THE EFFECTS OF BUFFER PATTERNS ON THROUGHPUT IN CONWIP FLOW LINES: A SIMULATION STUDY

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Abstract

This research was a simulation experiment which aimed to investigate the effects of buffer patterns on the throughput of lines controlled by a CONWIP release mechanism. The hypothetical lines simulated were stochastic 11-station flow lines with the middle station as the bottleneck. ANOVA tests were used for the analysis of the simulation output, followed by Duncan's Multiple Range tests. There were 6 buffer patterns which were distinguished by the amount of total buffer capacity and the buffer allocation approaches. The experiment was done at three levels of protective capacity (PC); 0%, 20%, and 40%, and two levels of coefficient of variation (CV) of processing times; 0.05 and 0.50. When CV = 0.05, ANOVA tests revealed a significant difference ($p < 0.01$) among buffer patterns only for the lines with PC of 0%, whereas when PC = 20% and 40%, there were insignificant differences among buffer patterns. When CV = 0.50, ANOVA tests indicated significant differences ($p < 0.01$) among buffer patterns at all PC levels. The important suggestion is that appropriate allocation of limited buffer capacity, an addition of protective capacity, and a reduction of system variation could increase the throughput rates to the desired level.

Keywords: Release mechanism, CONWIP, buffers, protective capacity, bottleneck

Introduction

An important factor for achieving target throughput rate of production lines is the method of controlling the release of new units into the production system called a release mechanism. One recent release mechanism which has been of interest to researchers is CONWIP, first introduced by Spearman *et al.* (1989). Under the CONWIP release mechanism, as a production unit is released from the final station, a signal is sent to the first station to release a new unit into the system, thus, the amount of work-in-process (WIP) in the lines is held constant. Thus CONWIP is considered as a pull-release mechanism where the release rate of new units into the system depends on the true capacity at that time. Other pull-release mechanisms are Kanban (see, for example, Krajewski *et al.*, 1987) and pull from bottleneck (PFB) (Hopp and Spearman, 1996). Under Kanban, each station starts production only when there is a release of a unit at its succeeding station, whereas PFB releases a new unit into the line

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upon the completion of another unit at the bottleneck station. The original concept of PFB is a scheduling approach called Drum-Buffer-Rope (DBR), which originated from the theory of constraints (Goldratt and Cox, 1986). Under the PFB release mechanism, the bottleneck stations have to be determined in order to set the correct pulling point, which may be difficult since the bottlenecks may shift around due to the variability in the system and the product type currently processed for mixed-model lines. Hence, Kanban and PFB mechanisms are more complicated than CONWIP.

Besides being less complicated, CONWIP was found to outperform other release mechanisms. For example, Spearman *et al.* (1990) argued that a CONWIP release mechanism could be applied to broader manufacturing environments compared with Kanban. Spearman and Zazanis (1992) demonstrated that, given the same amount of WIP, Kanban is not likely to give a higher throughput than an equivalent CONWIP. Thus, the pulling-everywhere strategy in a Kanban system seemed to be unnecessarily complicated. Duenyas and Keblis (1995) found that CONWIP achieved a target throughput rate with less maximum WIP in the system and also with less average WIP in the system when compared with Kanban. However, those studies on a CONWIP release mechanism assumed no restriction on inter-station buffer capacity or queue size, which may not be realistic since production lines usually have limited space.

How the inter-station buffer capacity affects the performance of production lines with a CONWIP release mechanism is not obvious. Thus, the purpose of this research is to explore these effects the results of which could give some suggestions for configuring buffer patterns in the ways that the desired performance can be reached. Although there have been various studies that investigated the methods of allocating limited buffer capacity, those studies explored lines with other release mechanisms, not with CONWIP. For example, Smith and Brumbaugh (1977) found that the best buffer allocation for a three station flow line is to split buffer capacity equally. Conway *et al.* (1988) also found that equal allocation is the best approach for production lines with balanced average processing time and variation. But for lines in which stations have unequal average processing time, more buffer capacity should be allocated toward stations with the highest average processing time. On the other hand, El-Rayah's (1979) work revealed an insignificant difference in the performance of equal and unequal allocations.

Since line performance can vary with different degrees of system random variations, this study will be conducted under both low and high processing time variability. To represent a line with low and high processing time variability, the ratio of the standard deviation to the mean station processing time (i.e., the coefficient of variation, CV) was set at 0.05 and 0.50, respectively.

With limited buffer capacity, the lines may lose the opportunity to process more units in a given time because stations will be idle owing to starvation and blocking from time to time. Blocking is the event of a station having no buffer space for storing a completed unit produced by the station, while starvation is the event of a station having no new unit to work on when it is ready to process more. One alternative to lessen the adverse consequence on line performance caused by limited buffer capacity is to provide some protective capacity (PC) to non-bottleneck stations (Atwater and Chakravorty, 1994; Kadipasaoglu *et al.*, 2000). According to the APICS Dictionary (Cox *et al.,* 1995), protective capacity is extra capacity at the non-bottleneck stations above the bottleneck stations' capacity used to protect against statistical fluctuation. The effect of buffer patterns on line performance could be influenced by protective capacity, thus the protective capacity was also varied in this study.

Research Method

The study was a simulation-based experiment on serial production lines with a CONWIP release mechanism using AWESIM! program

(Pritsker *et al.*, 1997). Each line was composed of eleven stations; thus, there were ten inter-station locations to place buffer slots for holding WIP (Figure 1). The bottleneck station was taken to be the one with the largest average processing time according to the identification given by Goldratt and Cox (1986). For this study, the bottleneck was located at station six. Lognormal was employed as the probability distribution of processing times at all stations to represent the task times in a real manufacturing environment (Muralidhar *et al.*, 1995) due to its quality as being right-skewness and covering only a non-negative value.

The dependent variable was the system throughput per day. The line operated 8 h a day. The average processing time of the bottleneck station was 15 min per unit; thus, the full system throughput would be 4 units per h or 32 units per day since the slowest station (i.e. the bottleneck) determines the average throughput rate of a production line.

The independent variable was the buffer pattern, distinguished by the total number of buffer slots (each buffer slot could hold one unit of WIP) and the allocation of buffer slots to inter-station buffer location. The effect of the independent variable was investigated under different levels of protective capacity and processing time variation. The protective capacity, which was calculated as the percentage of the deviation of the processing rate of non-bottleneck stations from that of the bottleneck station, was set at three levels consisting of 0%, 20%, and 40%. Although the PC of 0% represented the equal average processing rate at each station, for the simplicity of explanation, station six represents the line bottleneck for this PC level. The study was done under two levels of CV; 0.05 and 0.50. As the average processing time of the bottleneck station was 15 min per unit, the standard deviation of the processing time at the bottleneck was 0.75 min at 0.05 CV and 7.5 min at 0.50 CV. Coefficient of variation was the same for all stations in a given simulation run. The average processing time and the standard deviation of processing time of non-bottleneck stations at each level of PC are shown in Table 1.

Using Welch's procedure (1983), the length of the warm-up period (i.e. the beginning part of each replication) was set at 60 days. The length during the steady-state was set at 900 days or 15 times the warm-up period, which should be long enough according to the suggestion by Bank *et al.* (2001). Thus there was a total of 960 days in each replication with the output obtained during the first 60 days discarded from the computation of average throughput rates. Each simulation run had 25 replications which gave a relative error of less than 0.001.

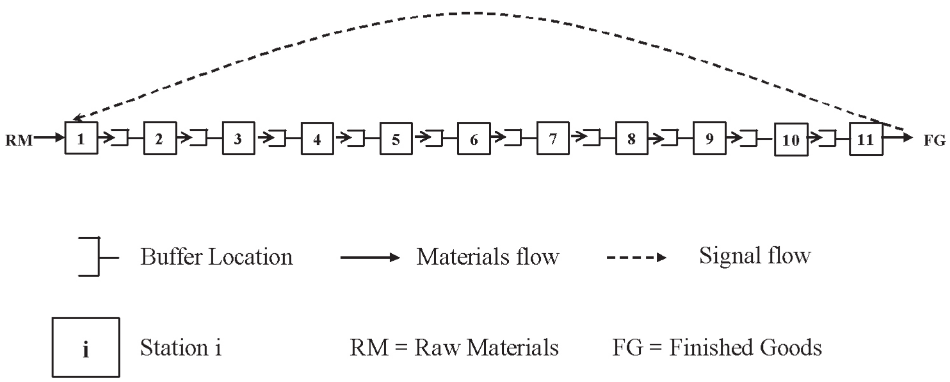

Figure 1. Modeled flow line with CONWIP release mechanism

The number of the WIP in the system to be allowed in the production line was required before determining the total number of buffer slots. Thus, a pilot simulation experiment of lines with unrestricted buffer slots and no protective capacity was made in order to specify the number of the system WIP. It was found that increasing the number of the system WIP beyond 21 units did not improve the throughput rates significantly at both 0.05 and 0.50 CV. Thus, the total number of the WIP in the system was constant at 21 units in which 11 units would be in the process at 11 stations and the rest, 10 units, would wait for processing in the inter-station buffer slots. Thus, the minimum total number of buffer slots used to store WIP waiting for processing was 10 units. Accordingly, this study set the total units of buffer slots to 10, 20 and unlimited. Setting unlimited units of buffer slots assumed that each inter-station buffer space could hold all the inventory in the system in compliance with the assumption of no restriction on inter-station buffer capacity of the original CONWIP release mechanism. This inclusion could give some comparative insights on the performance between lines with unrestricted and restricted buffer capacity.

Categorizing buffer patterns according to the available number of buffer slots and the placement of buffer slots led to a total of 6 patterns as shown in Table 2. UNLIMIT denoted the buffer pattern without restriction on the number of inter-station buffer slots. Both LIM10P1 and LIM10P2 denoted buffer patterns with 10 units of buffer slots but the allocation approaches of the two patterns differed. The former pattern allocated one unit of buffer slot to each location. The latter pattern allocated 5 units of buffer slots to the location before and after the bottleneck, leaving no slot at other locations. When the total number of buffer slots was 20 units, there were three patterns, LIM20P1, LIM20P2, and LIM20P3. LIM20P1 placed two slots at each buffer location equally. LIM20P2 and LIM20P3 placed more buffer slots toward the bottleneck, in which LIM20P2 placed 6 buffer

Table 1. Average processing time (min) and standard deviation of processing time (min) at non-bottleneck station

		PC		
		0 %	20 %	40 %
CV = 0.05	Average processing time	15.000	12.500	10.710
	SD of processing time	0.750	0.625	0.536
CV = 0.50	Average processing time	15.000	12.500	10.710
	SD of processing time	7.500	6.250	5.357

Table 2. Buffer patterns

Buffer Patterns	Number of Buffer Slots									
	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}	b_{11}
UNLIMIT	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
LIM10P1	1	1	1	1	1	1	1	1	1	1
LIM10P2	0	0	0	0	5	5	0	0	0	0
LIM20P1	2	2	2	2	2	2	2	2	2	2
LIM20P2	1	1	1	1	6	6	1	1	1	1
LIM20P3	0	0	0	0	10	10	0	0	0	0

b_i = *number of buffer slots in front of station i*

∞ = *unlimited number of buffer slots*

slots before and after the bottleneck leaving a slot at every other buffer location and LIM20P3 placed 10 buffer slots before and after the bottleneck leaving no slot at other buffer locations.

Using a full factorial research design with 25 replications, a total of 900 simulation runs was used (6 buffer patterns X 3 levels of protective capacity X 2 levels of CV X 25 replications). Analysis of variance (ANOVA) was applied to determine if there were differences among the buffer patterns when considering average throughput rates. Duncan's Multiple Range tests were performed as the post-hoc tests. An alpha of 0.05 was used in all significant tests.

Results and Discussion

The average throughput rates obtained from the simulation appear in Table 3. In this section, the results and discussion when CV = 0.05 and CV = 0.50 will be demonstrated.

CV = 0.05

Figure 2 demonstrates the graph of the average system throughput rates for each level of protective capacity across six buffer patterns when the CV = 0.05.

Table 3. Average throughput rates

CV = 0.05

PC	Buffer Patterns					
	UNLIMIT	LIM10P1	LIM10P2	LIM20P1	LIM20P2	LIM20P3
0%	31.923	31.846	30.480	31.915	31.861	30.479
20%	32.000	32.001	31.997	31.998	32.001	32.001
40%	32.003	32.000	32.002	32.000	32.000	32.000

CV = 0.50

PC	Buffer Patterns					
	UNLIMIT	LIM10P1	LIM10P2	LIM20P1	LIM20P2	LIM20P3
0%	27.298	24.537	20.797	26.642	25.280	20.813
20%	31.251	28.213	24.912	30.353	30.027	24.978
40%	31.999	30.379	28.884	31.611	31.932	29.066

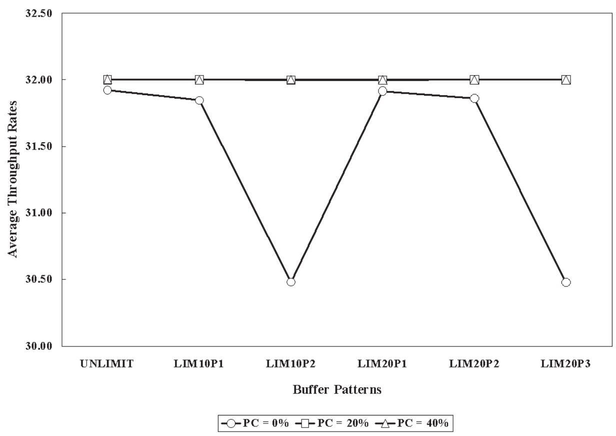

Figure 2. Average throughput rates when CV = 0.05

The ANOVA results indicated that there was a significant difference ($p < 0.01$) among buffer patterns when PC = 0%, whereas when PC = 20% and 40%, the ANOVA results found insignificant differences among buffer patterns (P-values = 0.396 and 0.744 for PC = 20% and 40% respectively). Since there was a significant difference among buffer patterns at PC = 0%, a Duncan's Multiple Range test was performed to compare the average throughput rates among each pair of buffer patterns at PC = 0%, as shown in Table 4.

When PC = 0%, the Duncan's Multiple Range test revealed that there were significant differences between every pair of buffer patterns except LIM10P2 and LIM20P3, in which the allocation of buffer slots to before and after bottlenecks only was assumed. Both patterns gave the lowest average throughput rates. The UNLIMIT pattern gave the highest average throughput rate at 31.923 units per day. LIM20P1, which allocated a total of 20 units of buffer slots to each buffer location of 2 units equally, achieved the second highest average throughput rate.

When PC was increased to 20% and 40%, any buffer pattern could obtain average throughput rates close or equal to the optimal system throughput rate of 32 units per day. This could imply that some level of protective capacity could increase throughput rates to the full level even with only a small number of buffer slots. It could be noted that total buffer slots as small as 10 units, no matter how the buffer slots were spread, gave a comparable performance to higher buffer capacity when protective capacity was provided.

Additional ANOVA and Duncan's Multiple Range tests comparing PC levels considering average throughput rates gave similar results at every buffer pattern. That was that PC of 0% gave a significantly lower average throughput rate than other PC levels, while there was no significant difference of average throughput rates between 20% and 40% protective capacity. This indicates that additional PC over 20% did not improve the throughput rates regardless of the selected buffer patterns.

There are four important findings for the low variation production system. First, managers can save the inter-station storage space in production lines with a CONWIP release mechanism, and still the lines are able to achieve average throughput rates at the full level by adding protective capacity to the non-bottleneck stations. Second, the protective capacity adds more flexibility to the system in that both equal and unequal allocation of buffer capacity could obtain average throughput rates close or equal to the full level. Thus, managers need not be concerned about the approach of allocating buffer slots if the production lines have adequate protective capacity. Third, for lines with a lack of protective capacity, the lines should have a greater number of buffer slots than those with some protective capacity and equal distribution of buffer slots seems to be the best allocation approach. And fourth, the protective capacity could increase throughput; however, once the optimal system throughput rate is achieved, increasing the protective capacity will not give any benefit. Adding protective capacity generates cost, thus managers should search for the optimal level of protective capacity to avoid the excess capacity investment.

CV = 0.50

Figure 3 shows the graph of the average throughput rates for each level of protective capacity across six buffer patterns when the CV = 0.50.

The ANOVA results indicated that there were significant differences ($p < 0.01$) among buffer patterns at all PC levels. The results of Duncan's Multiple Range tests comparing the average system throughput rates of all pairs of buffer patterns at each level of PC are demonstrated in Table 5.

When there was a lack of protective capacity, there was a significant difference between every pair of buffer patterns except LIM10P2 and LIM20P3. Regardless of PC levels, UNLIMIT had the highest average throughput rate while LIM10P2 had the lowest average throughput rate. All buffer patterns

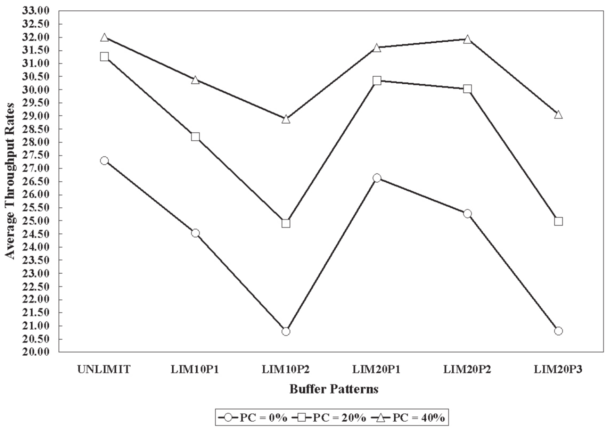

Figure 3. Average throughput rates when CV = 0.50

Table 4. Results of Duncan's Multiple Range tests when PC = 0% and CV = 0.05

Buffer patterns	LIM20P3	LIM10P2	LIM10P1	LIM20P2	LIM20P1	UNLIMIT
Ave. throughput rates	30.479	30.480	31.846	31.861	31.915	31.923

Underlining pairs of means that do not differ significantly at 0.05 significant level

Table 5. Results of Duncan's Multiple Range tests at each level of PC when CV = 0.50

PC = 0 %						
Buffer patterns	**LIM10P2**	**LIM20P3**	**LIM10P1**	**LIM20P2**	**LIM20P1**	**UNLIMIT**
Ave. throughput rates	20.797	20.813	24.537	25.280	26.642	27.298
PC = 20 %						
Buffer patterns	**LIM10P2**	**LIM20P3**	**LIM10P1**	**LIM20P2**	**LIM20P1**	**UNLIMIT**
Ave. throughput rates	24.912	24.978	28.213	30.027	30.353	31.251
PC = 40%						
Buffer patterns	**LIM10P2**	**LIM20P3**	**LIM10P1**	**LIM20P1**	**LIM20P2**	**UNLIMIT**
Ave. throughput rates	28.884	29.066	30.379	31.611	31.932	31.999

Underlining pairs of means that do not differ significantly at 0.05 significant level of lines without protective capacity had an average throughput rate considerably lower than the optimal 32 units per day. Even the line with the unrestricted buffer capacity (UNLIMIT) could achieve only 85.31% of the optimal throughput rate if there was no protective capacity.

At each level of PC, LIM10P2 gave the lowest average throughput rate, while LIM20P3 gave the second lowest. This confirms the result found when the CV was 0.05, that the inferior buffer patterns were the ones that distributed all buffer slots to only the bottleneck stations. It is also worth noticing that some patterns with a limited number of buffer slots supported by some protective capacity turned out to give higher average throughput rates than unlimited buffer slots with a lesser amount of PC. Lines operated with PC of 20% and with buffer patterns of LIM10P1, LIM20P1, and LIM20P2 had higher average throughput rates than lines with the UNLIMIT pattern but with no PC. All buffer patterns with PC of 40% gave higher average throughput rates than the UNLIMIT pattern with no PC. Also, lines with PC of 40% and with buffer patterns of LIM20P1 and LIM20P2 had higher average throughput rates than lines with unlimited buffer capacity supported by 20% PC.

Additional statistical tests by ANOVA and Duncan's Multiple Range tests revealed that there was a significant difference among protective capacity levels regardless of the selected buffer patterns. Higher amounts of protective capacity gave significantly larger average throughput rates.

There are two important points to be made for the case where system variation was high. First, the buffer patterns in CONWIP lines with high fluctuations affect the line performance; thus, managers need to determine the amount of system buffer capacity and the allocation approach that could obtain the desired throughput rates. The lines should have some buffer protection at every station. Mostly, the equal allocation had a relatively better performance than other allocation approaches. Second, if the system variation could not be reduced, some protective capacity may be unavoidable to obtain the desired throughput rates. Lines with high variation needed a higher amount of protective capacity than lines with low variation.

Conclusions

Production lines with a CONWIP release mechanism operated under low variations may need only a small amount of buffer capacity to make possible the reduction of production areas if protective capacity is allowed. Moreover, providing some protective capacity gives the lines with limited buffer slots more flexibility in the allocation approach.

In production lines with high variation, the buffer patterns gave different throughput rates at each level of protective capacity. Thus, in a practical situation where the production space is limited, a search for the adequate amount of buffer capacity and the right allocation of buffer capacity is required. At the same level of total buffer capacity, allocating buffer slots equally to each station in the line gave better average throughput rates than other approaches. Moreover, the high variation system may need greater protective capacity compared with the low variation system in order to reach the desired throughput rates.

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