Deconstructing Bottleneck Shiftiness:
The Impact of Bottleneck Position on Order Release Control in Pure Flow Shops

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Keywords: *Bottleneck Analysis; Drum-Buffer-Rope; Constant Work-In-Process (ConWIP); Workload Control; Bottleneck Position.*

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Abstract

Bottleneck shiftiness is an important managerial problem that negatively affects shop floor manageability. It has therefore received much research attention. Yet research has focused on how protective capacity can be used to influence bottleneck shiftiness rather than on assessing its operational impact. The latter is complex to evaluate since changing the degree of bottleneck shiftiness influences utilization, which makes the results of different experimental settings non-comparable. To overcome this problem, we take a different approach. Bottleneck shiftiness is decomposed by investigating its underlying phenomenon: the impact of the bottleneck position. Using a simulation model of a pure flow shop, we demonstrate that the bottleneck position has a negligible impact on performance if jobs are released immediately and control is exercised by a dispatching rule. But when order release is controlled, the bottleneck position does impact performance - tighter control can be exercised, and better performance achieved, the further upstream the bottleneck is positioned. Hence, control parameters need to be adjusted. Further, results show that it is important to be aware of the direction of the bottleneck shift. If the bottleneck shifts upstream (from the current bottleneck), performance is likely to improve rather than deteriorate as is implicitly assumed in the literature.

Keywords: *Bottleneck Analysis; Drum-Buffer-Rope; Constant Work-In-Process (ConWIP); Workload Control; Bottleneck Position.*

1. Introduction

Shifting bottlenecks is a phenomenon that often bedevils managers (Lawrence & Buss, 1994) and negatively affects shop floor manageability (Craighead *et al*., 2001). It is an important managerial problem in practice (Stevenson *et al*., 2011) and has consequently received significant research attention (e.g. Lawrence & Buss, 1994; Craighead, 2001; Patterson *et al*., 2002; Fredendall *et al*., 2010; Fernandes *et al*., 2014). Prior research however has focused on exploring how protective capacity can be used to influence bottleneck shiftiness rather than on assessing the operational impact of bottleneck shiftiness. Research has demonstrated that an increase in protective capacity (i.e. capacity at non-bottleneck stations) reduces bottleneck shiftiness, but it has not established a direct link between performance and bottleneck shiftiness. It appears to be implicitly assumed that a reduction in bottleneck shiftiness has a positive effect on performance. A study that may give support to this assumption is Atwater & Chakravorty (2002), who showed that protective capacity at the second most heavily utilized station can be used to improve performance. But the authors did not establish why this was effective, e.g. whether protective capacity at a non-bottleneck constraint reduces the likelihood of the bottleneck shifting. Hence the assumption remains without support.

In general, assessing the performance impact of bottleneck shiftiness is complex. To assess its impact, bottleneck shiftiness could be gradually changed. But this would require protective capacity to be increased or decreased, which affects the utilization level. Any change in the utilization level makes it difficult to compare the results obtained across different experimental settings. To overcome this problem, this study takes a different approach: bottleneck shiftiness is decomposed by investigating its underlying phenomenon – the impact of the bottleneck position. While there exist research on the impact of the bottleneck position (e.g. Fry *et al*., 1987; Kadipasaoglu *et al*., 2000) this research neglects the impact of bottleneck position (and consequently bottleneck shiftiness) on an order release controlled shop.

Land *et al*. (2015) recently demonstrated, in the context of shop floor dispatching rules, that dynamic phenomena are best understood by investigating their different states. We hereby talk about ‘ideal’ states in Max Weber’s (Weber, 2014) sense that can be used to ‘circumscribe’ the phenomenon under study, rather than capturing every possible state, which would be an unmanageable number in the stochastic context studied here. Bottleneck shiftiness is a dynamic phenomenon – the position of the bottleneck in the routing of orders constantly changes. However, research on bottleneck shiftiness typically aggregates the performance impact of these different bottleneck positions. This is a major shortcoming since it is argued here that the change in bottleneck position explains the performance impact of bottleneck shiftiness. In response, this study asks:

- What is the impact of the bottleneck position on performance in an order release controlled pure flow shop?
- How does this insight further our understanding of bottleneck shiftiness?

An exploratory study based on controlled simulation experiments will be used to provide an answer to these two questions. Our focus is on order release since it presents a major function of production planning and control. Meanwhile, our shop setting is the arguably very simple pure flow shop in which each job visits every station in the same sequence. This setting is justified by its unique property that routing position and the layout of stations overlap. This facilitates singling out the experimental factor of interest in our study – bottleneck position – compared to other, more complex routings.

The remainder of this paper is organized as follows. In Section 2, we first define the phenomena under study – bottleneck shiftiness and bottleneck position – before we review the literature on order release control to identify the release methods to be considered in our 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 summarized in Section 5, where limitations and future research directions are also outlined.

2. Literature Review

2.1 Bottleneck Shiftiness – A Definition

This study investigates the performance impact of bottleneck shiftiness. The shifting bottleneck phenomenon is here defined as a scenario in which the position of the bottleneck station in the routing of orders changes over time. This definition follows Hopp & Spearman (2001; e.g. p. 459) and recognizes the distinction between routing and layout. Other authors have adopted a different definition of bottleneck shiftiness that refers to a shift in the physical location of the bottleneck station on the shop floor (Lawrence & Buss, 1994); for example, one time Station C is the bottleneck, but the next time, Station E is the bottleneck. According to the definition followed here, a shift occurs even if a station remains the bottleneck: one time, Station C is the bottleneck and the first station in the routing of orders; the next time, Station C is still the bottleneck but has moved to being second in the routing sequence. Both a shift in routing sequence and a shift in the physical location of the bottleneck influence performance. But the latter only affects the performance of bottleneck-oriented control methods that rely on correctly identifying the bottleneck; hence, our focus is on the former. The release methods to be included in our study will be reviewed next.

2.2. Order Release in Shops with Bottlenecks

In an order release controlled shop, jobs are not released directly to the shop floor. Rather they flow into a pre-shop pool (or 'backlog' in Spearman *et al.*, 1990) from where they are released so as to create a mix of jobs on the shop floor that meets certain performance targets, such as due date adherence and/or reduced levels of work-in-process. Order release is a main function of production planning and control. Consequently, a wide range of release methods exists. In this study, we focus on Drum-Buffer-Rope (DBR; e.g. Goldratt & Cox, 1984; Simons & Simpson, 1997; Watson *et al.*, 2007), Constant Work-in-Process (ConWIP; e.g. Spearman *et al.*, 1990; Hopp & Spearman, 2001), and Workload Control based release methods (e.g. Glassey & Resende, 1988; Wiendahl, 1992; Land & Gaalman, 1996; Thürer *et al.*, 2012). These three approaches have been chosen as being most adequate to the production environment under study. Each will be discussed in turn in Section 2.2.1 to Section 2.2.3, respectively.

2.2.1 Drum-Buffer-Rope (DBR) and the Theory of Constraints (TOC)

The Theory of Constraints (Goldratt & Cox, 1984) can be considered a powerful production planning and control technique in shops with bottlenecks. It was originally conceived in the 1970s by Eliyahu M. Goldratt as a scheduling algorithm and later developed into a broader production planning and control concept (Simons & Simpson, 1997; Mabin & Balderstone, 2003). One of its main elements is Optimized Production Technology (OPT), a scheduling (or release) mechanism that is now more commonly known as Drum-Buffer-Rope – a descriptor for the way order release is realized (Simons & Simpson, 1997).

A DBR system is depicted in Figure 1 for a shop with three stations (including a single bottleneck). Its essential parts can be described as follows:

- *Drum*: This is the constraint (e.g. the bottleneck station, the market) and its schedule.
- *Buffer*: This is both the constraint buffer (i.e. the buffer before the bottleneck) and the shipping buffer (i.e. finished goods inventory; see e.g. Watson *et al.*, 2007). Buffers are time (e.g. Radovilsky, 1998; Schragenheim & Ronen, 1990; Simons & Simpson, 1997; Chakravorty & Atwater, 2005) or a time-equivalent amount of work-in-process. Since, in our study, jobs are considered to be delivered immediately after they are completed, the shipping buffer does not exist.

- *Rope*: This is the communication channel for providing feedback from the drum (bottleneck) to the beginning of the system, i.e. order release. Based on this feedback, order release aligns the input of work with the output rate of the bottleneck. In other words, a maximum limit on the number of jobs released to the bottleneck but not yet completed is established and a job is released whenever the number of jobs is below the prescribed limit (e.g. Ashcroft, 1989; Lambrecht & Segaert, 1990; Duclos & Spencer, 1995; Chakravorty & Atwater, 1996; Chakravorty, 2001; Watson & Patti, 2008). There are two ropes: Rope 1 determines the schedule at the bottleneck to exploit the constraint according to the organization's goal (Schragenheim & Ronen, 1990); Rope 2 then subordinates the system to the constraint (the bottleneck station).

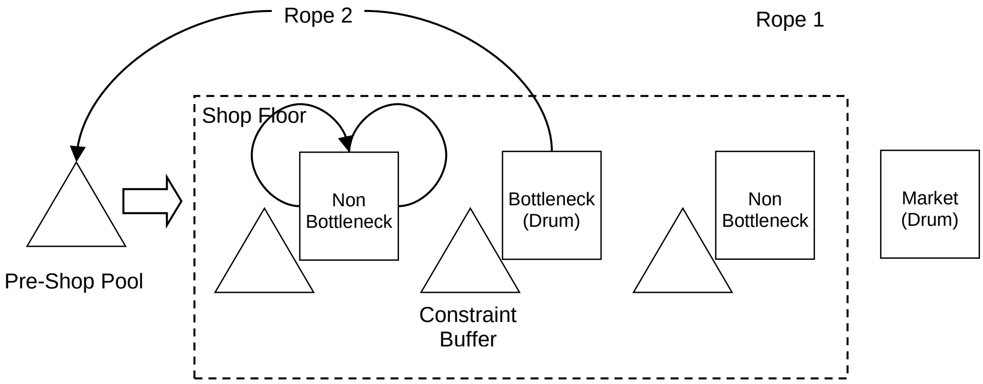

Figure 1: Drum-Buffer-Rope

2.2.2 Constant Work-In-Process (ConWIP)

ConWIP – as illustrated in Figure 2 – extends DBR by limiting the number of jobs on the whole shop floor rather than just the number of jobs released to the bottleneck but not yet completed. ConWIP has been outperformed by DBR in various production environments, including flow shops (e.g. Lambrecht & Segaert 1990; Gilland, 2002). Yet Framinan *et al.* (2003) argued that the relative performance of DBR compared to ConWIP is dependent on the bottleneck position. Therefore, ConWIP is included in our study regardless of previous results.

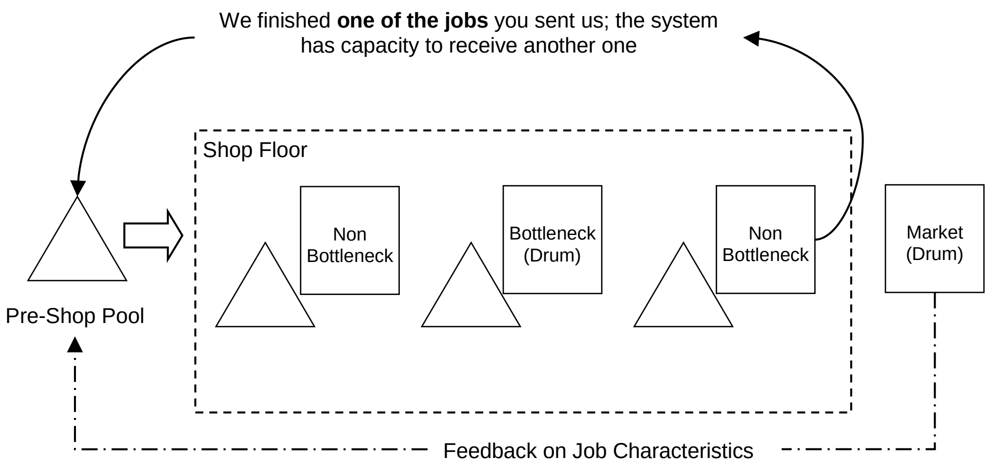

Figure 2: Constant Work-in-Process (ConWIP)

2.2.3 Workload Control in Shops with Bottlenecks

Workload Control is a production planning and control concept that has been developed over more than 30 years (Thürer *et al.*, 2011). While several different approaches to Workload Control exist, a major unifying element is the use of a load-based order release mechanism. Using the principles of input/output control, load-based release methods seek to stabilize the workload in the system by releasing work in accordance with the output rate.

Although Workload Control has been largely developed in the context of balanced shops, there is some evidence of its potential to improve performance in shops with bottlenecks (e.g. Glassey & Resende, 1988; Lingayat *et al.*, 1995; Enns & Prongue-Costa, 2002; Fernandes *et al.*, 2014). For example, Glassey & Resende (1988) proposed a Starvation Avoidance (SA) methodology that releases work whenever the workload of jobs released to the bottleneck but not yet completed falls below a certain limit. This is similar to DBR but controls the workload instead of the number of jobs. A periodic version of SA (i.e. where the release decision is only taken at periodic time intervals) was later shown by Roderick *et al.* (1992) to be outperformed in a shop with restricted routings by ConWIP. Meanwhile, Lingayat *et al.* (1995) showed that SA outperforms ConWIP in a job shop, where routings are not restricted. Finally, Enns & Prongue-Costa (2002) showed that controlling the workload released but not yet completed at the *bottleneck resource only*, rather than controlling the workload released but not yet completed by the whole shop, leads to better performance in a job shop with a bottleneck specifically when bottleneck severity is high.

A major strength of Workload Control, compared to DBR, is that it can balance workloads across resources, controlling the workload of all stations (Thürer *et al.*, 2012, 2014a). For example, the release method illustrated in Figure 3 is widely applied in the

Workload Control literature (e.g. Wiendahl, 1992; Cigolini & Portioli-Staudacher, 2002; Philipoom & Steele, 2011; Thürer *et al*., 2012). Fredendall *et al*. (2010) showed that, in job shops with a bottleneck, controlling the workload at each station outperforms bottleneck control. In this study, we include both bottleneck-oriented Workload Control order release and Workload Control order release that controls the workload at each station. The next section outlines how these methods have been modeled in our simulations together with other aspects of our experimental design.

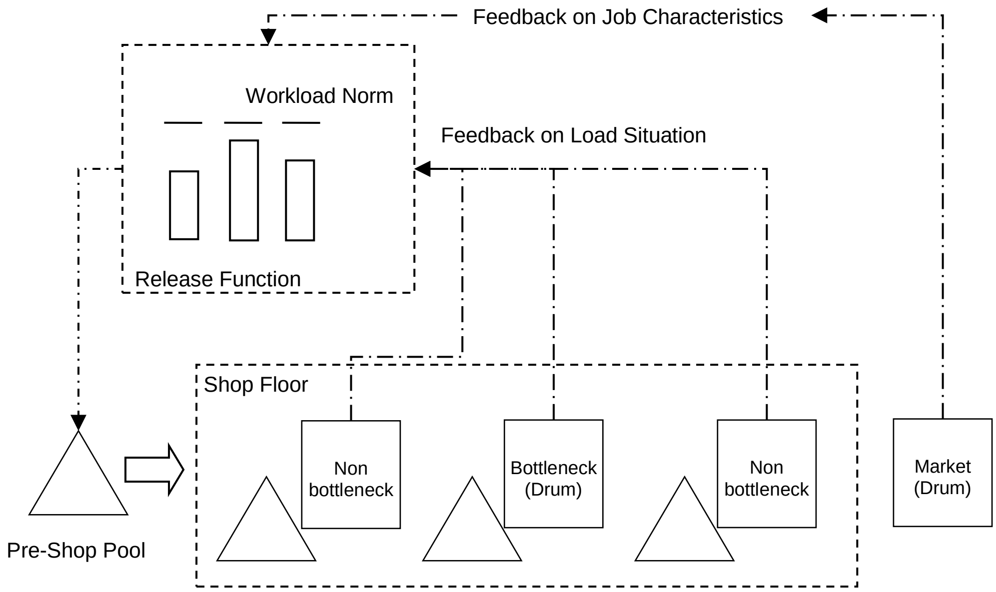

Figure 3: Workload Control - Using a Release Function to Balance the Workload across Resources

3. Simulation Model

How we modeled the order release methods considered in this study is first outlined in Section 3.1 before the priority dispatching rules applied for controlling the progress of orders on the shop floor are described in Section 3.2. The shop and job characteristics modeled in the simulations are then summarized in Section 3.3. Finally, the experimental design is outlined and the measures used to evaluate performance are presented in Section 3.4.

3.1 Order Release

As in previous simulation studies on DBR (e.g. Lambrecht & Segaert, 1990; Duclos & Spencer, 1995; Chakravorty & Atwater, 2005), ConWIP (e.g. Spearman *et al*., 1990; Bonvik *et al*., 1997; Herer & Masin, 1997; Jodlbauer & Huber, 2008), and 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 four alternative release methods – two from the Workload Control literature, plus DBR and ConWIP. The four methods are outlined in sections 3.1.1 to 3.1.4 below before Section 3.1.5 describes how the parameters for these methods have been set.

3.1.1 Workload Control Release, Controlling all Stations – Continuous

This is the upper bound release method typically applied in the Workload Control literature. The release decision can be formulated as follows:

(1) All jobs in the set of jobs J in the pre-shop pool are sorted according to their planned release date, given by their due date minus an allowance for the operation throughput time for each operation in their routing. This is equivalent to sorting jobs according to earliest due dates in our study, since all jobs share the same routing.

(2) The job $j \in J$ with the earliest due date 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^R released to station s (corresponding to operation i) and yet to be completed fits within the workload limit N_s^C at this station, that is $\frac{p_{ij}}{i} + W_s^R \leq N_s^C$ $\forall i \in R_j$, then the job is selected for release. That means it is removed from J, and its load contribution is included, i.e. $W_s^R := W_s^R + \frac{p_{ij}}{i} \quad \forall i \in R_j$.

    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^R until its operation at this station has been completed. 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 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.

The release decision may be executed at periodic time intervals (see e.g. Cigolini & Portioli-Staudacher, 2002; Fredendall *et al*., 2010) or continuously at any moment in time (see, e.g. Fernandes & Carmo-Silva, 2011; Fernandes *et al*., 2014; Thürer *et al*., 2014b). In this study, it is executed continuously at any moment in time since this approach was recently shown by Thürer *et al*. (2015a) to be particularly suitable for the pure flow shop environment considered in our study. In other words, the release decision is triggered whenever a new job arrives at the shop or an operation is completed (rather than at periodic time intervals).

3.1.2 Workload Control Release, Controlling the Bottleneck Only - SA COR

The Starvation Avoidance (SA) trigger presented by Glassey & Resende (1988) uses the aggregate of the processing times. Meanwhile, Continuous consider a corrected measure of the processing time. The corrected aggregate load will also be used for SA to make the approach consistent with Continuous. The resulting method is referred to as SA COR (Starvation Avoidance Corrected). SA COR is equivalent to Continuous except that it only limits the bottleneck load.

3.1.3 DBR

DBR controls the number of jobs released but not yet completed at the bottleneck. So it is equivalent to SA COR except that it controls the number of jobs instead of the corrected workload. Whenever a new job arrives at the shop or an operation is completed at the bottleneck, jobs are released until a pre-established buffer limit is reached. The sequence in which jobs are considered for release is the same as for the two Workload Control release methods described above.

3.1.4 ConWIP

While DBR controls the number of jobs released but not yet completed at the bottleneck, ConWIP controls the number of jobs released to the shop floor. Thus, it is equivalent to DBR if the last station in the routing is the bottleneck. Whenever a new job arrives or a job is completed and leaves the shop floor, jobs are released until a pre-established limit is reached. The sequence in which jobs are considered for release is the same as for the two Workload Control release methods and for DBR, as described above.

3.1.5 Parameter Setting

Twelve workload limits have been considered for each release method: from 4 to 15 time units for Continuous and SA COR; from 2 to 13 jobs for DBR; and, from 21 to 32 jobs for ConWIP. These levels were identified through preliminary simulation experiments such that the best performance of each performance measure was captured by our parameter settings. The tightest workload limit for Continuous and SA COR is, however, restricted by the maximum processing time (four time units) while, for DBR, a minimum of two jobs is needed (one job queuing and one being processed). DBR controls the number of jobs released but not yet completed at a station. Therefore the limit is increased by multiplying it by the station number of the bottleneck. We did not use different limits for bottleneck and non-bottleneck stations under Continuous since the performance effects were either not significant or negative in Fernandes *et al*. (2014). 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 Shop Floor Dispatching

Three dispatching rules are considered for controlling the flow of jobs on the shop floor: (i) the Planned Start Time (PST) rule, a time-based rule that considers the urgency of jobs; (ii) the Shortest Processing Time (SPT) rule, a load-based rule that has been previously shown to reduce throughput times in flow shops (e.g. Conway, 1967); and, (iii) the Modified Planned Start Time (MPST) rule, which combines the SPT and PST rules. The MPST rule is a variant of the Modified Operation Due Date (MODD) rule (e.g. Baker & Kanet, 1983).

The PST rule prioritizes jobs according to the earliest planned start time. The planned start time of an operation is determined by successively subtracting an allowance for the operation throughput time for each station in the routing of a job from the job’s due date. This is similar to the scheduling mechanism incorporated in DBR (see, e.g. Chakravorty & Atwater, 2005). The allowance for the operation throughput time is given by the cumulative moving average of the actually realized operation throughput times at each station (i.e. the average of all occurrences until the current simulation time). Meanwhile, the SPT rule selects the job with the shortest processing time from the queue. Finally, the MPST rule prioritizes jobs according to the lowest priority number, which is given by the maximum of the earliest planned finish time and earliest possible finish time, i.e. $max\ (PST_{ij}+p_{ij},\ t+p_{ij})$ for an operation with processing time p_{ij}, where t refers to the time when the dispatching decision is made. The MPST rule shifts between a focus on PSTs, to complete jobs on time, and a focus on speeding up jobs – through SPT effects – during periods of high load, i.e. when multiple jobs exceed their PST (Land *et al*., 2015).

3.3 Overview of Modeled Shop and Job Characteristics

A simulation model of a pure flow shop has been implemented in the Python© programming language using the SimPy© simulation module. In the pure flow shop, each job visits all stations in the same sequence in order of increasing station number. The shop contains seven stations, where each station is a single resource with constant capacity. There is one bottleneck station, the position of which varies according to the experimental setting. Since there are seven stations, there are seven different bottleneck positions. The unique property of the pure flow shop, i.e. that routing position and layout overlap, facilitates the fixing of the bottleneck position.

As in previous research (e.g. Kadipasaoglu *et al*., 2000; Enns & Prongue-Costa, 2002; Fernandes *et al*., 2014), non-bottlenecks are created by reducing the corresponding processing times. We experimented with different levels of bottleneck severity (5%, 20% and 35%), but the performance impact of bottleneck position and performance differences between release methods, were not affected by this factor. Therefore, we decided to present only the results for one level of bottleneck severity in this paper: a bottleneck severity of 20%. An equal adjustment was applied to all non-bottlenecks since the position of protective capacity is argued to have no effect on flow times (see Craighead *et al*., 2001). Operation processing times – before adjustment – 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 1.111 time units, which deliberately results in a utilization level of 90% at the bottleneck.

Finally, due dates are set exogenously by adding a random allowance factor, uniformly distributed between 32 and 48 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 (3.2 time units for non-bottleneck operations and 4 time units for the bottleneck operation) plus an allowance for the waiting or queuing times.

3.4 Experimental Design and Performance Measures

The experimental factors are: (i) the seven levels of bottleneck position; (ii) the four different release methods (Continuous, SA COR, DBR, and ConWIP); (iii) the 12 different limit levels for our release methods; and, (iv) the three different dispatching rules (PST, SPT, and MPST). A full factorial design was used with 1,008 (7*4*12*3) 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 allow us to obtain stable results while keeping the simulation run time to a reasonable level.

The principal performance measures considered in this study are as follows: *throughput time* – the mean of the completion date minus the release date across jobs; *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*, that is $T_j = \max(0, L_j)$, with L_j being the lateness of job *j* (i.e. the actual delivery date minus the due date of job *j*).

4. Results

Statistical analysis has been conducted by applying an Analysis of Variance (ANOVA) to obtain a first indication of the relative impact of the experimental factors. The ANOVA is here based on a block design with the limit level as the blocking factor, i.e. the different limit levels were treated as different systems. A block design allowed the main effect of the limit level and both the main and interaction effects of the bottleneck position, release method, and dispatching rule to be captured. As can be observed from Table 1, all main effects, two-way interactions, and three-way interactions were shown to be statistically significant.

Table 1: ANOVA Results

	Source of Variance	Sum of Squares	df[1]	Mean Squares	F-Ratio	p-Value
Throughput Time	Bottleneck Position (BP)	17077.683	6	2846.281	4029.010	0.000
	Release Method (R)	443.177	3	147.726	209.110	0.000
	Limit Level	43276.673	13	3328.975	4712.280	0.000
	Dispatching Rule (D)	470862.430	2	235431.220	330000.000	0.000
	R x D	2288.224	6	381.371	539.840	0.000
	R x BP	5691.061	18	316.170	447.550	0.000
	D x BP	1851.127	12	154.261	218.360	0.000
	R x D x BP	1015.949	36	28.221	39.950	0.000
	Error	71141.374	100703	0.706		
Lead Time	Bottleneck Position (BP)	491.266	6	81.878	64.380	0.000
	Release Method (R)	411.032	3	137.011	107.740	0.000
	Limit Level	27195.581	13	2091.968	1645.010	0.000
	Dispatching Rule (D)	589202.820	2	294601.410	230000.000	0.000
	R x D	1005.842	6	167.640	131.820	0.000
	R x BP	403.900	18	22.439	17.640	0.000
	D x BP	1332.292	12	111.024	87.300	0.000
	R x D x BP	615.528	36	17.098	13.440	0.000
	Error	128064.690	100703	1.272		
Percentage Tardy	Bottleneck Position (BP)	0.060	6	0.010	32.770	0.000
	Release Method (R)	0.084	3	0.028	91.640	0.000
	Limit Level	4.016	13	0.309	1015.810	0.000
	Dispatching Rule (D)	5.686	2	2.843	9348.880	0.000
	R x D	0.631	6	0.105	345.720	0.000
	R x BP	0.059	18	0.003	10.850	0.000
	D x BP	0.182	12	0.015	50.000	0.000
	R x D x BP	0.117	36	0.003	10.730	0.000
	Error	30.622	100703	0.000		
Mean Tardiness	Bottleneck Position (BP)	24.723	6	4.121	24.930	0.000
	Release Method (R)	4.245	3	1.415	8.560	0.000
	Limit Level	528.509	13	40.655	245.980	0.000
	Dispatching Rule (D)	7624.473	2	3812.237	23066.360	0.000
	R x D	140.837	6	23.473	142.020	0.000
	R x BP	28.173	18	1.565	9.470	0.000
	D x BP	44.155	12	3.680	22.260	0.000
	R x D x BP	54.665	36	1.518	9.190	0.000
	Error	16643.446	100703	0.165		

[1]) degree of freedom

The Scheffé multiple-comparison procedure was used in order to further examine the significance of the differences between the outcomes of the individual release methods and dispatching rules. The confidence intervals are summarized in Table 2 and Table 3, respectively. Differences are considered not significant at $\alpha=0.05$ if this interval includes zero. Significant differences between the outcomes of the different release methods can be identified for at least three performance measures, except between SA COR & Continuous and between ConWIP & DBR, which perform statistically equivalent in terms of lead time, percentage tardy and mean tardiness. In terms of dispatching rules, significant differences between outcomes can be identified for all performance measures. These results will be explored further in what now follows.

Table 2: Results for Scheffé Multiple Comparison Procedure: Release Method

Release Method (x)	Release Method (y)	Throughput Time		Lead Time		Percentage Tardy		Mean Tardiness	
		lower[1)]	upper	Lower	upper	lower	upper	lower	upper
SA COR	Continuous	0.041	0.083	-0.016*	0.040	0.000*	0.001	-0.008*	0.012
DBR	Continuous	0.106	0.151	0.110	0.170	0.001	0.002	0.000*	0.021
ConWIP	Continuous	-0.081	-0.039	0.107	0.163	0.002	0.002	0.006	0.027
DBR	SA COR	0.044	0.089	0.098	0.158	0.001	0.002	-0.003*	0.019
ConWIP	SA COR	-0.143	-0.101	0.095	0.151	0.001	0.002	0.004	0.024
ConWIP	DBR	-0.210	-0.166	-0.035*	0.025	0.000*	0.001	-0.005*	0.017

[1)] 95% confidence interval; * not significant at α=0.05

Table 3: Results for Scheffé Multiple Comparison Procedure: Dispatching Rule

Dipatching Rule (x)	Dispatching Rule (y)	Throughput Time		Lead Time		Percentage Tardy		Mean Tardiness	
		lower[1)]	upper	lower	upper	lower	upper	lower	upper
SPT	PST	-4.665	-4.634	-5.288	-5.246	-0.004	-0.004	0.524	0.539
MPST	PST	-0.148	-0.116	-0.310	-0.267	-0.018	-0.017	-0.100	-0.085
MPST	SPT	4.501	4.533	4.957	5.000	-0.014	-0.013	-0.632	-0.617

[1)] 95% confidence interval; * not significant at α=0.05

Our first research question asked: What is the impact of the bottleneck position on performance in an order release controlled pure flow shop? To answer this question, detailed performance results are presented next in Section 4.1 for PST dispatching. Section 4.2 then presents a discussion of the results to address our second research question on how insights gained from our results further our understanding of bottleneck shiftiness. Finally, the impact of the dispatching rule on our results is assessed in Section 4.3.

4.1 The Impact of Bottleneck Position on Order Release Control

Table 4 gives the throughput time, lead time, percentage tardy and mean tardiness results obtained for our four release methods. Due to space restrictions, we only present the results for the bottleneck being the first (Station 1), center (Station 4), and final station (Station 7) in the routing.

Table 4: Performance Impact of Bottleneck Position under PST Dispatching

Release Method	Parameter Setting	First Station is the Bottleneck				Center Station is the Bottleneck				Last Station is the Bottleneck			
		TT[1)]	LT[2)]	PT[3)]	MT[4)]	TT	LT	PT	MT	TT	LT	PT	MT
IMM	None	18.27	18.27	2.45%	0.18	18.16	18.16	2.01%	0.14	18.24	18.24	2.44%	0.20
Cont.	N15	17.44	18.03	1.21%	0.12	18.15	18.16	2.01%	0.14	18.24	18.24	2.44%	0.20
	N14	17.31	17.99	1.14%	0.13	18.15	18.16	2.01%	0.14	18.24	18.24	2.44%	0.20
	N13	17.15	17.92	0.97%	0.14	18.15	18.16	2.01%	0.14	18.23	18.24	2.43%	0.20
	N12	16.97	17.86	0.92%	0.15	18.14	18.15	2.01%	0.14	18.23	18.24	2.44%	0.20
	N11	16.77	17.78	0.86%	0.16	18.12	18.15	2.01%	0.13	18.22	18.24	2.43%	0.20
	N10	16.52	17.67	0.85%	0.18	18.10	18.15	2.00%	0.13	18.22	18.24	2.44%	0.20
	N9	16.22	17.55	0.84%	0.20	18.05	18.14	2.00%	0.13	18.20	18.23	2.43%	0.20
	N8	15.87	17.39	0.90%	0.23	17.97	18.12	1.94%	0.12	18.16	18.22	2.42%	0.19
	N7	15.43	17.18	0.95%	0.26	17.83	18.09	1.70%	0.10	18.10	18.21	2.41%	0.19
	N6	14.91	16.92	0.99%	0.29	17.56	18.02	1.30%	0.09	17.97	18.18	2.41%	0.18
	N5	14.24	16.56	1.08%	0.34	17.08	17.88	0.92%	0.10	17.70	18.11	2.22%	0.15
	N4	13.36	16.10	1.21%	0.36	16.19	17.54	0.71%	0.15	17.05	17.89	1.34%	0.12
SA COR	N15	17.44	18.03	1.21%	0.12	18.16	18.16	2.01%	0.14	18.24	18.24	2.44%	0.20
	N14	17.31	17.99	1.14%	0.13	18.15	18.16	2.01%	0.14	18.24	18.24	2.44%	0.20
	N13	17.15	17.92	0.97%	0.14	18.15	18.16	2.01%	0.14	18.24	18.24	2.44%	0.20
	N12	16.97	17.86	0.92%	0.15	18.14	18.16	2.01%	0.14	18.24	18.24	2.44%	0.20
	N11	16.77	17.78	0.87%	0.17	18.13	18.15	2.01%	0.13	18.24	18.24	2.44%	0.20
	N10	16.52	17.68	0.87%	0.18	18.12	18.15	2.01%	0.13	18.24	18.24	2.44%	0.20
	N9	16.23	17.55	0.85%	0.20	18.09	18.15	2.00%	0.13	18.23	18.24	2.44%	0.20
	N8	15.88	17.39	0.88%	0.23	18.03	18.13	1.96%	0.12	18.22	18.23	2.44%	0.19
	N7	15.45	17.18	0.92%	0.26	17.91	18.11	1.72%	0.10	18.19	18.23	2.44%	0.19
	N6	14.95	16.93	1.00%	0.29	17.70	18.05	1.32%	0.09	18.13	18.22	2.43%	0.18
	N5	14.33	16.59	1.10%	0.34	17.31	17.94	0.92%	0.10	17.97	18.18	2.24%	0.15
	N4	13.54	16.15	1.21%	0.38	16.59	17.69	0.73%	0.16	17.55	18.07	1.32%	0.13
DBR	13 jobs	17.02	18.27	2.45%	0.18	18.15	18.16	2.01%	0.14	18.24	18.24	2.44%	0.20
	12 jobs	16.84	18.27	2.45%	0.18	18.14	18.16	2.01%	0.14	18.24	18.24	2.44%	0.20
	11 jobs	16.62	18.27	2.45%	0.18	18.13	18.16	2.01%	0.14	18.24	18.24	2.44%	0.20
	10 jobs	16.38	18.27	2.45%	0.18	18.11	18.16	2.01%	0.14	18.24	18.24	2.44%	0.20
	9 jobs	16.09	18.27	2.45%	0.18	18.07	18.16	2.01%	0.14	18.23	18.24	2.44%	0.20
	8 jobs	15.77	18.27	2.45%	0.18	18.00	18.16	2.01%	0.14	18.22	18.24	2.44%	0.20
	7 jobs	15.39	18.27	2.45%	0.18	17.87	18.16	2.01%	0.14	18.18	18.24	2.44%	0.20
	6 jobs	14.95	18.27	2.45%	0.18	17.62	18.16	2.01%	0.14	18.11	18.24	2.44%	0.20
	5 jobs	14.45	18.27	2.45%	0.18	17.19	18.16	2.01%	0.14	17.93	18.24	2.44%	0.20
	4 jobs	13.88	18.27	2.45%	0.18	16.43	18.21	2.06%	0.14	17.45	18.25	2.45%	0.20
	3 jobs	13.21	18.27	2.45%	0.18	15.17	18.65	2.68%	0.19	16.32	18.47	2.70%	0.23
	2 jobs	12.44	18.27	2.45%	0.18	13.07	25.84	15.98%	2.32	13.97	24.35	12.13%	1.95
ConWIP	32 jobs	17.82	18.27	2.45%	0.18	17.78	18.16	2.01%	0.14	17.77	18.24	2.44%	0.20
	31 jobs	17.76	18.27	2.45%	0.18	17.72	18.16	2.01%	0.14	17.71	18.24	2.44%	0.20
	30 jobs	17.68	18.27	2.45%	0.18	17.65	18.16	2.02%	0.14	17.63	18.24	2.44%	0.20
	29 jobs	17.60	18.28	2.46%	0.18	17.57	18.17	2.02%	0.14	17.55	18.24	2.44%	0.20
	28 jobs	17.51	18.28	2.47%	0.18	17.47	18.17	2.03%	0.14	17.45	18.25	2.45%	0.20
	27 jobs	17.40	18.29	2.49%	0.18	17.37	18.18	2.03%	0.14	17.34	18.26	2.45%	0.20
	26 jobs	17.27	18.30	2.51%	0.18	17.24	18.19	2.04%	0.14	17.22	18.26	2.46%	0.20
	25 jobs	17.13	18.31	2.54%	0.19	17.10	18.20	2.06%	0.14	17.08	18.28	2.48%	0.20
	24 jobs	16.97	18.33	2.57%	0.19	16.94	18.22	2.09%	0.14	16.93	18.30	2.51%	0.21
	23 jobs	16.79	18.36	2.63%	0.20	16.76	18.25	2.13%	0.15	16.75	18.34	2.55%	0.21
	22 jobs	16.59	18.42	2.71%	0.21	16.56	18.30	2.21%	0.15	16.55	18.39	2.60%	0.22
	21 jobs	16.36	18.50	2.84%	0.22	16.34	18.37	2.32%	0.16	16.32	18.47	2.70%	0.23

[1)]TT – Throughput Time; [2)]LT – Lead Time; [3)]PT – Percentage Tardy; [4)]MT – Mean Tardiness

Only the results under PST dispatching are presented here, with the impact of the dispatching rule discussed in Section 4.3. In addition, and as a reference point, the results obtained when jobs are released immediately are also included. These results are referred to as IMM (IMMediate release). Note that we only present the average of the 100 replications for each experimental setting given that the impact of variance has been assessed by our ANOVA and by the multiple comparison procedure.

4.1.1 Performance Differences between Release Methods

Continuous and SA COR perform statistically equivalent and lead to the best performance in terms of percentage tardy and lead time. An advantage of Continuous over SA COR is that it automatically identifies the bottleneck while, for SA COR, the bottleneck has to be determined in advance. Thus, in the context of shifting bottlenecks, Continuous would automatically switch the focus while SA COR would require the decision to control a different station to be made. However, both rules – Continuous and SA COR – have a direct detrimental effect on mean tardiness performance if the limits are tight and the bottleneck is the first station. Continuous and SA COR gain their advantage by creating SPT effects specifically in periods of high load since both rules seek to continuously fill up the workload limit. But these SPT effects should be restricted to periods in which jobs are at risk of becoming tardy (Land *et al.*, 2015; Thürer *et al.*, 2015b). If the limits are too tight, SPT effects are active for longer periods, leading to the negative effect on the mean tardiness results observed. If the bottleneck is downstream (e.g. Station 4, Station 7) then less control can be exercised and SPT effects are restricted to periods in which jobs are at risk of becoming tardy. This leads to performance improvement in terms of both percentage tardy and mean tardiness.

Our multi-comparison procedure indicated that the performance of ConWIP and DBR is statistically equivalent in terms of lead time, percentage tardy and mean tardiness. This appears to contradict prior research, which found that DBR outperforms ConWIP (e.g. Lambrecht & Segaert, 1990; Gilland, 2002). It also appears to contradict Framinan *et al.*'s (2003) more nuanced argument that performance differences between DBR and ConWIP are dependent on the position of the bottleneck. Taking a closer look at our detailed results, we can observe that ConWIP does not perform better than DBR in any of the experiments. If the bottleneck is the first station, i.e. at the furthest upstream point, then DBR arguably outperforms ConWIP. Therefore, there is some evidence that the bottleneck position impacts performance differences, although these are not statistically significant. Hence, our results appear to partially support previous research.

4.1.2 The Performance Impact of Bottleneck Position

The performance impact of the bottleneck position can be evaluated by moving from left to right in Table 4. To assess the impact of bottleneck position in isolation, we first focus on the results for immediate release. There is a performance improvement if the bottleneck is (close to) the center of the shop, but the performance level achieved when the bottleneck is the first station is equivalent to the performance achieved when the bottleneck is the last station. This appears to contradict previous research. In particular, Kadipasaoglu *et al*. (2000) showed that the further downstream the bottleneck, the higher the work-in-process and associated flow times in the system since the probability of the bottleneck being starved increases due to the cumulative effect of upstream variability. This contradiction is explained by differences in the choice of dispatching rule – Fry *et al*. (1987) showed that the effect of the bottleneck position depends on the choice of dispatching rule.

Meanwhile, there are significant two-way interactions between the release method and bottleneck position for each release method except ConWIP, which maintains its performance impact regardless of the bottleneck position. For all other release methods, we observe a loss in control if the bottleneck position moves downstream. ConWIP and DBR are equivalent if the last station is the bottleneck (Station 7). Consequently, the performance of DBR approaches the performance of ConWIP when the bottleneck position moves downstream.

4.2 Discussion: What does this mean for Bottleneck Shiftiness?

Our presentation of results in Section 4.1 focused on the impact of the bottleneck position on performance. We argued that investigating this impact will further our understanding of bottleneck shiftiness since it decomposes bottleneck shiftiness into its different ‘ideal’ states; in a pure flow shop with bottleneck shiftiness, each of the stations (or a subset of them) is by definition the bottleneck during certain time periods.

Bottleneck shiftiness appears to have a negligible effect on the performance of the dispatching rule in isolation, i.e. if jobs are released immediately to the shop floor. Meanwhile bottleneck shiftiness appears to have a direct impact on the performance improvement that can be achieved if order release is controlled – the further upstream the bottleneck is positioned, the tighter the control that can be exercised by the order release method. DBR controls the number of jobs that are released and on their way to the bottleneck. Once a job has been completed at the bottleneck, it is subtracted from the DBR limit. This means that the further downstream the bottleneck is positioned, the more jobs should be allowed to be on their way to the bottleneck (and still at upstream stations). This means that DBR's limit needs to be continuously adjusted to obtain stable performance, avoiding both a loss of control, leading to congestion, and control that is too tight, resulting in premature station idleness (Kanet, 1988). Meanwhile, SA COR accounts for the inter-dependency between the limit and the bottleneck position by using the corrected aggregate load to automatically allow more work to be on its way to a station the further downstream a station is located. As a result, although the bottleneck position affects the strength of control that can be exercised under SA COR and Continuous, the positive performance effects are maintained.

Before concluding our study, the next section briefly assesses the impact of the shop floor dispatching rule on performance.

4.3 The Impact of Priority Dispatching

In Section 4.1, we focused on the PST dispatching rule, whereas here we examine the use of the SPT and MPST rules. Table 5 gives the throughput time, lead time, percentage tardy, and mean tardiness results that were obtained with SPT dispatching.

Table 5: Performance Impact of Bottleneck Position under SPT Dispatching

Release Method	Parameter Setting	First Station is the Bottleneck				Center Station is the Bottleneck				Last Station is the Bottleneck			
		TT[1)]	LT[2)]	PT[3)]	MT[4)]	TT	LT	PT	MT	TT	LT	PT	MT
IMM	None	12.83	12.83	1.94%	0.82	12.85	12.85	1.91%	0.78	12.96	12.96	1.94%	0.79
Cont.	N15	12.41	12.97	1.91%	0.72	12.85	12.85	1.91%	0.78	12.96	12.96	1.94%	0.79
	N14	12.36	12.99	1.90%	0.71	12.85	12.86	1.91%	0.78	12.96	12.96	1.94%	0.79
	N13	12.29	13.02	1.92%	0.69	12.85	12.86	1.91%	0.77	12.96	12.96	1.94%	0.79
	N12	12.21	13.05	1.89%	0.67	12.84	12.86	1.91%	0.77	12.96	12.96	1.93%	0.79
	N11	12.13	13.09	1.89%	0.66	12.83	12.86	1.91%	0.77	12.95	12.96	1.93%	0.79
	N10	12.03	13.13	1.91%	0.64	12.82	12.86	1.90%	0.77	12.95	12.96	1.93%	0.79
	N9	11.91	13.18	1.92%	0.61	12.80	12.86	1.90%	0.77	12.94	12.96	1.92%	0.79
	N8	11.78	13.23	1.88%	0.58	12.76	12.87	1.90%	0.76	12.92	12.97	1.92%	0.79
	N7	11.65	13.33	1.92%	0.55	12.69	12.89	1.88%	0.75	12.89	12.97	1.92%	0.78
	N6	11.49	13.43	1.94%	0.51	12.56	12.91	1.89%	0.72	12.83	12.99	1.90%	0.78
	N5	11.26	13.49	1.87%	0.47	12.35	12.97	1.86%	0.68	12.71	13.02	1.89%	0.76
	N4	10.93	13.55	1.75%	0.44	11.97	13.07	1.83%	0.61	12.44	13.08	1.86%	0.72
SA COR	N15	12.41	12.97	1.91%	0.72	12.85	12.85	1.91%	0.78	12.96	12.96	1.94%	0.79
	N14	12.36	12.99	1.90%	0.71	12.85	12.85	1.91%	0.78	12.96	12.96	1.94%	0.79
	N13	12.29	13.02	1.92%	0.69	12.85	12.85	1.91%	0.77	12.96	12.96	1.94%	0.79
	N12	12.21	13.05	1.89%	0.67	12.85	12.86	1.91%	0.77	12.96	12.96	1.94%	0.79
	N11	12.13	13.09	1.89%	0.66	12.84	12.86	1.91%	0.77	12.96	12.96	1.94%	0.79
	N10	12.03	13.13	1.91%	0.64	12.83	12.86	1.91%	0.77	12.96	12.96	1.94%	0.79
	N9	11.91	13.18	1.92%	0.61	12.82	12.86	1.91%	0.77	12.96	12.96	1.94%	0.79
	N8	11.78	13.23	1.88%	0.58	12.79	12.86	1.91%	0.76	12.95	12.96	1.94%	0.79
	N7	11.65	13.34	1.92%	0.55	12.73	12.87	1.91%	0.75	12.94	12.96	1.94%	0.79
	N6	11.49	13.43	1.95%	0.51	12.63	12.89	1.90%	0.73	12.91	12.96	1.93%	0.78
	N5	11.28	13.49	1.86%	0.47	12.46	12.92	1.90%	0.69	12.85	12.97	1.94%	0.77
	N4	10.98	13.55	1.78%	0.45	12.16	12.99	1.90%	0.62	12.68	13.00	1.94%	0.73
DBR	13 jobs	12.79	12.86	1.93%	0.81	12.85	12.85	1.91%	0.78	12.96	12.96	1.94%	0.79
	12 jobs	12.78	12.88	1.93%	0.80	12.85	12.85	1.91%	0.78	12.96	12.96	1.94%	0.79
	11 jobs	12.75	12.91	1.92%	0.79	12.85	12.85	1.91%	0.78	12.96	12.96	1.94%	0.79
	10 jobs	12.71	12.96	1.91%	0.78	12.85	12.85	1.91%	0.78	12.96	12.96	1.94%	0.79
	9 jobs	12.66	13.02	1.90%	0.76	12.85	12.85	1.91%	0.78	12.96	12.96	1.94%	0.79
	8 jobs	12.57	13.11	1.89%	0.74	12.85	12.85	1.91%	0.78	12.96	12.96	1.94%	0.79
	7 jobs	12.45	13.26	1.88%	0.70	12.85	12.86	1.91%	0.78	12.96	12.96	1.94%	0.79
	6 jobs	12.28	13.47	1.88%	0.65	12.85	12.86	1.91%	0.77	12.96	12.96	1.94%	0.79
	5 jobs	12.02	13.79	1.90%	0.59	12.83	12.87	1.90%	0.77	12.96	12.96	1.94%	0.79
	4 jobs	11.66	14.29	1.94%	0.49	12.75	12.91	1.89%	0.75	12.95	12.96	1.92%	0.79
	3 jobs	11.17	15.08	2.02%	0.36	12.41	13.15	1.77%	0.64	12.82	13.03	1.87%	0.75
	2 jobs	10.56	16.38	2.22%	0.18	11.33	14.72	1.87%	0.29	11.92	13.94	1.93%	0.47
ConWIP	32 jobs	12.83	12.83	1.94%	0.82	12.85	12.86	1.91%	0.77	12.96	12.96	1.94%	0.79
	31 jobs	12.83	12.83	1.94%	0.82	12.85	12.86	1.91%	0.77	12.95	12.96	1.93%	0.79
	30 jobs	12.83	12.83	1.94%	0.82	12.85	12.86	1.91%	0.77	12.95	12.96	1.93%	0.79
	29 jobs	12.83	12.83	1.94%	0.82	12.85	12.86	1.91%	0.77	12.95	12.96	1.93%	0.79
	28 jobs	12.82	12.83	1.94%	0.82	12.84	12.86	1.91%	0.77	12.95	12.96	1.92%	0.79
	27 jobs	12.82	12.84	1.93%	0.82	12.84	12.86	1.90%	0.77	12.94	12.97	1.92%	0.79
	26 jobs	12.81	12.84	1.93%	0.81	12.83	12.86	1.90%	0.77	12.93	12.97	1.92%	0.78
	25 jobs	12.80	12.84	1.92%	0.81	12.82	12.87	1.90%	0.77	12.92	12.97	1.91%	0.78
	24 jobs	12.79	12.85	1.92%	0.81	12.81	12.87	1.89%	0.76	12.91	12.98	1.91%	0.77
	23 jobs	12.77	12.86	1.91%	0.80	12.80	12.88	1.89%	0.76	12.88	12.99	1.90%	0.77
	22 jobs	12.75	12.88	1.89%	0.79	12.77	12.89	1.88%	0.75	12.86	13.01	1.89%	0.76
	21 jobs	12.71	12.90	1.88%	0.78	12.74	12.91	1.87%	0.74	12.82	13.03	1.87%	0.75

[1)]TT – Throughput Time; [2)]LT – Lead Time; [3)]PT – Percentage Tardy; [4)]MT – Mean Tardiness

As expected, e.g. from Conway *et al*. (1967), a reduction in throughput time, lead time and percentage tardy performance compared to PST dispatching can be observed (Table 4 *vs.* Table 5), but this is achieved at the expense of deterioration in mean tardiness performance. The strong reduction in throughput times and lead times diminishes performance differences across release methods. Meanwhile, the release method limits the number of jobs on the shop floor and thus the selection possibilities for the dispatching rule. As a consequence, the effect of the SPT rule weakens with tighter norms leading to an increase in throughput and lead times. Finally, Continuous and SA COR lose their advantage compared to the alternative release methods since SPT effects are now created by the dispatching rule.

A similar effect on the relative performance across release methods can also be observed in Table 6, which shows the results for MPST dispatching. MPST dispatching is a powerful rule that leads to the best performance across the three shop floor dispatching rules. Order release control has the potential to improve performance, allowing for a reduction in throughput times and consequently work-in-process, and it is able to maintain the positive performance effect of MPST. However, in contrast to their use in conjunction with PST dispatching, Continuous and SA COR have a direct detrimental effect on percentage tardy and mean tardiness performance when MPST dispatching is applied since they create SPT effects in periods when this is not appropriate. This makes DBR and ConWIP the preferred release methods in this context.

Table 6: Performance Impact of Bottleneck Position under MPST Dispatching

Release Method	Parameter Setting	First Station is the Bottleneck				Center Station is the Bottleneck				Last Station is the Bottleneck			
		TT[1]	LT[2]	PT[3]	MT[4]	TT	LT	PT	MT	TT	LT	PT	MT
IMM	None	17.96	17.96	0.45%	0.11	17.93	17.93	0.39%	0.08	17.96	17.96	0.45%	0.12
Cont.	N15	17.33	17.91	0.46%	0.12	17.93	17.93	0.39%	0.08	17.95	17.96	0.45%	0.12
	N14	17.22	17.89	0.48%	0.12	17.93	17.93	0.39%	0.08	17.95	17.96	0.45%	0.12
	N13	17.08	17.84	0.49%	0.13	17.92	17.93	0.39%	0.08	17.95	17.96	0.45%	0.12
	N12	16.91	17.80	0.52%	0.14	17.92	17.93	0.39%	0.08	17.95	17.96	0.45%	0.12
	N11	16.72	17.73	0.57%	0.16	17.90	17.93	0.39%	0.08	17.94	17.95	0.45%	0.12
	N10	16.48	17.63	0.59%	0.18	17.88	17.93	0.39%	0.08	17.93	17.95	0.45%	0.12
	N9	16.19	17.52	0.66%	0.20	17.84	17.93	0.40%	0.08	17.92	17.95	0.45%	0.12
	N8	15.85	17.37	0.75%	0.22	17.78	17.93	0.40%	0.08	17.89	17.95	0.45%	0.12
	N7	15.42	17.16	0.83%	0.26	17.66	17.92	0.40%	0.08	17.83	17.94	0.46%	0.12
	N6	14.91	16.91	0.94%	0.29	17.44	17.89	0.39%	0.08	17.72	17.93	0.46%	0.12
	N5	14.24	16.56	1.05%	0.34	17.01	17.80	0.40%	0.10	17.49	17.89	0.47%	0.12
	N4	13.36	16.10	1.20%	0.37	16.16	17.52	0.53%	0.14	16.93	17.77	0.45%	0.12
SA COR	N15	17.33	17.91	0.46%	0.12	17.93	17.93	0.39%	0.08	17.96	17.96	0.45%	0.12
	N14	17.22	17.89	0.48%	0.12	17.93	17.93	0.39%	0.08	17.96	17.96	0.45%	0.12
	N13	17.08	17.84	0.49%	0.13	17.93	17.93	0.39%	0.08	17.96	17.96	0.45%	0.12
	N12	16.91	17.80	0.52%	0.14	17.92	17.93	0.39%	0.08	17.96	17.96	0.45%	0.12
	N11	16.72	17.73	0.56%	0.16	17.92	17.93	0.39%	0.08	17.96	17.96	0.45%	0.12
	N10	16.48	17.63	0.60%	0.18	17.90	17.93	0.39%	0.08	17.96	17.96	0.45%	0.12
	N9	16.20	17.52	0.66%	0.20	17.88	17.93	0.40%	0.08	17.95	17.96	0.45%	0.12
	N8	15.86	17.38	0.75%	0.22	17.83	17.94	0.40%	0.08	17.94	17.96	0.45%	0.12
	N7	15.44	17.17	0.83%	0.26	17.74	17.94	0.40%	0.08	17.92	17.96	0.46%	0.12
	N6	14.94	16.92	0.95%	0.29	17.57	17.92	0.39%	0.08	17.88	17.96	0.46%	0.12
	N5	14.32	16.59	1.05%	0.34	17.23	17.86	0.40%	0.10	17.76	17.96	0.47%	0.12
	N4	13.54	16.15	1.19%	0.38	16.56	17.66	0.55%	0.16	17.43	17.95	0.45%	0.13
DBR	13 jobs	16.97	17.99	0.47%	0.09	17.93	17.93	0.39%	0.08	17.96	17.96	0.45%	0.12
	12 jobs	16.78	18.00	0.49%	0.09	17.93	17.93	0.39%	0.08	17.96	17.96	0.45%	0.12
	11 jobs	16.57	18.00	0.50%	0.09	17.93	17.93	0.39%	0.08	17.96	17.96	0.45%	0.12
	10 jobs	16.32	18.01	0.52%	0.09	17.93	17.93	0.39%	0.08	17.96	17.96	0.45%	0.12
	9 jobs	16.03	18.02	0.55%	0.09	17.92	17.93	0.39%	0.08	17.96	17.96	0.45%	0.12
	8 jobs	15.70	18.03	0.59%	0.09	17.89	17.93	0.39%	0.08	17.96	17.96	0.45%	0.12
	7 jobs	15.32	18.04	0.65%	0.09	17.80	17.94	0.39%	0.08	17.95	17.96	0.45%	0.12
	6 jobs	14.88	18.05	0.74%	0.09	17.58	17.94	0.39%	0.08	17.94	17.96	0.45%	0.12
	5 jobs	14.37	18.07	0.88%	0.09	17.16	17.95	0.41%	0.08	17.84	17.96	0.46%	0.12
	4 jobs	13.79	18.10	1.08%	0.10	16.40	18.00	0.47%	0.08	17.43	17.97	0.46%	0.12
	3 jobs	13.12	18.13	1.35%	0.11	15.12	18.33	0.69%	0.09	16.29	18.12	0.57%	0.12
	2 jobs	12.36	18.19	1.73%	0.14	12.90	21.94	4.32%	0.36	13.83	21.14	3.13%	0.33
ConWIP	32 jobs	17.73	17.97	0.46%	0.10	17.72	17.94	0.39%	0.08	17.73	17.96	0.46%	0.12
	31 jobs	17.67	17.97	0.46%	0.10	17.67	17.94	0.40%	0.08	17.67	17.96	0.46%	0.12
	30 jobs	17.61	17.97	0.46%	0.10	17.60	17.94	0.40%	0.08	17.60	17.96	0.46%	0.12
	29 jobs	17.54	17.97	0.46%	0.10	17.53	17.94	0.40%	0.08	17.52	17.97	0.46%	0.12
	28 jobs	17.45	17.98	0.46%	0.10	17.44	17.95	0.40%	0.08	17.43	17.97	0.46%	0.12
	27 jobs	17.35	17.98	0.47%	0.10	17.34	17.95	0.41%	0.08	17.33	17.98	0.46%	0.12
	26 jobs	17.23	17.99	0.47%	0.10	17.22	17.96	0.41%	0.08	17.20	17.98	0.46%	0.12
	25 jobs	17.09	18.00	0.48%	0.10	17.08	17.97	0.42%	0.08	17.07	18.00	0.47%	0.12
	24 jobs	16.94	18.02	0.49%	0.10	16.92	17.99	0.44%	0.08	16.91	18.01	0.48%	0.12
	23 jobs	16.76	18.04	0.50%	0.10	16.74	18.01	0.46%	0.08	16.73	18.04	0.50%	0.12
	22 jobs	16.55	18.07	0.53%	0.09	16.54	18.04	0.48%	0.08	16.52	18.07	0.53%	0.12
	21 jobs	16.32	18.13	0.57%	0.09	16.31	18.09	0.50%	0.08	16.29	18.12	0.57%	0.12

[1]TT – Throughput Time; [2]LT – Lead Time; [3]PT – Percentage Tardy; [4]MT – Mean Tardiness

5. Conclusions

Bottleneck shiftiness is an important managerial problem that often bedevils managers. Consequently, the phenomenon has received significant research attention. The focus of the extant literature has however largely been on assessing the impact of protective capacity on bottleneck shiftiness rather than on its actual performance impact. One reason for this may be that the operational impact of bottleneck shiftiness is complex to capture since changing the level of bottleneck shiftiness (by altering the level of protective capacity) typically leads to a change in the utilization level. Motivated by Land *et al*. (2015), who argued that dynamic phenomena are best understood by investigating the different states that constitute them, this study took a different approach and decomposed bottleneck shiftiness to investigate its underlying phenomenon – the impact of the bottleneck position.

In response to our first research question concerning the impact of the bottleneck position on performance in an order release controlled pure flow shop, our simulation results demonstrate that while the bottleneck position has a negligible impact on performance if jobs are released immediately and control is exercised by the dispatching rule, there is an impact if order release is controlled. If the bottleneck position shifts upstream, tighter control can be exercised. Consequently, parameters need to be adjusted over time to stabilize performance. Our second research question was concerned with how this new insight furthers our understanding of bottleneck shiftiness. We saw that it is important to be aware of the stations that the bottleneck shifts between. If the shift tends towards stations upstream from the current bottleneck, then performance may improve since the time period during which tighter control can be exercised by order release increases. On the other hand, performance is likely to deteriorate if the shift tends towards stations downstream of the current bottleneck.

5.1. Managerial Implications

In terms of the impact of shifting bottlenecks on performance, the following can be concluded from our results:

- *Continuous* controls the load of all stations. Hence, the bottleneck is always controlled regardless of which station becomes the current bottleneck. This makes Continuous the most suitable method for shops with shifting bottlenecks if PST or SPT dispatching is applied.
- *SA COR* controls the bottleneck workload on its way to the bottleneck station. Since this workload is corrected by the position of a station in the routing of a job, the parameters are more robust than under DBR.

- *DBR* controls the number of jobs on their way to the bottleneck. If the routing position of the bottleneck shifts, the limit applied needs to be adjusted to allow for more jobs at upstream stations (if the shift is to a downstream station) or it needs to be tightened (if the shift is to an upstream station) in order to keep the bottleneck load under control.
- *ConWIP* controls the number of jobs in the system. It is consequently not affected by shifts in the bottleneck position – this is an advantage that makes ConWIP a viable option in situations with severe or very severe bottlenecks, especially if the bottleneck tends to be downstream in the system. ConWIP is the most suitable release method for shops with shifting bottlenecks if MPST dispatching is applied.

Our study highlighted that it is important to monitor the bottleneck even if the bottleneck does not physically change or the release method necessarily includes the bottleneck, since there is a significant impact on order release performance if the position of the bottleneck in the routing of orders changes. A company should therefore be able to quickly detect any shift in the bottleneck position in order to obtain the right level of control over the bottleneck. Another important finding of our study is that it is beneficial to change the position of the bottleneck since better control can be exercised at upstream stations. This may be achieved, for example, by manipulating the positioning of protective capacity, by redistributing capacity, or by influencing the work undertaken by the shop.

5.2 Limitations and Future Research

The position of the bottleneck influences the parameters that should be set for all of the order release methods considered in this study except ConWIP. Consequently, whenever there is a shift in the bottleneck, the workload limit needs to be adjusted. Future research should explore dynamic solutions for how the bottleneck position and workload limit can be linked. Meanwhile, both a shift in the physical location or identity of the bottleneck and a shift in the routing position of a bottleneck influence performance. A major limitation of our study is that we have focussed on the latter, but further research is also required to assess the impact of the former. Another limitation is our focus on a simple, pure flow shop. In a pure flow shop, the physical location of a station and its position in the routing of jobs overlap, and this has aided our analysis. Nonetheless, future research could extend our setting and explore the impact of the bottleneck position in more complex environments, including convergent and divergent flow shops.

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