AN EXPERIMENTAL COMPARISON OF PRODUCTION CONTROL STRATEGIES

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Abstract: This paper presents a comparison of following Production Control Strategies (PCS) Kanban Control Strategy (KCS), CONWIP, CONWIP/Pull, Basestock Control Strategy (BSCS) and Extended Kanban Control Strategies (EKCS). The PCS were examined under medium demand load with increasing co-efficient of variation. A Markov Decision Process (MDP) is used to model each PCS examined and these models are analysed using simulation. Detailed descriptions of the models of the PCS are given. The different strategies were compared under the criteria of obtaining a given service level with minimal WIP. The results show that under medium variable load CONWIP/PULL is the best strategy.

Keywords: Production Control Strategies, CONWIP/Pull, CONWIP, JIT, Kanban

1 Introduction

Bonvik et al. [1] presented a comparison of Kanban Control Strategy (KCS), Basestock Control Strategy (BSCS), CONWIP Control Strategy and CONWIP/Pull Control Strategy for a deterministic demand of 1 part per minute with shortages resulting in a lost opportunity (i.e. no backlogging). The Production Control Strategies (PCS) examined in the research presented here were, KCS, CONWIP, CONWIP/Pull, BSCS and EKCS. The PCS were examined under medium demand load with increasing co-efficient of variation. In addition, any unsatisfied demand was backlogged to succeeding production periods rather than being treated as a lost opportunity.

A Markov Decision Process (MDP) model presented by Hodgson and Wang [3, 4] for Horizontally Integrated Hybrid Production Control Strategies (HIHPCS) was adapted and expanded to model each PCS examined. Detailed descriptions of the models of the PCS are presented in Section 2. The experimental conditions under which the PCS were compared are detailed in Section 3. The results of the experimental process are presented in Section 4. Finally, Sections 5 and 6 provide a discussion of and conclusions drawn from the results of the experimental process.

2 Description Of Models

The system modelled for the purposes of these experiments was the five stage parallel/serial line described by Hodgson and Wang [4] (see Figure 1). To determine the quantity to produce at a production stage in a given production period the model presented in Hodgson and Wang [3, 4] required solving two equations, referred to as the Production Trigger and Production Objective. For the purposes of the work presented in this paper these two terms have been combined into one term, namely the Production Authorisation, $PA_j(n)$. In addition, for the purposes of the experimental work presented here it is assumed that minimum production level (P_j^{Min}) of stage j in period n is zero. The reliability of stage j in period n was modelled by the Probability Mass Function given in Table 1. The probability that stage j produces q units in period n given that the production authorisation is $PA_j(n)$, i.e. $\Pr[P_j(n) = q|PA_j(n)]$, is given by:

$$\Pr[P_j(n) = q|PA_j(n)] = \Pr[P_j(n) = q], \qquad q = 0, 1, \ldots, PA_j(n) - 1 \tag{1}$$

$$\begin{aligned}\Pr[P_j(n) = PA_j(n)|PA_j(n)] = {} & \Pr[P_j(n) = PA_j(n)] \\ & + \Pr[P_j(n) = PA_j(n) + 1] \quad q \geq PA_j(n) \\ & + \ldots + \Pr\left[P_j(n) = P_j^{\max}\right]\end{aligned} \tag{2}$$

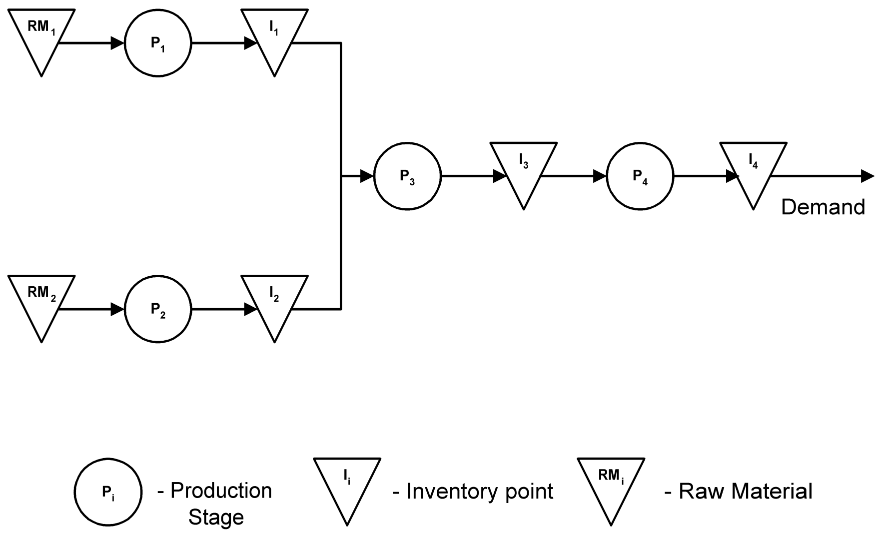


Figure 1: Parallel/Serial four stage production system modelled by Hodgson and Wang [3]

q	3	4	5
Pr[q]	0.2	0.6	0.2

Table 1: Probability Mass Function for Reliability in Production of Individual Stages

The remainder of this section describes the PCS modelled for the comparison experiments. Subsection 2.1 provides a description of Kanban Control Strategy (KCS). Subsection 2.2 provides a description of the CONWIP PCS modelled, while subsection 2.3 describes the CONWIP/Pull model. The Basestock Control Strategy (BSCS) and the Extended Kanban Control Strategy (EKCS) are detailed in subsection 2.4. Table 2 provides a description of the notation used throughout the discussion presented in this paper.

Notation

j, J:	Unique number identifying a production stage where $1 \leq j \leq J$.
n:	Production period.
$d(n)$:	The actual demand quantity in period n.
$PA_j(n)$:	The Production Authorisation for stage j in period n.
P_j^{Min}:	The minimum production capacity of stage j
P_j^{Max}:	The maximum production capacity of stage j
$P_j(n)$:	Production quantity for stage j in period n.
q:	The production reliability of a stage, which is modelled by a Probability Mass Function
I_j:	The output buffer of stage j.
$I_j(n)$:	The amount of inventory held in the output buffer of production stage j in period n.
$\{B_j(n)\}$:	The set of inventories held in the output buffers of the immediate predecessors of stage j in period n
$c_j(n)$:	The sum of inventories held in the output buffers of stages parallel to, but with stage number greater than, production stage j
K_j:	The number of Kanbans allocated to production stage j.
CC:	The cap on total inventory allowed in CONWIP and CONWIP/Pull lines.
$DC_j(n)$:	Number of demand cards held at stage j in period n in BSCS and EKCS lines.
S_j:	The initialisation stock level for stage j in BSCS and EKCS lines
S_j^{min}:	The minimum initialisation stock level for stage j in BSCS and EKCS lines
P_j:	Production center at stage j

Table 2: Notation List

2.1 Kanban Control Strategy

In a KCS system, production at stage j is authorised by the presence of Kanban cards and parts. When stage j begins production on a part, a Kanban card is attached to the part and travels downstream with the part. When the succeeding stage begins production on the part the Kanban card is removed and passed back to stage j to be available to authorise production of a new part. The Production Authorisation for period n for KCS stage j, where $1 \leq j \leq J-1$, is obtained from Equation 3. The Production Authorisation for the final stage is obtained from Equation 4 and is different from the model in [3, 4] in that the number of Kanbans available to the final stage cannot be increased temporarily in response to a shortage.

$$PA_j\left(n\right) = \mathrm{Min}\left[K_j - I_j\left(n-1\right), \left\{B_j\left(n-1\right)\right\}, P_j^{Max}\right] \tag{3}$$

$$\begin{aligned} PA_J\left(n\right) = \mathrm{Min}&\left[K_J - Max\left[0, I_J\left(n-1\right) - d(n)\right],\right. \\ &\left.\left\{B_j\left(n-1\right)\right\}, P_J^{Max}\right] \end{aligned} \tag{4}$$

2.2 CONWIP Control Strategy

For CONWIP systems, $PA_j(n)$ for an input stage ($j = 1, 2$) was modelled by Equation 5. $PA_j(n)$ for an input stage is constrained by a cap (CC) on the total inventory in the system, the number of components available in the raw material buffers and the maximum production capacity of the stage. For the purposes of the experiments conducted raw material was assumed to be always available. For this situation the term $\{B_j(n-1)\}$ would be infinitely large. $PA_j(n)$ for all other stages is only constrained by the maximum amount of units that the stage can produce in a production period and the availability of components in the stage's input buffer. Therefore, Equation 6 was used to model $PA_j(n)$ for all stages that are not input stages, i.e $3 \leq j \leq J$,.

$$\begin{aligned} PA_j\left(n\right) = \mathrm{Min}&\left[CC - \left(\left(\sum_{i=j}^{J} I_i\left(n-1\right)\right) - c_j\left(n-1\right) - d\left(n\right)\right),\right. \\ &\left.\left\{B_j\left(n-1\right)\right\}, P_j^{Max}\right] \end{aligned} \tag{5}$$

$$PA_j\left(n\right) = \mathrm{Min}\left[\left\{B_j\left(n-1\right)\right\}, P_j^{Max}\right] \tag{6}$$

2.3 CONWIP/Pull Control Strategy

Production Authorisations for production stages in a CONWIP/Pull system were determined by combining the equations used to model $PA_j(n)$ for KCS and CONWIP. For an input stage of a CONWIP/Pull system ($j = 1, 2$), $PA_j(n)$ was modelled by Equation 7. This equation was developed by further constraining equation 4 such that sufficient Kanbans must also be available at the stage to authorise production. For stage j, where $3 \leq j \leq J-1$, $PA_j(n)$ was modelled by Equation 3. For the final stage $PA_j(n)$ was modelled by Equation 6.

$$\begin{aligned} PA_j\left(n\right) = \mathrm{Min}&\left[CC - \left(\left(\sum_{i=j}^{J} I_i\left(n-1\right)\right) - c_j\left(n-1\right) - d\left(n\right)\right),\right. \\ &\left.K_j - I_j\left(n-1\right), \left\{B_j\left(n-1\right)\right\}, P_j^{Max}\right] \end{aligned} \tag{7}$$

2.4 Basestock Control Strategy and Extended Kanban Control Strategy

In a system employing BSCS, production at stage j in period n is authorised by the presence of demand cards at the production stage. When a demand occurs the equivalent number of demand cards are dispatched to each production stage to authorise the production of new parts. When the stage begins production of a new part the demand card is destroyed. The number of demand cards available to production stage j in period n ($DC_j(n)$) was determined from Equation 8. $PA_j(n)$ for a BSCS system was determined by employing Equation 9

$$DC_j(n) = DC_j(n-1) - P_j(n-1) + d(n) \tag{8}$$

$$PA_j(n) = \text{Min}\left[DC_j(n), \{B_j(n-1)\}, P_j^{Max}\right], \quad 1 \leq j \leq J \tag{9}$$

The production in period n of stage j in an EKCS system is constrained by the availability of Kanban and Demand cards. When a demand occurs, as with BSCS, the equivalent number of demand cards are dispatched to each production stage to authorise the production of new parts. However, before production can be authorised by the presence of a demand card, the demand card must be matched with a Kanban card and an available part. A demand card is destroyed when stage j begins production on the part while the associated Kanban card is attached to the part and travels downstream with the part. When the succeeding stage begins production on the part the Kanban card is removed and passed back to stage j to be available to authorise production of a new part. For an EKCS, $DC_j(n)$ was also modelled by Equation 8 while $PA_j(n)$ for an EKCS system was determined by employing Equation 10, for $1 \leq j \leq J-1$, and Equation 11, for the final production stage.

$$PA_j(n) = \text{Min}\left[DC_j(n), K_j - I_j(n-1), \{B_j(n-1)\}, P_j^{Max}\right] \tag{10}$$

$$\begin{aligned} PA_j(n) = \text{Min}\,[&DC_J(n), K_J - Max\,[0, I_J(n-1) - d(n)], \\ &\{B_j(n-1)\}, P_J^{Max}] \end{aligned} \tag{11}$$

3 Experimental Conditions

The models just described for each PCS were translated into discrete event simulation models using the simulation software eM-Plant from Tecnomatix. For the purposes of the experimental process the simulation run-time over which statistics were collected was $10,000$ periods with a warm-up period of $1,000$ periods and the simulation was ran for 10 replications. The performances of the PCS were evaluated for a total of seven different distributions for the demand event. The demand distributions used are detailed in subsection 3.1. The PCS were compared by conducting a partial enumeration of the solution space for their control parameters. A detailed description of the solution spaces evaluated for each PCS for each demand distribution is provided in subsection 3.2.

3.1 Demand Distributions

The seven demand distributions used are detailed in Table 3. Distribution No 1 is the original distribution for the demand process used by Hodgson and Wang [4]. All distributions have the same mean of 3.5 parts per period but the coefficient of variation increases from a low value of 14.29% to a high value of 42.86%. The mean demand represents a medium load on the system and is 87.5% of the mean production capacity of a production stage in the system. Additionally, for all distributions the value of the skewness is zero.

	$Pr[d_i]$							
No.	**2**	**3**	**4**	**5**	**Mean**	**Std Dev**	**Skewness**	**CV (%)**
1	0.00	0.50	0.50	0.00	3.5	0.5000	0.0000	14.29
2	0.05	0.45	0.45	0.05	3.5	0.6708	0.0000	19.17
3	0.10	0.40	0.40	0.10	3.5	0.8062	0.0000	23.04
4	0.15	0.35	0.35	0.15	3.5	0.9220	0.0000	26.34
5	0.25	0.25	0.25	0.25	3.5	1.1180	0.0000	31.94
6	0.35	0.15	0.15	0.35	3.5	1.2845	0.0000	36.70
7	0.50	0.00	0.00	0.50	3.5	1.5000	0.0000	42.86

Table 3: Description of Demand Distributions Examined

3.2 Search Spaces

The comparison of the strategies was achieved by conducting a partial enumeration of the control parameters of the five PCS examined. The search spaces for each PCS are described in Tables 4 to 6. For each simulation run the models of the individual PCS were initialised with inventory as described by Table 7.

3.2.1 Minimum Kanban Allocations for KCS and CONWIP/Pull

The minimum values for the Kanban allocations for both the KCS and CONWIP/Pull models were eight for each stage. This was selected since preliminary work indicated that values below this level significantly degraded the solution. For instance setting the Kanban levels of the input stages ($j = 1, 2$) equal to 7 always resulted in a service level of 0 regardless of the number of Kanbans allocated to the remaining stages for both KCS and CONWIP/Pull.

3.2.2 Kanban Allocations for EKCS

For the EKCS model it would have been impossible to conduct a partial enumeration of the solution space for all parameters (i.e. all possible combinations of Kanban and initialisation stock levels). The amount of computer time required would not have been feasible. For instance, suppose a partial enumeration of the solution space for the EKCS model were conducted with minimum values as detailed in Table 4 and maximum values for K_i and S_i equal to the maximum values for K_i for the KCS model given in Table 5. Over 90,000,000 hours of CPU time would have been required to conduct this experiment (based on 5.3 seconds per replication and 10 replications per iteration on a 1.8GHz Intel Pentium 4 Dell PC with 256Mb of RAM). Therefore, in order to minimise the time requirements a method had to be found to predetermine the Kanban distribution or the initialisation stock levels. Dallery and Liberopoulos [2] noted that the production capacity of the EKCS only depends on K_i and not on S_i; i =1, ... , N. They suggested that a reasonable design procedure for the EKCS could be to first design parameters K_i to obtain a desirable production capacity level, and subsequently design parameters S_i to obtain a desirable customer satisfaction level.

It seemed that a reasonable design for the Kanban allocation for the EKCS model might be the allocation that achieved 100% service level for the CONWIP/Pull model for the same demand distribution. Therefore, it is not claimed that EKCS was compared for optimality with the other PCS. Just that a reasonable design for EKCS was compared. Under CONWIP/Pull Kanbans are not allocated to the final stage since the maximum amount of inventory that can be in the output buffer of the final stage in any period is CC. Therefore, if it is desired to design the Kanban allocation for the EKCS such that it has at most the equivalent amount of inventory as a CONWIP/Pull line then the number of Kanbans to allocate to the final stage for the EKCS model would be the maximum inventory from CONWIP/Pull minus the minimum inventory to be allocated to the internal buffers in the EKCS design, i.e. $CC - 12$[1].

3.2.3 Minimum WIP Cap for CONWIP and CONWIP/Pull

Values below 16 for the CONWIP Cap, CC, resulted in service levels of less than 10% for both CONWIP and CONWIP/Pull.

3.2.4 Minimum Initialisation Stock Levels for BSCS and EKCS

The minimum value of four parts selected for the initialisation stocks (S_i) for both the BSCS and EKCS was selected because (i) the nature of the control strategies implies that the initialisation stocks must be greater than zero and (ii) mean demand for all distributions was greater than 3 and it was desired to initialise the buffers such that they could satisfy the mean demand.

Strategy	$\mathbf{K}_1$	$\mathbf{K}_2$	$\mathbf{K}_3$	$\mathbf{K}_4$	$\mathbf{K}_5$	**CC**	$\mathbf{S}_1$	$\mathbf{S}_2$	$\mathbf{S}_3$	$\mathbf{S}_4$	$\mathbf{S}_5$
KCS	8	8	8	8	8	-	-	-	-	-	-
CONWIP	-	-	-	-	-	16	-	-	-	-	-
CONWIP/Pull	8	8	8	8	-	16	-	-	-	-	-
BSCS	-	-	-	-	-	-	4	4	4	4	4
EKCS	8	8	8	8	8	-	4	4	4	4	4

Table 4: Minimum Values for the Parameters of Each PCS Examined

Strategy	$\mathbf{K}_1$	$\mathbf{K}_2$	$\mathbf{K}_3$	$\mathbf{K}_4$	$\mathbf{K}_5$	**CC**	$\mathbf{S}_1$	$\mathbf{S}_2$	$\mathbf{S}_3$	$\mathbf{S}_4$	$\mathbf{S}_5$
KCS	16	16	16	20	50	-	-	-	-	-	-
CONWIP	-	-	-	-	-	50	-	-	-	-	-
CONWIP/Pull	16	16	16	20	-	50	-	-	-	-	-
BSCS	-	-	-	-	-	-	12	12	12	16	50

Table 5: Maximum Values for the Parameters of Each PCS Examined excluding EKCS

No.	$\mathbf{S}_1$	$\mathbf{S}_2$	$\mathbf{S}_3$	$\mathbf{S}_4$	$\mathbf{S}_5$
1	10	10	15	9	13
2	10	10	15	11	17
3	10	10	12	14	23
4	11	11	14	12	23
5	13	13	16	13	25
6	10	10	13	12	31
7	13	13	15	12	35

Table 6: Maximum Values for the Parameters of EKCS for each Distribution

[1] CC is a component based inventory cap, therefore the internal inventory for a component in this parallel/serial model in period n is $I_1(n)+I_3(n)+I_4(\text{n})$ or $I_2(n)+I_3(n)+I_4(\text{n})$ and the value 12 is arrived at as $S_1^{min}+S_3^{min}+S_4^{min}$ or $S_2^{min}+S_3^{min}+S_4^{min}$

Strategy	I_1	I_2	I_3	I_4	I_5
KCS	K_1	K_2	K_3	K_4	K_5
CONWIP	0	0	0	0	CC
CONWIP/Pull	0	0	0	0	CC
BSCS	S_1	S_2	S_3	S_4	S_5
EKCS	S_1	S_2	S_3	S_4	S_5

Table 7: Initialisation levels for each Buffer under each PCS

4 Experimental Results

This section documents the results of the experimental procedure. The Service Level - WIP tradeoff is examined in subsection 4.1. Finally the inventory placements patterns of the individual PCS are examined and compared in subsection 4.2.

	CV(%)						
Policy	***14.29***	***19.17***	***23.04***	***26.34***	***31.94***	***36.70***	***42.86***
CONWIP	8.9	8.1	1.7	6.1	17.4	4.1	18.3
CONWIP/Pull	9.0	8.7	2.9	6.7	17.6	7.1	18.8
BSCS	7.8	7.1	0.9	5.3	16.8	3.6	17.9
EKCS	7.9	7.9	2.3	6.1	17.1	6.9	18.5

Table 8: Percentage Reduction in WIP Achieved Over KCS for 100% Service Level.

	CV(%)						
Policy	***14.29***	***19.17***	***23.04***	***26.34***	***31.94***	***36.70***	***42.86***
CONWIP	14.0	9.2	11.4	11.6	11.0	6.7	13.0
CONWIP/Pull	14.5	10.0	11.8	12.3	12.4	10.0	14.7
BSCS	12.8	8.1	10.4	10.8	10.4	3.7	12.6
EKCS	12.9	9.1	8.9	11.6	10.7	7.3	13.4

Table 9: Percentage Reduction in WIP Achieved Over KCS for 99.9% Service Level.

4.1 Service Level Vs. WIP Tradeoff

Table 8 and Table 9 summarise the average percentage reduction in minimum WIP requirements of CONWIP, CONWIP/Pull, BSCS and EKCS over KCS to achieve service levels of 100% and 99.9% respectively. Figures 2(a) and 2(b) show the minimum total inventory requirements for the PCS examined to achieve service levels of 100% and 99.9% respectively. As can be seen from these results CONWIP/Pull was consistently the best performer of the five PCS examined. For all demand distributions examined, there was a large difference in performance between KCS and the other PCS, in terms of minimum WIP required to achieve a given service level. That is with the exception of distribution 3 for 100% service level, where the difference between KCS and the other PCS reduced to between 1 and 3%. A small, but significant difference in performance between CONWIP and BSCS was noted, with CONWIP requiring on average 0.5% to 1.0% less WIP than BSCS to achieve the same service level.

4.2 Inventory Placement

Figures 2(c) and 2(d) summarise the minimum average internal inventory levels maintained by each PCS to achieve 100% and 99.9% service levels respectively. Internal inventory refers to semi-finished WIP and therefore, for the five-stage parallel/serial line examined this was the sum of the inventories maintained in buffers I_1, I_2, I_3 and I_4. As can be seen from these figures CONWIP/Pull and CONWIP maintained consistently less internal inventory than the other PCS. As co-efficient of variation of the demand distribution increased, CONWIP/Pull required increasing lower internal inventory than CONWIP to maintain the same service level.

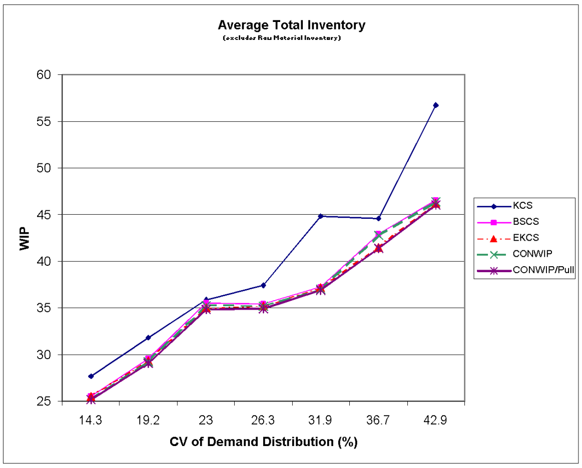
External inventory is the amount of inventory maintained in the finished goods buffer and, therefore was the inventory maintained in buffer I_5. Figures 2(e) and 2(f) summarise the minimum average external inventory levels maintained by each PCS to achieve 100% and 99.9% service levels respectively. CONWIP/Pull and CONWIP maintained on average a larger external (finished goods) inventory level than the other PCS examined. There was minimal difference between CONWIP/Pull and CONWIP with regards to external inventory levels. For $CV \geq 26.34\%$ and a service level of 99.9%, KCS maintained at least the same if not more external inventory than BSCS and EKCS. A similar, although slightly more erratic, performance was noted for a service level of 100%. However, KCS consistently required much larger internal inventory levels than BSCS and EKCS, which as can be seen from Figures 2(a) and 2(b) resulted in BSCS and EKCS outperforming KCS in terms of the total WIP - service level trade-off. Examination of Figures 2(c) to 2(f) also shows that EKCS and BSCS maintained on average more internal inventory and less external inventory than CONWIP and CONWIP/Pull.

5 Discussion

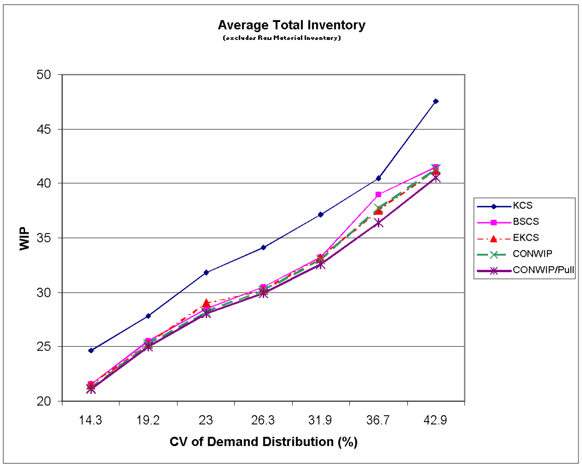
Overall, KCS was least effective PCS in addressing the WIP - Service Level trade-off. There was minimal difference between the other four PCS. The good performance of these four PCS over KCS is due to the manner in which demand information is used by the policies. In a KCS system demand information gradually travels back up-stream, one stage each period, until it reaches the initial stages. The other four policies instantly inform the initial stages of a demand event when it occurs. CONWIP and CONWIP/Pull achieve this through the CONWIP Cap and BSCS and EKCS achieve it through the use of demand cards that are instantly passed to each stage when a demand event occurs. Therefore, the poorer performance of KCS relative to the other four PCS is primarily due to information delay. As can be seen from Figures 2(c) and 2(d) KCS requires significantly more inventory to be maintained internally in the line to buffer against the information delay.

CONWIP/Pull is much more complex to design, implement and maintain than CONWIP. This may result in increased costs that are not addressed by the WIP - Service Level trade-off. We therefore, feel that while CONWIP/Pull may result in the best trade-off between WIP and Service Level it may be much more efficient and economical to implement CONWIP in preference to CONWIP/Pull. Since CONWIP is a subset of CONWIP/Pull in which all the kanban levels are infinitely large it should be possible to implement CONWIP/Pull in a phased manner as part of a continual improvement program by initially implementing and perfecting CONWIP and gradually experimenting with the introduction of Kanbans.

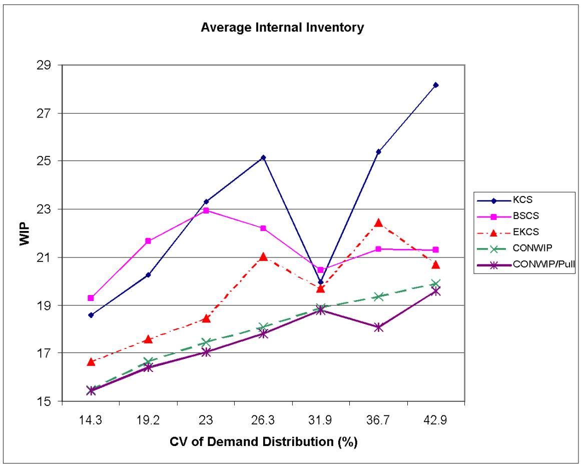
The performance of EKCS was, on average similar to that of CONWIP and CONWIP/Pull in addressing the Total WIP - Service Level trade-off. However, both EKCS and BSCS maintained on average more internal inventory and less external inventory than CONWIP and CONWIP/Pull. Therefore, while the average performance of the policies for Total Inventory were similar, the policies differed in terms of inventory placement. A policy that places more of given amount of inventory in the external/finished goods buffer provides greater flexibility in dealing with unexpected increases in the demand rate. It also has been noted that at no time was an



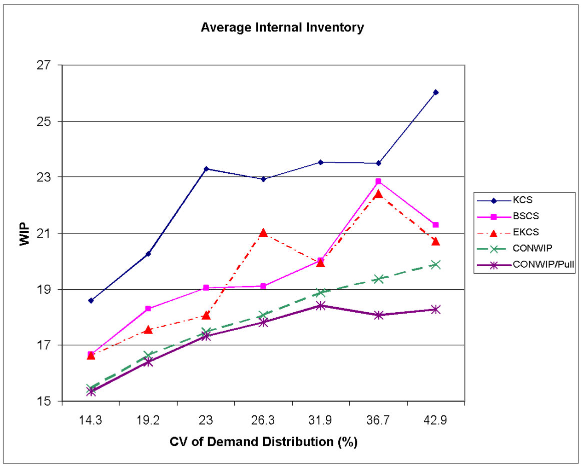
(a) Total Inventory — 100% Service Level



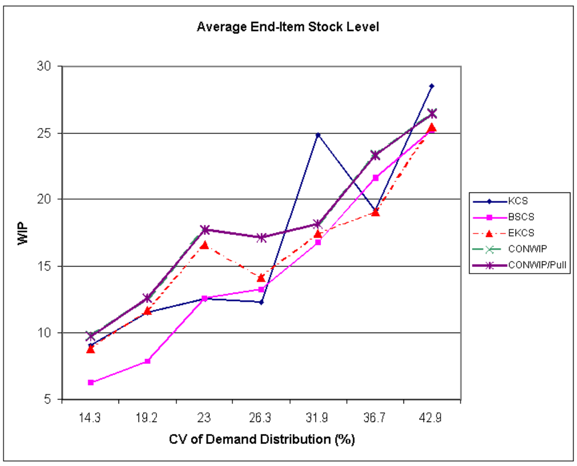
(b) Total Inventory — 99.9% Service Level



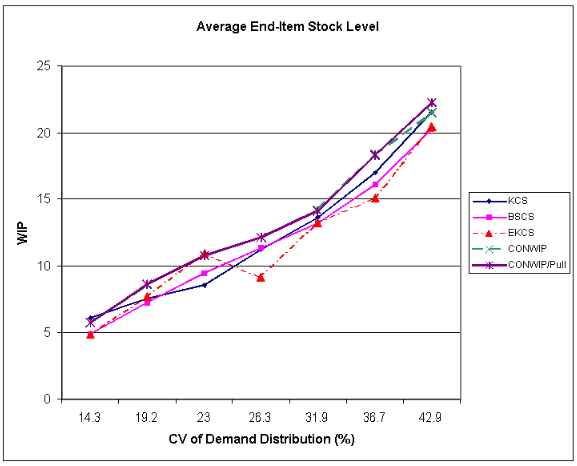
(c) Internal Inventory — 100% Service Level



(d) Internal Inventory — 99.9% Service Level



(e) External Inventory — 100% Service Level



(f) External Inventory — 99.9% Service Level

Figure 2: Average Internal/External Inventory required to meet specified service level

optimal EKCS policy compared against the other PCS examined. However, instead it is felt that a reasonable design for EKCS was used for each demand distribution. In comparision to CONWIP and CONWIP/Pull and even BSCS the design of a good/optimal EKCS policy is much more difficult. It is felt that EKCS adds complexity that is not justified by performance.

Three outliers can be readily observed from the results given in Table 8 and Figure 2(a). Firstly, for $CV = 23.04\%$ (and Service Level = 100%) the performances of CONWIP, CONWIP/Pull, BSCS and EKCS relative to that of KCS dramatically disapproved in comparison to their relative performances at other values for CV (and Service Level). As can be seen from Figure 2(e) the average external inventories (or finished goods inventories) of all four policies increased dramatically for $CV = 23.04\%$. In addition, from Figure 2(c) it can be seen that this increase was not accompanied by proportionally similar decrease in internal inventory. The second and third outliers are the performances of KCS for $CV = 31.94\%$ and $CV = 42.86\%$. In both instances KCS required a lot more inventory to achieve a 100% Service Level than the remaining four PCS relative to its comparative requirements at other values for CV. As can be seen from Figure 2(e) the average external inventory for KCS for both distributions for the demand event increased dramatically relative to the trend observed for the other five distributions. For $CV = 31.94\%$ as can be seen from Figure 2(c) the increase in external inventory was accompanied by a decrease in internal inventory. However, the decrease in internal inventory was not sufficient to compensate for the increase in external inventory. For the demand distribution where $CV = 42.86\%$, there was no accompanying decrease in internal inventory. Therefore, KCS performed comparatively worse against the other four PCS for these demand distributions ($CV = 31.94\%$ and $CV = 42.86\%$) than for other demand distributions. Further investigation of the data and possibly further experimentation will be required to determine causes for these outliers.

For all policies minimum inventory requirements to achieve a given Service Level increased as the CV of the demand distribution increased. With the exception of the outliers mentioned above, no other effect of CV of the demand distribution was noticed on the comparative performances of the policies. For instance it was not shown that as CV increases the magnitude of the difference in performance between any two policies increases.

Finally it is worth noting that the experimental results presented here are for a situation where average demand represents a medium load on the system. As a further extension to this work, we will examine the comparative performances of all five PCS for demand distributions that represent a heavier load on the system. We will seek to determine what effects co-efficient of variation has on the choice of and performances of PCS as the mean demand approaches the capacity of the system. In addition, by comparison to the results presented here, we will seek to determine whether mean demand influences choice of and performances of PCS.

6 Conclusions

CONWIP/Pull has been shown to be the best PCS in terms of minimising average WIP to obtain a given Service Level. However, while the improvement in performance over KCS was dramatic, the improvement over CONWIP, EKCS and BSCS was minimal. It may be that the implementation of CONWIP/Pull would not be justified in terms of performance improvement over the less complicated (and less costly) CONWIP. As suggested earlier, a policy for an organisation might be to pursue implementation of CONWIP/Pull through a continuous improvement programme by initially implementing CONWIP and gradually introducing Kanbans internally to the line.

The effect of the co-efficient of variation of the demand distribution was to correspondingly increase or decrease the minimum inventory requirements of each policy to achieve a targeted Service Level. There was no change in the magnitude of the differences in performance between policies relative to direction of change in CV of the demand distribution. It is noted however, that the mean demand was a medium load on the system and that different results might be obtained if the mean demand represented a heavier load. Further work is being conducted to determine what the influence of mean demand might be on the choice of policy and on relative performances of policies and whether CV will influence the magnitude of the differences between policies at heavier system loads. Finally, some outliers in the results have been noted and as yet remain to be fully explained.

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