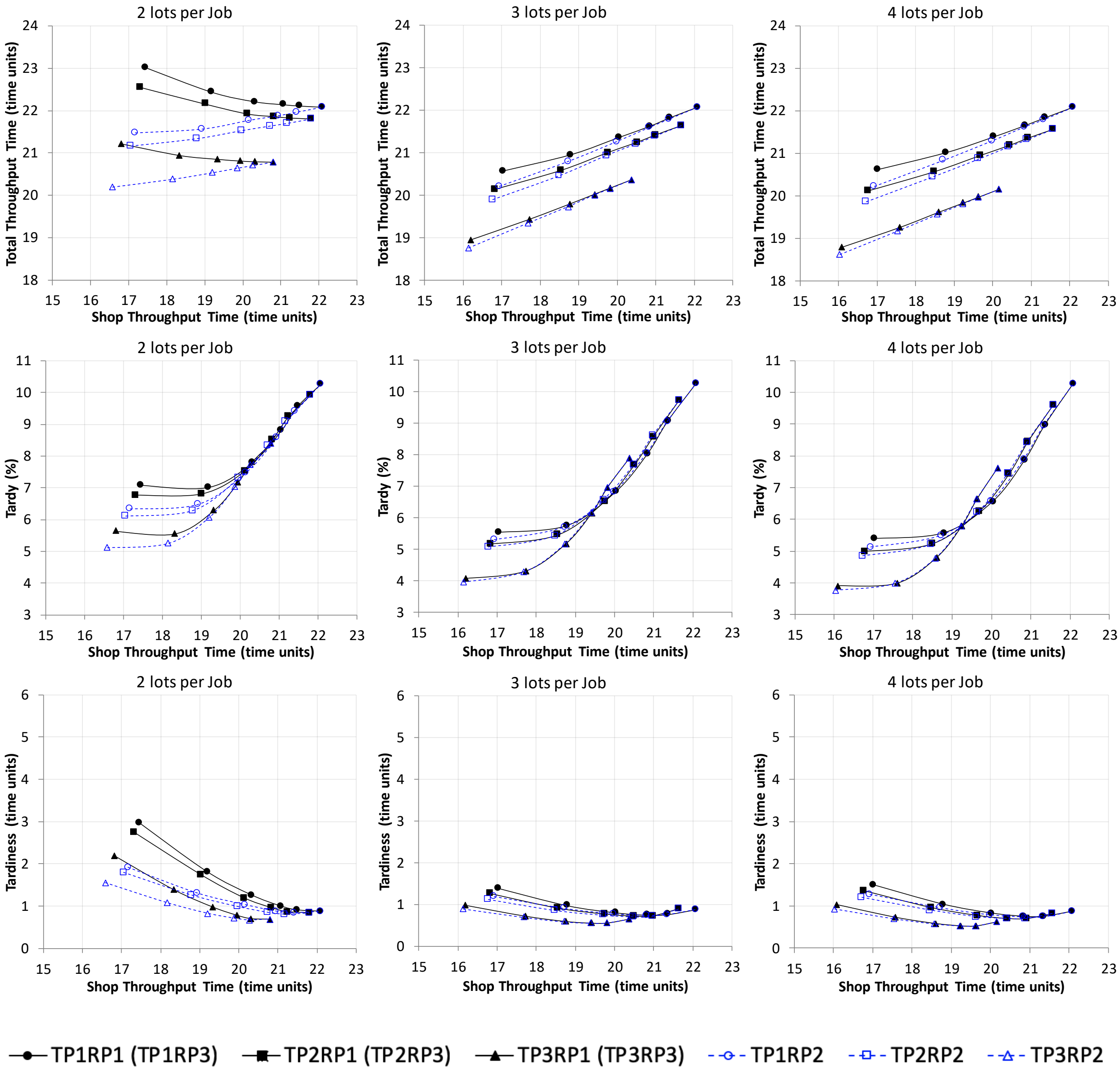

Figure 1: Results for the Transfer (TP) and Release (RP) Policies when Controlling the Number of Lots.

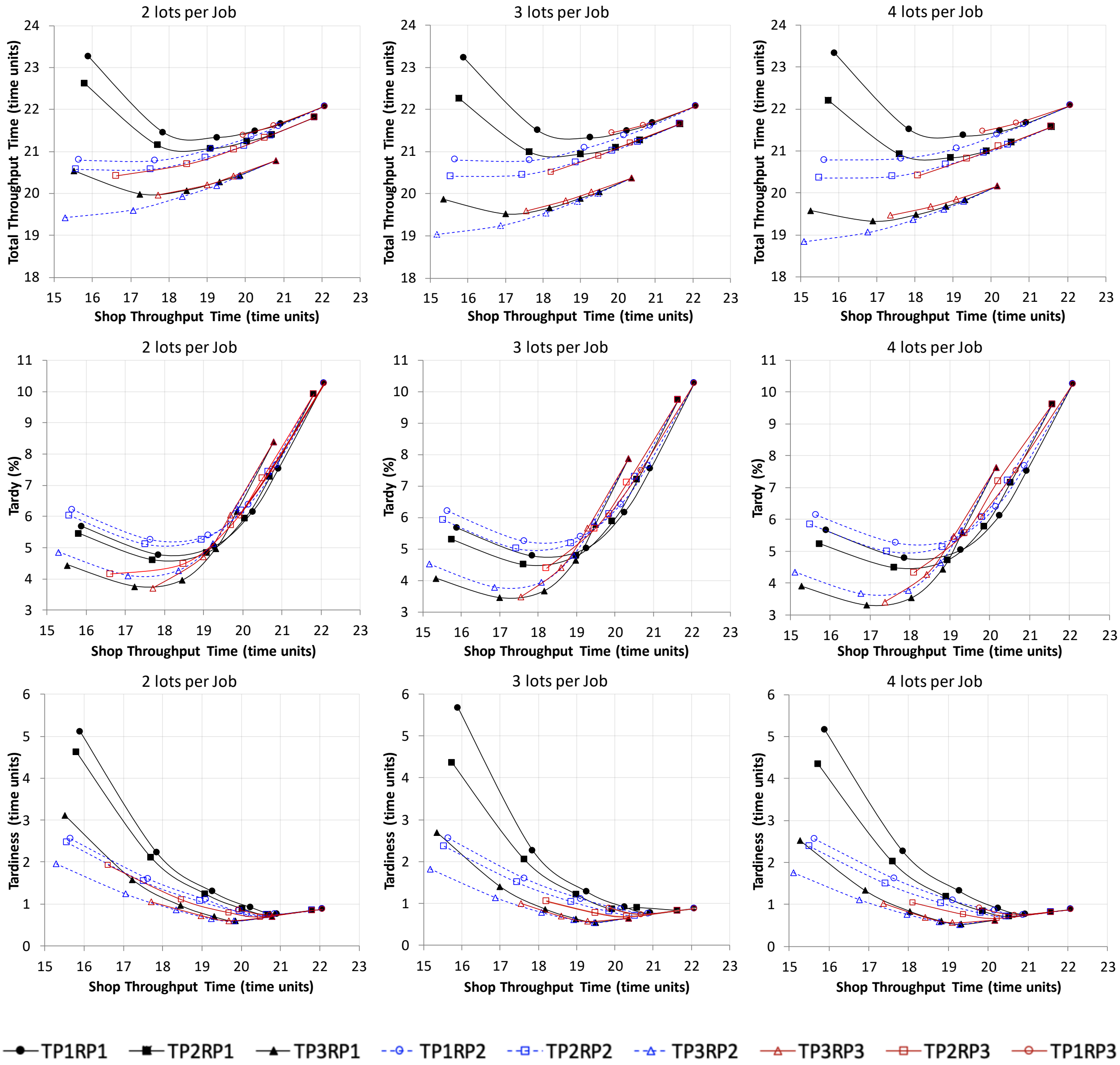

Figure 2: Results for the Transfer (TP) and Release (RP) Policies when Controlling the Shop Load.

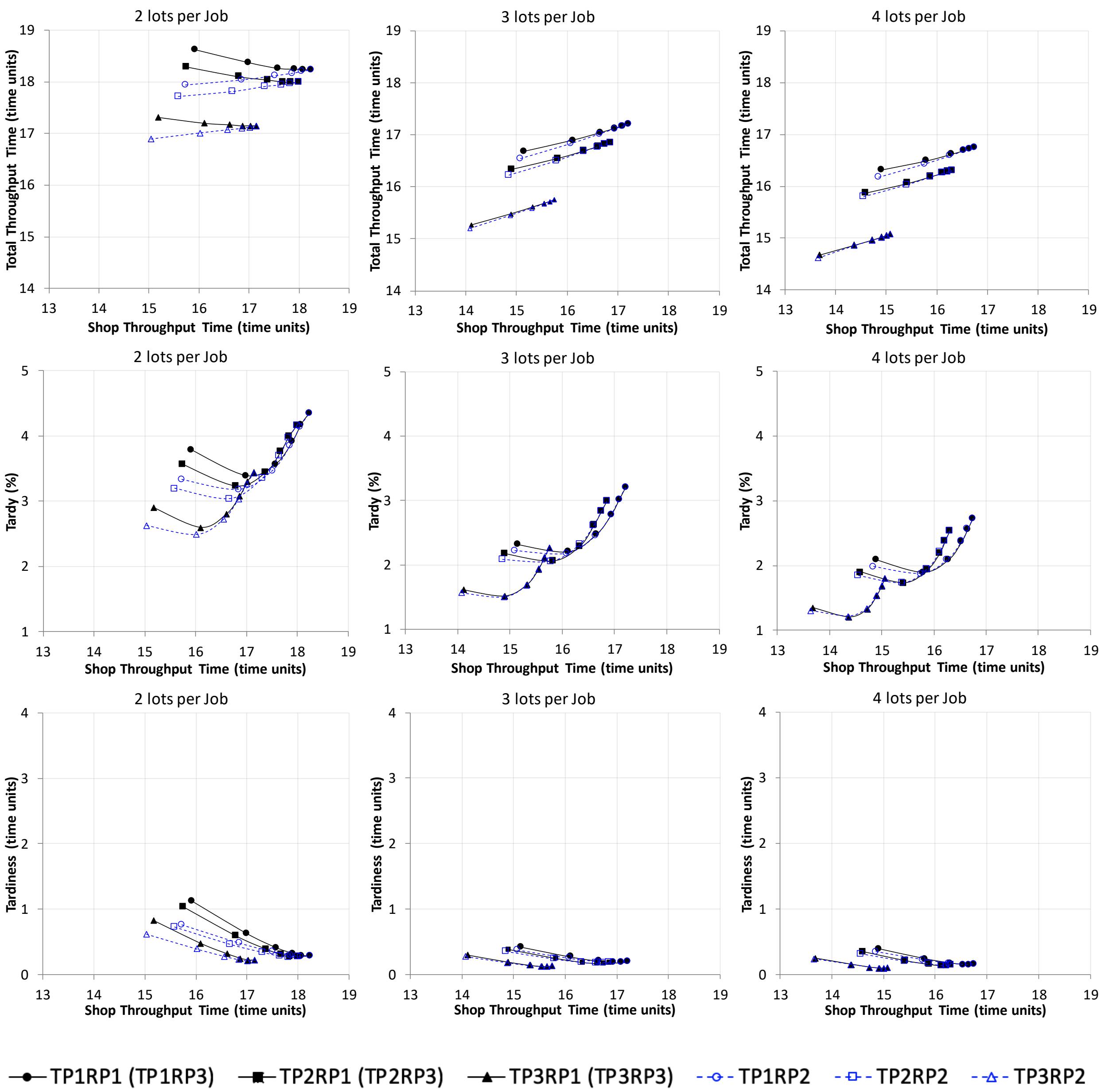

Figure 3: Results for the Transfer (TP) and Release (RP) Policies with a Setup Factor of 5% when Controlling the Number of Lots.

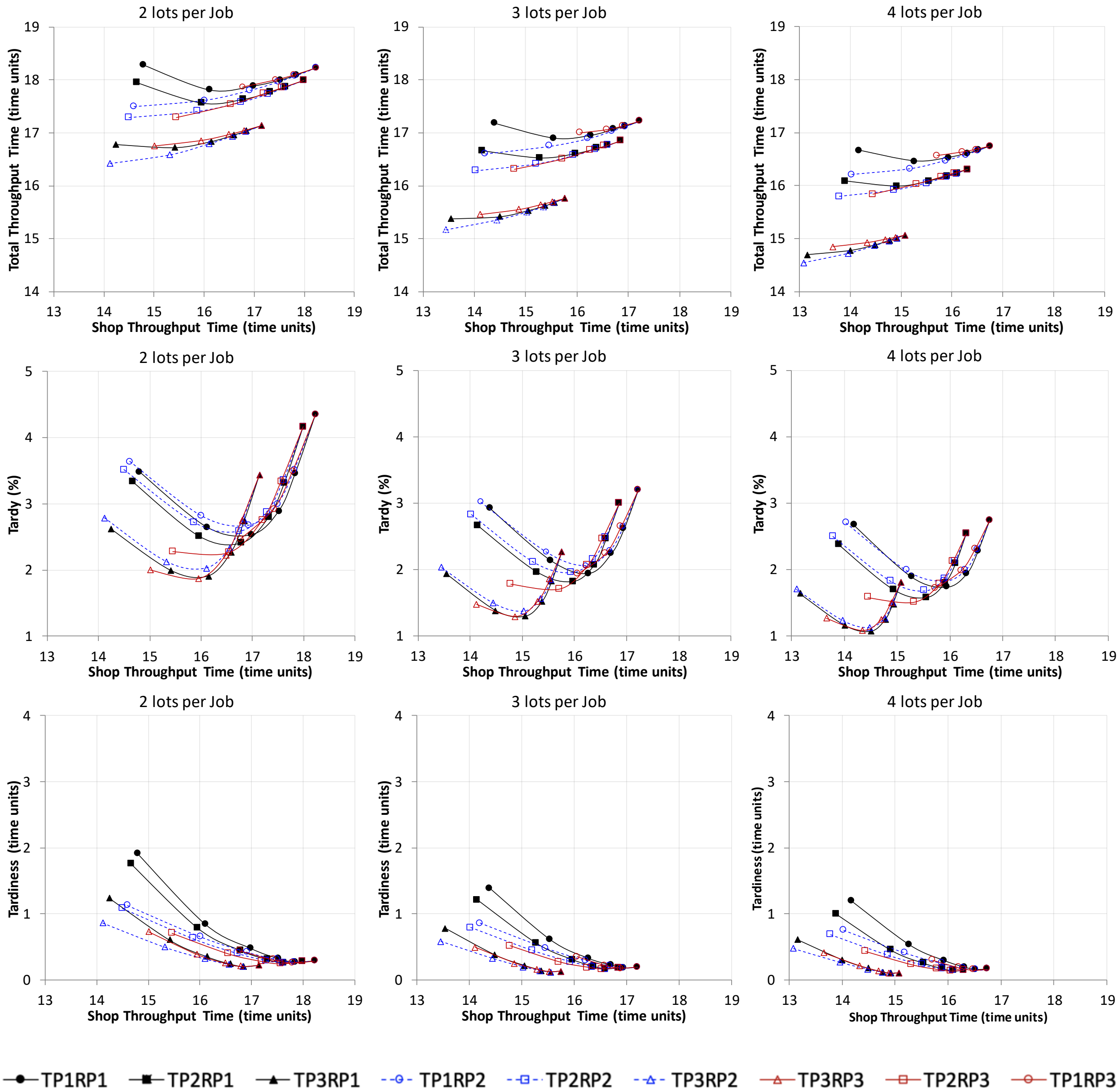

Figure 4: Results for the Transfer (TP) and Release (RP) Policies with a Setup Factor of 5% when Controlling the Shop Load

Appendix A

Table A1: Results for the Transfer Policies (TP) and Release Policies (RP) when Controlling the Number of Lots – 2 Lots per Job.

Performance measure	Policy	Limit 1‡	Limit 2	Limit 3	Limit 4	Limit 5	No Limit
Shop Throughput Time (time units)	TP1RP1*	17.447	19.182	20.319	21.061	21.489	22.084
	TP2RP1**	17.317	19.016	20.124	20.825	21.240	21.808
	TP3RP1***	16.804	18.326	19.328	19.939	20.307	20.789
	TP1RP2	17.169	18.928	20.152	20.939	21.416	22.084
	TP2RP2	17.051	18.782	19.969	20.723	21.169	21.808
	TP3RP2	16.576	18.150	19.197	19.860	20.261	20.789
Total Throughput Time (time units)	TP1RP1*	23.018	22.438	22.211	22.143	22.111	22.084
	TP2RP1**	22.571	22.160	21.296	21.863	21.830	21.808
	TP3RP1***	21.221	20.947	20.856	20.815	20.798	20.789
	TP1RP2	21.471	21.526	21.769	21.882	21.966	22.084
	TP2RP2	21.159	21.334	21.527	21.638	21.701	21.808
	TP3RP2	20.197	20.383	20.538	20.647	20.708	20.789
Tardy (%)	TP1RP1*	7.076	7.009	7.791	7.798	9.576	10.269
	TP2RP1**	6.772	6.801	7.526	8.517	9.234	9.907
	TP3RP1***	5.636	5.560	6.303	7.165	7.819	8.397
	TP1RP2	6.331	6.479	7.476	8.566	9.409	10.269
	TP2RP2	6.102	6.279	7.316	8.322	9.080	9.907
	TP3RP2	5.119	5.256	6.070	7.025	7.718	8.397
Tardiness (time units)	TP1RP1*	2.982	1.82	1.265	1.003	0.909	0.875
	TP2RP1**	2.758	1.751	1.198	0.965	0.868	0.841
	TP3RP1***	2.198	1.395	0.985	0.793	0.710	0.696
	TP1RP2	1.913	1.311	1.037	0.884	0.845	0.875
	TP2RP2	1.793	1.265	0.995	0.860	0.816	0.841
	TP3RP2	1.551	1.083	0.831	0.719	0.674	0.696

Equivalent to TP1RP3; ** Equivalent to TP2RP3; * Equivalent to TP3RP3; ‡Tightest limit level on shop WIP*

Table A2: Results for the Transfer Policies (TP) and Release Policies (RP) when Controlling the Number of Lots – 3 Lots per Job.

Performance measure	Policy	Limit 1‡	Limit 2	Limit 3	Limit 4	Limit 5	No Limit
Shop Throughput Time (time units)	TP1RP1*	17.031	18.791	20.038	20.842	21.362	22.084
	TP2RP1**	16.831	18.546	19.750	20.509	20.988	21.651
	TP3RP1***	16.200	17.727	18.759	19.418	19.816	20.368
	TP1RP2	16.931	18.732	19.987	20.825	21.342	22.084
	TP2RP2	16.772	18.486	19.710	20.480	20.969	21.651
	TP3RP2	16.135	17.685	18.722	19.405	19.804	20.368
Total Throughput Time (time units)	TP1RP1*	20.580	20.962	21.368	21.633	21.832	22.084
	TP2RP1**	20.140	20.591	21.011	21.257	21.430	21.651
	TP3RP1***	18.953	19.439	19.795	20.031	20.172	20.368
	TP1RP2	20.214	20.808	21.275	21.604	21.802	22.084
	TP2RP2	19.910	20.467	20.947	21.220	21.401	21.651
	TP3RP2	18.768	19.354	19.739	20.014	20.157	20.368
Tardy (%)	TP1RP1*	5.538	5.754	6.839	8.033	9.078	10.269
	TP2RP1**	5.178	5.462	6.530	7.682	8.572	9.727
	TP3RP1***	4.078	4.310	5.179	6.153	6.961	7.883
	TP1RP2	5.299	5.715	6.821	8.063	9.050	10.269
	TP2RP2	5.066	5.431	6.569	7.682	8.601	9.727
	TP3RP2	3.969	4.293	5.173	6.175	6.959	7.883
Tardiness (time units)	TP1RP1*	1.382	0.971	0.802	0.744	0.759	0.875
	TP2RP1**	1.260	0.906	0.762	0.709	0.717	0.892
	TP3RP1***	0.980	0.721	0.594	0.555	0.559	0.650
	TP1RP2	1.179	0.898	0.770	0.737	0.752	0.875
	TP2RP2	1.116	0.853	0.742	0.703	0.712	0.892
	TP3RP2	0.892	0.689	0.583	0.553	0.560	0.650

Equivalent to TP1RP3; ** Equivalent to TP2RP3; * Equivalent to TP3RP3; ‡Tightest limit level on shop WIP*

Table A3: Results for the Transfer Policies (TP) and Release Policies (RP) when Controlling the Number of Lots – 4 Lots per Job.

Performance measure	Policy	Limit 1‡	Limit 2	Limit 3	Limit 4	Limit 5	No Limit
	TP1RP1*	17.021	18.801	20.041	20.852	21.364	22.084
	TP2RP1**	16.881	18.498	19.687	20.447	20.930	21.577
Shop Throughput Time (time units)	TP3RP1***	16.086	17.592	18.610	19.242	19.632	20.160
	TP1RP2	16.924	18.729	19.988	20.828	21.335	22.084
	TP2RP2	16.722	18.455	19.644	20.421	20.900	21.577
	TP3RP2	16.030	17.544	18.574	19.226	19.626	20.160
	TP1RP1*	20.628	21.026	21.397	21.662	21.841	22.084
	TP2RP1**	20.115	20.570	20.955	21.197	21.370	21.577
Total Throughput Time (time units)	TP3RP1***	18.802	19.268	19.627	19.841	19.977	20.160
	TP1RP2	20.234	20.846	21.301	21.624	21.799	22.084
	TP2RP2	19.866	20.454	20.874	21.162	21.329	21.577
	TP3RP2	18.620	19.180	19.571	19.818	19.967	20.160
	TP1RP1*	5.400	5.583	6.575	7.874	8.978	10.269
	TP2RP1**	5.001	2.239	6.255	7.431	8.453	9.615
Tardy (%)	TP3RP1***	3.919	3.996	4.813	5.793	6.648	7.635
	TP1RP2	5.136	5.511	6.581	7.910	8.963	10.269
	TP2RP2	4.859	5.216	6.232	7.468	8.439	9.615
	TP3RP2	3.782	3.995	4.788	5.802	6.652	7.635
	TP1RP1*	1.505	1.040	0.827	0.752	0.752	0.875
	TP2RP1**	1.364	0.961	0.773	0.702	0.703	0.817
Tardiness (time units)	TP3RP1***	1.023	0.729	0.586	0.534	0.531	0.625
	TP1RP2	1.268	0.956	0.794	0.746	0.746	0.875
	TP2RP2	1.197	0.898	0.743	0.698	0.697	0.817
	TP3RP2	0.931	0.699	0.576	0.531	0.531	0.625

Equivalent to TP1RP3; ** Equivalent to TP2RP3; * Equivalent to TP3RP3; ‡Tightest limit level on shop WIP*

Table A4: Results for the Transfer Policies (TP) and Release Policies (RP) when Controlling the Shop Load – 2 Lots per Job.

Performance measure	Policy	Limit 1‡	Limit 2	Limit 3	Limit 4	Limit 5	No Limit
Shop Throughput Time (time units)	TP1RP1	15.900	17.858	19.272	20.256	20.920	22.084
	TP2RP1	15.811	17.709	19.087	20.052	20.698	21.808
	TP3RP1	15.509	17.233	18.456	19.315	19.857	20.789
	TP1RP2	15.656	17.643	19.117	20.160	20.871	22.084
	TP2RP2	15.571	17.523	18.965	19.965	20.663	21.808
	TP3RP2	15.295	17.071	18.353	19.239	19.827	20.789
	TP1RP3				19.928	20.743	22.084
	TP2RP3			18.485	19.699	20.501	21.808
	TP3RP2			17.711	18.989	19.692	20.789
Total Throughput Time (time units)	TP1RP1	23.263	21.452	21.333	21.487	21.650	22.084
	TP2RP1	22.617	21.144	21.060	21.231	21.401	21.808
	TP3RP1	20.539	19.982	20.070	20.282	20.438	20.789
	TP1RP2	20.798	20.783	21.063	21.357	21.607	22.084
	TP2RP2	20.570	20.568	20.852	21.127	21.376	21.808
	TP3RP2	19.416	19.602	19.922	20.186	20.413	20.789
	TP1RP3				21.396	21.621	22.084
	TP2RP3			20.699	21.042	21.323	21.808
	TP3RP3			19.965	20.201	20.420	20.789
Tardy (%)	TP1RP1	5.671	4.768	5.035	6.148	7.256	10.269
	TP2RP1	5.445	4.597	4.830	5.944	7.272	9.907
	TP3RP1	4.445	3.755	3.955	4.975	6.174	8.397
	TP1RP2	6.221	5.261	5.385	6.381	7.643	10.269
	TP2RP2	6.031	5.108	5.266	6.183	7.427	9.907
	TP3RP2	4.863	4.111	4.268	5.129	6.288	8.397
	TP1RP3				6.032	7.517	10.269
	TP2RP3			4.476	5.716	7.217	9.907
	TP3RP3			3.712	4.713	6.056	8.397
Tardiness (time units)	TP1RP1	5.103	2.212	1.290	0.914	0.758	0.875
	TP2RP1	4.606	2.094	1.231	0.872	0.732	0.841
	TP3RP1	3.100	1.571	0.961	0.693	0.595	0.696
	TP1RP2	2.546	1.593	1.097	0.743	0.749	0.875
	TP2RP2	2.467	1.529	1.062	0.818	0.728	0.841
	TP3RP2	1.960	1.237	0.858	0.650	0.591	0.696
	TP1RP3				0.862	0.728	0.875
	TP2RP3			1.095	0.785	0.684	0.841
	TP3RP3			1.044	0.723	0.602	0.696

‡*Tightest limit level on shop WIP*

Table A5: Results for the Transfer Policies (TP) and Release Policies (RP) when Controlling the Shop Load – 3 Lots per Job.

Performance measure	Policy	Limit 1‡	Limit 2	Limit 3	Limit 4	Limit 5	No Limit
Shop Throughput Time (time units)	TP1RP1	15.902	17.859	19.267	20.256	20.937	22.084
	TP2RP1	15.758	17.639	19.003	19.941	20.589	21.651
	TP3RP1	15.348	17.003	18.172	18.991	19.502	20.368
	TP1RP2	15.652	17.647	19.121	20.165	20.872	22.084
	TP2RP2	15.536	17.449	18.876	19.863	20.532	21.651
	TP3RP2	15.172	16.877	18.090	18.929	19.471	20.368
	TP1RP3				19.838	20.682	22.084
	TP2RP3			18.225	19.493	20.330	21.651
	TP3RP2			17.555	18.603	19.291	20.368
Total Throughput Time (time units)	TP1RP1	23.217	21.504	21.327	21.488	21.675	22.084
	TP2RP1	22.260	20.999	20.942	21.094	21.282	21.651
	TP3RP1	19.863	19.514	19.656	19.883	20.037	20.368
	TP1RP2	20.802	20.785	21.079	21.373	21.608	22.084
	TP2RP2	20.408	20.439	20.736	21.009	21.225	21.651
	TP3RP2	19.035	19.239	19.547	19.824	20.007	20.368
	TP1RP3				21.444	21.630	22.084
	TP2RP3			20.505	20.899	21.198	21.651
	TP3RP3			19.598	19.838	20.036	20.368
Tardy (%)	TP1RP1	5.663	4.778	5.025	6.163	7.539	10.269
	TP2RP1	5.296	4.500	4.781	5.866	7.191	9.727
	TP3RP1	4.068	3.452	3.671	4.641	5.790	7.883
	TP1RP2	6.193	5.236	5.396	6.411	7.654	10.269
	TP2RP2	5.916	5.004	5.172	6.105	7.296	9.727
	TP3RP2	4.522	3.792	3.945	4.816	5.878	7.883
	TP1RP3			6.068	7.504	10.269	6.068
	TP2RP3			4.376	5.642	7.104	9.727
	TP3RP3			3.484	4.408	5.658	7.883
Tardiness (time units)	TP1RP1	5.663	2.259	1.282	0.916	0.767	0.875
	TP2RP1	4.348	2.043	1.207	0.854	0.892	0.826
	TP3RP1	2.692	1.400	0.867	0.633	0.547	0.650
	TP1RP2	2.559	1.591	1.105	0.851	0.751	0.875
	TP2RP2	2.365	1.499	1.040	0.807	0.709	0.826
	TP3RP2	1.821	1.141	0.786	0.612	0.539	0.650
	TP1RP3				0.897	0.733	0.875
	TP2RP3			1.050	0.769	0.678	0.826
	TP3RP3			1.003	0.695	0.575	0.650

‡*Tightest limit level on shop WIP*

Table A6: Results for the Transfer Policies (TP) and Release Policies (RP) when Controlling the Shop Load – 4 Lots per Job.

Performance measure	Policy	Limit 1‡	Limit 2	Limit 3	Limit 4	Limit 5	No Limit
Shop Throughput Time (time units)	TP1RP1	15.904	17.864	19.278	20.252	20.929	22.084
	TP2RP1	15.734	17.603	18.941	19.873	20.529	21.577
	TP3RP1	15.279	16.903	18.037	18.821	19.319	20.160
	TP1RP2	15.647	17.648	19.110	20.167	20.883	22.084
	TP2RP2	15.505	17.419	18.828	19.813	20.458	21.577
	TP3RP2	15.108	16.770	17.953	18.761	19.283	20.160
	TP1RP3				19.779	20.660	22.084
	TP2RP3			18.096	19.371	20.211	21.577
	TP3RP2			17.368	18.423	19.097	20.160
Total Throughput Time (time units)	TP1RP1	23.318	21.509	21.366	21.472	21.663	22.084
	TP2RP1	22.208	20.923	20.846	21.004	21.214	21.577
	TP3RP1	19.578	19.325	19.478	19.678	19.834	20.160
	TP1RP2	20.780	20.813	21.051	21.377	21.621	22.084
	TP2RP2	20.357	20.392	20.669	20.943	21.145	21.577
	TP3RP2	18.845	19.059	19.355	19.614	19.799	20.160
	TP1RP3				21.471	21.659	22.084
	TP2RP3			20.411	20.811	21.100	21.577
	TP3RP3			19.474	19.675	19.851	20.160
Tardy (%)	TP1RP1	5.654	4.787	5.046	6.131	7.537	10.269
	TP2RP1	5.232	4.481	4.715	5.788	7.156	9.615
	TP3RP1	3.911	3.322	3.543	4.456	5.605	7.635
	TP1RP2	6.144	5.266	5.394	6.407	7.685	10.269
	TP2RP2	5.839	4.994	5.133	6.073	7.217	9.615
	TP3RP2	4.357	3.678	3.785	4.650	5.659	7.635
	TP1RP3				6.076	7.551	10.269
	TP2RP3			4.338	5.576	7.209	9.615
	TP3RP3			3.414	4.290	5.476	7.635
Tardiness (time units)	TP1RP1	5.152	2.260	1.316	0.904	0.765	0.875
	TP2RP1	4.339	2.009	1.180	0.836	0.716	0.817
	TP3RP1	2.525	1.339	0.839	0.606	0.526	0.625
	TP1RP2	2.556	1.611	1.094	0.855	0.752	0.875
	TP2RP2	2.375	1.491	1.030	0.796	0.701	0.817
	TP3RP2	1.753	1.105	0.756	0.582	0.518	0.625
	TP1RP3				0.926	0.751	0.875
	TP2RP3			1.043	0.766	0.672	0.817
	TP3RP3			1.028	0.691	0.563	0.625

‡*Tightest limit level on shop WIP*

Table A7: Results for the Transfer Policies (TP) and Release Policies (RP) with a Setup Factor of 5% when Controlling the Number of Lots – 2 Lots per Job.

Performance measure	Policy	Limit 1‡	Limit 2	Limit 3	Limit 4	Limit 5	No Limit
Shop Throughput Time (time units)	TP1RP1*	15.916	16.987	17.570	17.903	18.073	18.233
	TP2RP1**	15.746	16.789	17.375	17.675	17.837	17.991
	TP3RP1***	15.175	16.095	16.608	16.869	17.021	17.144
	TP1RP2	15.724	16.847	17.508	17.858	18.053	18.233
	TP2RP2	15.580	16.669	17.309	17.641	17.819	17.991
	TP3RP2	15.038	16.014	16.556	16.845	17.003	17.144
Total Throughput Time (time units)	TP1RP1*	18.620	18.371	18.261	18.245	18.237	18.233
	TP2RP1**	18.289	18.102	18.040	18.001	17.989	17.991
	TP3RP1***	17.316	17.197	17.165	17.143	17.148	17.144
	TP1RP2	17.945	18.039	18.120	18.167	18.202	18.233
	TP2RP2	17.714	17.810	17.905	17.937	17.961	17.991
	TP3RP2	16.889	17.009	17.067	17.096	17.122	17.144
Tardy (%)	TP1RP1*	3.788	3.394	3.568	3.917	4.179	4.349
	TP2RP1**	3.571	3.239	3.446	3.770	4.002	4.169
	TP3RP1***	2.899	2.596	2.804	3.084	3.301	3.444
	TP1RP2	3.332	3.180	3.469	3.855	4.143	4.349
	TP2RP2	3.197	3.037	3.353	3.698	3.974	4.169
	TP3RP2	2.632	2.493	2.732	3.042	3.269	3.440
Tardiness (time units)	TP1RP1*	1.125	0.627	0.408	0.319	0.290	0.282
	TP2RP1**	1.034	0.589	0.390	0.306	0.274	0.271
	TP3RP1***	0.824	0.473	0.315	0.245	0.220	0.219
	TP1RP2	0.763	0.483	0.349	0.293	0.277	0.282
	TP2RP2	0.726	0.461	0.338	0.281	0.265	0.271
	TP3RP2	0.615	0.391	0.279	0.228	0.213	0.219

Equivalent to TP1RP3; ** Equivalent to TP2RP3; * Equivalent to TP3RP3; ‡Tightest limit level on shop WIP*

Table A8: Results for the Transfer Policies (TP) and Release Policies (RP) with a Setup Factor of 5% when Controlling the Number of Lots – 3 Lots per Job.

Performance measure	Policy	Limit 1‡	Limit 2	Limit 3	Limit 4	Limit 5	No Limit
Shop Throughput Time (time units)	TP1RP1*	15.145	16.113	16.656	16.943	17.093	17.215
	TP2RP1**	14.903	15.816	16.335	16.609	16.747	16.854
	TP3RP1***	14.115	14.895	15.326	15.548	15.658	15.753
	TP1RP2	15.086	16.079	16.641	16.936	17.087	17.215
	TP2RP2	14.852	15.788	16.329	16.600	16.744	16.854
	TP3RP2	14.077	14.879	15.313	15.544	15.656	15.753
Total Throughput Time (time units)	TP1RP1*	16.682	16.899	17.045	17.129	17.177	17.215
	TP2RP1**	16.336	16.548	16.695	16.783	16.824	16.854
	TP3RP1***	15.265	15.479	15.611	15.681	15.717	15.753
	TP1RP2	16.550	16.837	17.022	17.120	17.169	17.215
	TP2RP2	16.224	16.501	16.686	16.771	16.821	16.854
	TP3RP2	15.195	15.450	15.591	15.676	15.715	15.753
Tardy (%)	TP1RP1*	2.318	2.206	2.477	2.781	3.013	3.202
	TP2RP1**	2.178	2.062	2.291	2.622	2.831	2.997
	TP3RP1***	1.608	1.512	1.689	1.930	2.111	2.265
	TP1RP2	2.217	2.175	2.452	2.777	3.016	3.202
	TP2RP2	2.082	2.055	2.317	2.617	2.833	2.997
	TP3RP2	1.564	1.499	1.680	1.937	2.113	2.265
Tardiness (time units)	TP1RP1*	0.420	0.267	0.202	0.180	0.179	0.192
	TP2RP1**	0.386	0.248	0.187	0.170	0.168	0.180
	TP3RP1***	0.288	0.185	0.137	0.122	0.122	0.133
	TP1RP2	0.374	0.249	0.198	0.179	0.179	0.192
	TP2RP2	0.344	0.234	0.185	0.168	0.168	0.180
	TP3RP2	0.268	0.177	0.134	0.122	0.122	0.133

Equivalent to TP1RP3; ** Equivalent to TP2RP3; * Equivalent to TP3RP3; ‡Tightest limit level on shop WIP*

Table A9: Results for the Transfer Policies (TP) and Release Policies (RP) with a Setup Factor of 5% when Controlling the Number of Lots – 4 Lots per Job.

Performance measure	Policy	Limit 1‡	Limit 2	Limit 3	Limit 4	Limit 5	No Limit
Shop Throughput Time (time units)	TP1RP1*	14.909	15.793	16.284	16.531	16.651	16.747
	TP2RP1**	14.592	15.425	15.883	16.115	16.219	16.306
	TP3RP1***	13.685	14.374	14.730	14.914	15.007	15.074
	TP1RP2	14.848	15.761	16.261	16.534	16.649	16.747
	TP2RP2	14.558	15.406	15.872	16.112	16.219	16.306
	TP3RP2	13.651	14.367	14.725	14.908	15.009	15.074
Total Throughput Time (time units)	TP1RP1*	16.317	16.491	16.617	16.686	16.717	16.747
	TP2RP1**	15.873	16.059	16.189	16.254	16.280	16.306
	TP3RP1***	14.676	14.863	14.963	15.019	15.052	15.074
	TP1RP2	16.176	16.432	16.589	16.686	16.715	16.747
	TP2RP2	15.794	16.027	16.176	16.253	16.279	16.306
	TP3RP2	14.612	14.852	14.957	15.013	15.054	15.074
Tardy (%)	TP1RP1*	2.090	1.898	2.093	2.369	2.568	2.735
	TP2RP1**	1.900	1.732	1.939	2.193	2.382	2.537
	TP3RP1***	1.351	1.209	1.330	1.536	1.684	1.803
	TP1RP2	1.983	1.877	2.096	2.383	2.573	2.735
	TP2RP2	1.846	1.736	1.951	2.213	2.388	2.537
	TP3RP2	1.305	1.220	1.342	1.534	1.692	1.803
Tardiness (time units)	TP1RP1*	0.396	0.240	0.171	0.150	0.147	0.159
	TP2RP1**	0.354	0.214	0.158	0.137	0.135	0.147
	TP3RP1***	0.251	0.155	0.110	0.095	0.095	0.103
	TP1RP2	0.347	0.222	0.168	0.148	0.147	0.159
	TP2RP2	0.319	0.205	0.168	0.138	0.136	0.147
	TP3RP2	0.234	0.151	0.109	0.095	0.095	0.103

Equivalent to TP1RP3; ** Equivalent to TP2RP3; * Equivalent to TP3RP3; ‡Tightest limit level on shop WIP*

Table A10: Results for the Transfer Policies (TP) and Release Policies (RP) with a Setup Factor of 5% when Controlling the Shop Load – 2 Lots per Job.

Performance measure	Policy	Limit 1‡	Limit 2	Limit 3	Limit 4	Limit 5	No Limit
Shop Throughput Time (time units)	TP1RP1	14.789	16.109	16.987	17.519	17.838	18.233
	TP2RP1	14.661	15.953	16.784	17.315	17.622	17.991
	TP3RP1	14.243	15.411	16.138	16.590	16.846	17.144
	TP1RP2	14.603	16.006	16.919	17.486	17.817	18.233
	TP2RP2	14.493	15.866	16.736	17.278	17.605	17.991
	TP3RP2	14.114	15.318	16.096	16.561	16.825	17.144
	TP1RP3			16.773	17.418	17.784	18.233
	TP2RP3		15.451	16.541	17.196	17.557	17.991
	TP3RP2		15.003	15.942	16.485	16.793	17.144
Total Throughput Time (time units)	TP1RP1	18.281	17.810	17.888	17.998	18.095	18.233
	TP2RP1	17.947	17.566	17.637	17.771	17.868	17.991
	TP3RP1	16.787	16.727	16.842	16.964	17.045	17.144
	TP1RP2	17.492	17.612	17.804	17.968	18.079	18.233
	TP2RP2	17.297	17.412	17.582	17.736	17.853	17.991
	TP3RP2	16.415	16.582	16.793	16.938	17.025	17.144
	TP1RP3			17.875	18.006	18.098	18.233
	TP2RP3		17.295	17.535	17.740	17.852	17.991
	TP3RP3		16.747	16.855	16.967	17.047	17.144
Tardy (%)	TP1RP1	3.483	2.646	2.531	2.892	3.462	4.349
	TP2RP1	3.336	2.516	2.410	2.799	3.314	4.169
	TP3RP1	2.621	1.992	1.905	2.265	2.743	3.440
	TP1RP2	3.640	2.820	2.678	3.003	3.515	4.349
	TP2RP2	3.520	2.720	2.586	2.879	3.362	4.169
	TP3RP2	2.790	2.129	2.027	2.335	2.773	3.440
	TP1RP3			2.474	2.924	3.491	4.349
	TP2RP3		2.281	2.267	2.757	3.335	4.169
	TP3RP3		2.003	1.873	2.229	2.754	3.440
Tardiness (time units)	TP1RP1	1.906	0.834	0.471	0.318	0.265	0.282
	TP2RP1	1.754	0.782	0.441	0.302	0.254	0.271
	TP3RP1	1.234	0.601	0.349	0.239	0.200	0.219
	TP1RP2	1.127	0.653	0.415	0.305	0.263	0.282
	TP2RP2	1.084	0.622	0.394	0.289	0.251	0.271
	TP3RP2	0.855	0.491	0.315	0.230	0.198	0.219
	TP1RP3			0.445	0.303	0.254	0.282
	TP2RP3		0.704	0.393	0.277	0.241	0.271
	TP3RP3		0.731	0.386	0.252	0.203	0.219

‡*Tightest limit level on shop WIP*

Table A11: Results for the Transfer Policies (TP) and Release Policies (RP) with a Setup Factor of 5% when Controlling the Shop Load – 3 Lots per Job.

Performance measure	Policy	Limit 1‡	Limit 2	Limit 3	Limit 4	Limit 5	No Limit
Shop Throughput Time (time units)	TP1RP1	14.393	15.548	16.273	16.708	16.945	17.215
	TP2RP1	14.152	15.281	15.973	16.380	16.603	16.854
	TP3RP1	13.548	14.491	15.054	15.375	15.560	15.753
	TP1RP2	14.207	15.465	16.217	16.676	16.932	17.215
	TP2RP2	14.027	15.207	15.934	16.353	16.592	16.854
	TP3RP2	13.451	14.442	15.023	15.354	15.553	15.753
	TP1RP3			16.056	16.589	16.889	17.215
	TP2RP3		14.774	15.713	16.250	16.533	16.854
	TP3RP2		14.116	14.867	15.289	15.525	15.753
Total Throughput Time (time units)	TP1RP1	17.176	16.892	16.949	17.064	17.122	17.215
	TP2RP1	16.660	16.520	16.606	16.704	16.769	16.854
	TP3RP1	15.375	15.413	15.530	15.617	15.681	15.753
	TP1RP2	16.604	16.747	16.890	17.029	17.112	17.215
	TP2RP2	16.280	16.410	16.570	16.684	16.760	16.854
	TP3RP2	15.167	15.350	15.498	15.598	15.677	15.753
	TP1RP3			16.999	17.060	17.129	17.215
	TP2RP3		16.311	16.507	16.670	16.748	16.854
	TP3RP3		15.457	15.549	15.638	15.696	15.753
Tardy (%)	TP1RP1	2.918	2.131	1.937	2.242	2.611	3.202
	TP2RP1	2.656	1.958	1.817	2.070	2.459	2.997
	TP3RP1	1.932	1.377	1.294	1.514	1.820	2.265
	TP1RP2	3.018	2.258	2.057	2.288	2.647	3.202
	TP2RP2	2.826	2.113	1.951	2.151	2.479	2.997
	TP3RP2	2.029	1.493	1.372	1.561	1.846	2.265
	TP1RP3			1.932	2.239	2.650	3.202
	TP2RP3		1.781	1.708	2.063	2.467	2.997
	TP3RP3		1.472	1.290	1.519	1.853	2.265
Tardiness (time units)	TP1RP1	1.393	0.611	0.329	0.227	0.182	0.192
	TP2RP1	1.212	0.555	0.308	0.206	0.170	0.180
	TP3RP1	0.783	0.379	0.217	0.145	0.120	0.133
	TP1RP2	0.862	0.482	0.295	0.214	0.181	0.192
	TP2RP2	0.795	0.446	0.278	0.200	0.168	0.180
	TP3RP2	0.579	0.323	0.199	0.140	0.121	0.133
	TP1RP3			0.349	0.216	0.177	0.192
	TP2RP3		0.513	0.270	0.188	0.160	0.180
	TP3RP3		0.490	0.257	0.162	0.125	0.133

‡*Tightest limit level on shop WIP*

Table A12: Results for the Transfer Policies (TP) and Release Policies (RP) with a Setup Factor of 5% when Controlling the Shop Load – 4 Lots per Job.

Performance measure	Policy	Limit 1‡	Limit 2	Limit 3	Limit 4	Limit 5	No Limit
Shop Throughput Time (time units)	TP1RP1	14.181	15.271	15.933	16.317	16.527	16.747
	TP2RP1	13.900	14.925	15.552	15.909	16.109	16.306
	TP3RP1	13.164	14.005	14.498	14.775	14.924	15.074
	TP1RP2	14.034	15.184	15.887	16.288	16.516	16.747
	TP2RP2	13.783	14.869	15.512	15.889	16.095	16.306
	TP3RP2	13.089	13.968	14.481	14.766	14.918	15.074
	TP1RP3			15.715	16.212	16.481	16.747
	TP2RP3		14.447	15.313	15.794	16.053	16.306
	TP3RP2		13.664	14.340	14.698	14.887	15.074
Total Throughput Time (time units)	TP1RP1	16.669	16.467	16.534	16.617	16.676	16.747
	TP2RP1	16.087	15.990	16.091	16.182	16.243	16.306
	TP3RP1	14.694	14.775	14.885	14.972	15.019	15.074
	TP1RP2	16.210	16.319	16.478	16.588	16.665	16.747
	TP2RP2	15.800	15.918	16.055	16.170	16.233	16.306
	TP3RP2	14.552	14.729	14.872	14.963	15.015	15.074
	TP1RP3			16.566	16.634	16.687	16.747
	TP2RP3		15.839	16.031	16.166	16.239	16.306
	TP3RP3		14.850	14.928	14.993	15.027	15.074
Tardy (%)	TP1RP1	2.664	1.889	1.737	1.937	2.271	2.735
	TP2RP1	2.371	1.695	1.571	1.794	2.091	2.537
	TP3RP1	1.632	1.158	1.064	1.237	1.478	1.803
	TP1RP2	2.698	1.984	1.829	1.988	2.292	2.735
	TP2RP2	2.496	1.825	1.676	1.861	2.122	2.537
	TP3RP2	1.700	1.228	1.122	1.264	1.494	1.803
	TP1RP3			1.712	1.980	2.312	2.735
	TP2RP3		1.577	1.508	1.775	2.116	2.537
	TP3RP3		1.265	1.081	1.240	1.495	1.803
Tardiness (time units)	TP1RP1	1.188	0.526	0.287	0.187	0.152	0.159
	TP2RP1	0.996	0.453	0.252	0.170	0.138	0.147
	TP3RP1	0.610	0.301	0.169	0.114	0.094	0.103
	TP1RP2	0.748	0.410	0.251	0.177	0.150	0.159
	TP2RP2	0.678	0.372	0.229	0.166	0.138	0.147
	TP3RP2	0.469	0.259	0.157	0.109	0.093	0.103
	TP1RP3			0.292	0.181	0.147	0.159
	TP2RP3		0.428	0.230	0.159	0.133	0.147
	TP3RP3		0.411	0.211	0.129	0.098	0.103

‡*Tightest limit level on shop WIP*