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PERFORMANCE COMPARISON OF MULTIPLE PRODUCT KANBAN CONTROL SYSTEMS

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ABSTRACT

Kanban control systems have been around for decades and have been used to control work-in-process of manufacturing systems. Lately many variations of the basic control system have been developed; however much of the work in the development and comparison of control systems has focused on a single stage manufacturing system producing a single product type.

In this research we present optimization procedures for multiple product kanban control systems, such as Base Stock, Traditional Kanban Control System and Extended Kanban Control System (both dedicated and shared type). We then conduct a detailed simulation study to compare the performance of the systems using a common total cost measure. Numerical results show that the dedicated and shared extended kanban control systems outperform the other two systems. The study also shows that, inspite of their different schematics and contrary to conventional wisdom, the performance of dedicated and shared extended kanban control systems doesn't differ much.

Keywords: Kanban control system; multiple products; base-stock; traditional kanban control; extended kanban control.

1. INTRODUCTION AND LITERATURE REVIEW

Just-in-time (JIT) production control philosophy gained considerable traction in the late 1970s, its implementation facilitated by the use of kanbans. Kanbans are production authorization cards (PACs) that signal to upstream stations the appropriate time to replenish stock of downstream stations. Kanbans travel with a batch of products/components as it continues its journey through various stages of manufacturing. Upon receipt of a customer order (or order from a downstream station) the lot is sent to the customer/downstream station, its kanban is detached and transferred upstream to re-initiate the production process. Kanbans thus become the only way to control work-in-process (WIP) and to authorize upstream stations to initiate production of a new lot to replenish the downstream stock.

Several empirical studies have documented the potential of kanban control to significantly improve operations (Fullerton & McWatters, 2001; White et al., 1999). The main advantage of a kanban control system (KCS) is its simplicity: in a kanban system, the number of kanbans determines the number of full containers (of parts) that circulate in the system (Monden, 1998). Since full containers must always have a kanban attached to them and those kanbans can be removed only when a container is depleted, the number of kanbans also represents the WIP in the system.

Many different versions of kanban systems have been discussed in the literature (Buzacott & Shanthikumar, 1993; Gershwin, 2000; Liberopoulos & Dallery, 2002). For the sake of simplicity most researchers analyse kanban systems with one product (Aghajani et al., 2012; Al-Tahay et al., 2012; Diaz & Ardalan, 2010; Moran & Brayer, 2010). A number of analytical procedures have also been proposed but they are all for systems processing a single product either at a single stage (Di Mascolo, 1996; Jordan, 1988; Kim & Tang, 1997; Nori & Sarker, 1998; So & Pinault, 1988; Wang & Hsu-Pin, 1991), or at multiple stages (Bonvik et al., 2000; Buzacott & Shanthikumar, 1993; Deleersnyder et al., 1992; Di Mascolo, 1996; Fujiwara et al., 1998; Gstettner and Kuhn, 1996; Karmarkar, 1986; Siha, 1994; Siha & David, 1994; So & Pinault, 1988; Tayur, 1993). Despite the fact that kanban systems in industry control the production of several products in a single manufacturing facility (Anupindi & Tayur, 1998; Krieg & Kuhn, 2002), only one researcher has discussed different forms of Multiple Product Kanban Control Systems (Baynat et al., 2002). In addition, hardly any

approaches exist to guide the control of a Single Stage, Multiple Product Kanban System (Askin et al., 1993; Krieg, 2005; Krieg & Kuhn, 2002, 2004).

Various types of KCS have been introduced in the literature the notable ones being:

1. Traditional Kanban Control System (TKCS) (Sugimori et al., 1977)
2. Constant Work-In-Process (CONWIP) system (Spearman et al., 1990)
3. Generalized Kanban Control System (GKCS) (Buzacott, 1989)
4. Extended Kanban Control System (EKCS) (Dallery, 2000)
5. Extended CONWIP Kanban system (ECKS) (Boonlertvanich, 2005)
6. Flexible Kanban System (FKS) (Gupta et al., 1999)
7. Adaptive Kanban System (AKS) (Tardif & Maaseidvaag, 2001)
8. Reactive Kanban System (RKS) (Takahashi et al., 2004)
9. Knowledge Kanban (KK) (Lin et al., 2013)
10. E-Kanban (Al-Hawari and Aqlan, 2012)

One novel KCS is Extended Kanban Control System (EKCS) which is a hybrid of the TKCS and the Base Stock. Dallery (2000) was the first to propose this system but only discussed a single product version; Baynat et al., (2002) then introduced the multi-product version. Ang and Piplani (2010) conduct a performance comparison of Single Stage, Single Product Kanban Control Systems (SS/SP/KCS) including EKCS. Using simulation they show that Extended-KCS outperforms Traditional KCS and Base-stock, but only under specific conditions of low utilization rate and low backorder and shortage costs. TKCS still performs very well whereas BS performs the worst. This is the only work to date that has conducted a comprehensive study of kanban control systems for a single stage and a single product.

In this research, we extend the work of (Ang & Piplani, 2010) and conduct a detailed study of the following control systems, modeled as a single-stage, but producing multiple products:

- Base Stock (SS/MP/BS),
- Dedicated-Traditional Kanban Control System (SS/MP/De-TKCS),
- Shared-Extended Kanban Control System (SS/MP/Sh-EKCS), and
- Dedicated-Extended Kanban Control System (SS/MP/De-EKCS).

In the literature, two kinds of MP/TKCS have been proposed: dedicated and shared; however, they have proven to be equivalent (Baynat et al., 2002). Thus, in this research only the

dedicated version is considered and in further discussion the system is simply termed as SS/MP/TKCS.

The rest of the paper is organized as follows: base-stock and three kanban control systems being the focus of this research, section 2 contains a schematic and discussion of the base-stock system, followed by a discussion of the three KCS in section 3. Section 4 then presents optimization procedures for optimizing the four systems, which is followed by a simulation study in section 5 that compares the four systems using a common total cost measure. Section 6 presents the conclusions and future work.

2. SINGLE STAGE, MULTIPLE PRODUCT BASE STOCK SYSTEM (SS/MP/BS)

Figure 1 shows the schematic of SS/MP/BS system for 2 product types. In initial state of the system, buffers B_0^1 and B_0^2 have infinite component parts, B_1^1 and B_1^2 have base stock levels S_1^1 and S_1^2 , respectively; all the other queues are empty. When a customer demand arrives, it is instantaneously transmitted to the two demand queues, D_1^j and D_2^j , for product type 'j'.

The MP/ BS system operates as follows: when a customer demand for part type j arrives at the system, it is duplicated and immediately transmitted to its respective queues D_1^j . The last one joins the Queue D_2^j requesting the release of a finished product from B_1^j to the customer.

At this time there are two possibilities:

- a. A part is available in B_1^j , and is released immediately to the downstream stage; MP then begins producing a part to top up the base stock S_1^j in B_1^j .
- b. No part is available in B_1^j the demand is backordered and waits in Queue D_2^j until a new part is completed by the MP.

Whenever the base-stock level in B_1^j drops below S_1^j the MP begins to produce another lot, drawing the components from the the buffer B_0^j which are assumed to contain infinite components. Thus the system operates on one-for-one lot replacement basis, continuously striving to maintain the base-stock in B_1 buffers.

Figure 1: Single Stage, Multiple Product Base Stock (SS/MP/BS) System (Baynat et al., 2002)

3. SINGLE STAGE, MULTIPLE PRODUCT, KANBAN CONTROL SYSTEM (SS/MP/KCS)

In this section, we first present three kanban control systems: traditional KCS followed by the dedicated and shared versions of extended KCS. In all these control systems, Buffer B_0^j is the component buffer and is assumed to contain infinite number of component parts.

3.1. SINGLE STAGE, MULTIPLE PRODUCT, TRADITIONAL KANBAN CONTROL SYSTEM (SS/MP/TKCS)

Figure 2 displays the schematic of a Traditional KCS for multiple products, where kanban movement is shown by the dashed lines. When the system is in its initial state, B_1^j contains K_i^j finished parts, each with a stage i Kanban attached. All the other queues are empty. The system operates as follows: when a customer demand, for part type j arrives at the system it joins Queue D^j requesting the release of a finished product from B_1^j . At that time there are two possibilities:

- A part is available in B_1^j (which is initially the case), and is released to the customer after detaching its kanban. The detached kanban is moved upstream to K^j , where it

authorizes the production of a new part by pulling a component from buffer B_0^j .

- b. No part is available in B_1^j , the demand is backordered and waits in queue D^j until a new part is completed and arrives in B_1^j . The newly completed part is then released to the customer and the detached kanban is transferred upstream to queue K^j .

3.2. SINGLE STAGE, MULTIPLE PRODUCT, DEDICATED-EXTENDED KANBAN CONTROL SYSTEM (SS/MP/De-EKCS)

Figure 3 shows the process flow of a MP/De-EKCS; Buffer B_1^j is the output buffer for product type j and contains dedicated kanbans attached to finished products. Queue D_2^j contains incoming customer demands and queue K_1^j contains undispached kanbans. De-EKCS depends on two parameters per stage: number of undispached kanbans, K^j , and base stock level S^j . Initially, output buffer B_1^j contains S^j finished parts attached with dedicated kanbans and queue K_1^j contains K^j undispached kanbans. All the other queues are empty. The De-EKCS operates as follows:

1. When a customer demand for product type j arrives at the system, it is duplicated and transmitted to the two demand queues for the j^{th} product. If a part is available in output buffer B_1^j , it is released to the customer after detaching the dedicated Kanban, which is then transferred upstream to undispached kanban queue K_1^j ; otherwise the demand is backordered.
2. The duplicated demand signal that joins demand queue D_1 results in the undispached kanban from queue K_1^j being attached to a component from component buffer B_0^j .

This part is then released into the MP since all three, a component (infinite supply), demand signal and a Kanban, are available. However, if there are no undispached kanbans available, the demand signal waits. Since we assume that the component buffer (B_0^j) contains infinite number of components, the pre-requisite for MP to start producing a new lot is the availability of a demand signal in D_1^j and a Kanban in K_1^j .

Figure 2: Single Stage, Multiple Product, Traditional Kanban Control System (Adopted from SS/MP/TKCS)(Baynat et al., 2002)

Figure 3: Single Stage, Multiple Product, Dedicated-Extended Kanban Control System (SS/MP/De-EKCS) (Baynat et al., 2002)

3.3 SINGLE STAGE, MULTIPLE PRODUCT, SHARED-EXTENDED KANBAN CONTROL SYSTEM (SS/MP/Sh-EKCS)

In Figure 4, Buffer B_1^j is the output buffer for product type j and contains finished parts with kanbans attached. Queue D_1^j contains incoming customer demand and queue K_0 contains shared kanbans. Sh-EKCS depends on two parameters per stage: number of shared, undispatched kanbans, K , and base stock level S_1^j . The operation of shared-EKCS is similar to De-EKCS, except that the kanbans are shared and wait in a single queue K_0 .

Figure 4: Single Stage, Multiple Product, Shared-Extended Kanban Control System (SS/MP/Sh-EKCS) (Baynat et al., 2002)

4 Optimization of Kanban Control Systems (Single stage, Multiple Products)

For sake of tractability, in this research, the kanban control systems are assumed to control a single stage manufacturing process which processes two product types. Each MP contains only one server/machine and its processing rate is different for different product types. It is also assumed, without loss of generality, that product type 1 is the higher priority product.

4.1 MANUFACTURING PROCESS (MP) FOR SINGLE STAGE, MULTIPLE PRODUCT KANBAN CONTROL SYSTEM (SS/MP/KCS)

The detailed processing at a MP was first discussed by Baynat et al. (2002) who made no assumption about the internal processing of parts; the focus, instead, was on external routing. However, for a detailed simulation of the control systems, an understanding of the internal mechanism at the MP is also necessary.

4.2 M/M/1 with Priority Queues

Figure 5 shows the detailed arrival and processing operations at the server of an MP/KCS,

modeled as an M/M/1 server.

Figure 5: Manufacturing Process (MP) as an M/M/1 queue serving two product types with different arrival rates and priorities

The single server operates as per the following assumptions:

- Type 1 and 2 demands have Poisson arrival rates of λ_1 and λ_2 , respectively.
- Type 1 demand arrivals have higher priority.
- Type 1 and 2 demands have exponential service rates with mean μ_1 and μ_2 , respectively.
- There is no pre-emption of service.
- $\lambda_1 < \lambda_2$: Demand arrival rate of type 2 is higher than arrival rate of type 1. As part type 1 has higher priority in processing, this assumption is required to ensure that some part type 2 also get processed.
- $\lambda_1 < \mu_1$ and $\lambda_2 < \mu_2$ is a standard queuing theory assumption; arrival rate is lower than the processing rate for each part type.
- $\lambda_2 < \mu_1$: Demand arrival rate for type 2 is smaller than the processing rate for type 1. This assumption is required to prevent the system from getting overwhelmed with type 2 arrivals. Consider the alternative $\mu_1 < \lambda_2$: each time a type 1 product enters, it has priority for processing. Since it has a slower processing rate compared to type 2 arrivals, by the time its processing completes, the system would be overflowing with type 2 demands.
- $\lambda_1 < \mu_2$: Demand arrival rate for type 1 is smaller than service rate for type 2. This assumption is similar to the previous assumption and is needed to prevent the system from being overwhelmed with type 1 demands.

Since the fundamental queuing theory assumption requires that average demand arrival rate, λ_A , be lower than average service rate, μ_A , only the following two combinations satisfy all the assumptions listed above, and are considered in the rest of the paper:

- i. $\lambda_1 < \lambda_2 < \mu_1 < \mu_2$
- ii. $\lambda_1 < \lambda_2 < \mu_2 < \mu_1$

4.3 Average Manufacturing Process Rate

Since the processing rates for the two part types are different, average MP rate needs to be computed for use in the optimization of MP/KCS. Ross (2007) uses a general service time to compute the average arrival rate λ_A and distribution of arrivals as follows:

$$\lambda_A = \lambda_1 + \lambda_2 \quad (1)$$

$$G(x) = \frac{\lambda_1}{\lambda} G_1(x) + \frac{\lambda_2}{\lambda} G_2(x) \quad (2)$$

Equation (1) states the average arrival rate of two Poisson arrival rates, while Equation (2) shows the average arrival distribution of two independent arrival distributions. Equations (1) and (2) hold since the combination of two independent Poisson Processes is itself a Poisson Process whose mean is the sum of the means of the component processes. Simplifying equations (1) and (2) for exponential distribution leads to

$$\mu_A = \frac{\lambda \mu_1 \mu_2}{\lambda_1 \mu_2 + \lambda_2 \mu_1} \quad (3)$$

4.4 SS/MP/BS Optimization

The SS/MP/BS system is considered a dedicated system as products use separate component types and dedicated buffers. It is basically a combination of two dedicated single product systems as both demands and products are type specific. Thus the single product optimization methods can be used in the multiple product system, except that during the calculation of optimal base stock levels, S_1^* and S_2^* , the average MP rate needs to be used. In a multiple product base stock system, each type's optimal base stock can be computed individually (Zipkin, 2000).

Hopp and Spearman's (2008) method can be used to compute individual optimal base stock levels, S_1^* and S_2^* in the multi-product BS system. The required inputs are the individual demand arrival rates λ_i , and holding and backorder costs, C_{hi} and C_{bi} .

4.5 SS/MP/TKCS Optimization

Askin et al. (1993) optimized the SS/MP/TKCS using Markov chains. In this research, we modify their technique for improved computational efficiency.

$$\text{Minimize}_k ETC(k) = \frac{C_s(\lambda^k) + C_h \left[\sum_{x=1}^k x \left(\frac{k!}{(k-x)!} \lambda^{k-x} \rho^x \right) \right]}{\sum_{x=0}^k \frac{k!}{(k-x)!} \lambda^{k-x} \rho^x} \quad (4)$$

Equation 4 is the expression for the Expected Total Cost (ETC) for a MP/TKCS, developed by Ang (2013); the development is also shown in Appendix A. To find the minimum cost, exhaustive enumeration can be used where ETC is computed over the feasible range of K until $ETC(K+1) - ETC(K) \geq 0$.

4.6 SS/MP/De-EKCS Optimization

This section details a method to determine the optimal number of base stock, S^* , and kanbans, K^* , for each of the products in a SS/MP/De-EKCS. The proposed method is based on markov chains technique. The expression for ETC for SS/MP/De-EKCS can be written as (see Appendix B for its development):

$$\begin{aligned} ETC(S, K) &= C_h(I[S, K]) + C_s(E\{t_{stockout}\}) \\ &= C_h\left(S + \frac{K}{2}\right) + C_s\left(\frac{\lambda^{S+K}}{\sum_{x=0}^{S+K} \frac{(S+K)!}{(S+K-x)!} \lambda^{S+K-x} \rho^x}\right) \end{aligned} \quad (5)$$

To optimize eq. (5) with respect to S and K we again resort to exhaustive enumeration. However, optimization of MP/De-EKCS entails optimizing two parameters, S and K. Total holding cost (first term in Eqn. 5) is an increasing function of S and K. However, an upper bound for S and K exists from the total shortage cost (second term in Eqn. 5). We again adopt the strategy of incremental search (or exhaustive enumeration) to determine the optimal

parameters. Firstly, treating $(S+K)$ as the total WIP, we search for its optimum value that minimizes the total shortage cost. Then, we search through each combination of S and K that adds up to the optimal $(S+K)$ determined in the first step, and minimizes the total cost, leading to the optimal S^* and K^* pair.

4.7 SS/MP/Sh-EKCS Optimization

In dedicated kanban systems, for minimizing ETC, holding cost and shortage costs can be computed separately for each product type. Since kanbans are shared in a SS/MP/Sh-EKCS, the enumeration technique to obtain optimal S^* and K^* for dedicated EKCS cannot be used and obtaining an optimal shared K^* becomes difficult. In this section a new heuristic is developed to optimize the SS/MP/Sh-EKCS: the heuristic partitions the shared Queue K_0 into two parts, each to serve one of the two product types separately.

Total WIP in the the MP/Sh-EKCS system is $S_1 + S_2 + K$, where K represents the number of shared un-dispatched kanbans in the queue. Askin et al. (1993) and Ross (2007) discuss total number of jobs in process (or total WIP for all product types, $i = 1, \dots, m$) 'L' in an M/G/1 queue. Since Sh-EKCS can be modelled as an M/M/1 queue (an instantiation of the M/G/1 queue), $L = S_1 + S_2 + K$. The utilization rate of MP for product type 'i' can be written as λ_i / μ . Next, L is apportioned as per the utilization rate and the WIP assigned to the two product types, equal to $(S_1 + K_1)$ and $(S_2 + K_2)$. Note that K_1 and K_2 are not dedicated kanbans, but shared undispatched kanbans in the kanban queue K_0 . However, they are assigned the subscript 'i' as they represent the number of undispatched kanbans required to meet the demand for product type 'i'.

With the WIP for each product type computed, the expression for ETC can then be used to obtain S_i^* and K_i^* for each product type. ETC expression for Sh-EKCS is the same as De-EKCS. Finally, K_1^* and K_2^* are summed up to obtain the total shared K^* . The flow chart for optimizing Sh/EKCS is shown in Figure 6. Development of expected inventory level for MP/Sh-EKCS can be found in Appendix C.

Figure 6: Algorithm for optimizing SS/MP/Sh-EKCS

5 SIMULATION STUDY

Motivated by the practice of automobile platform sharing we next discuss a manufacturing system which would be the basis for comparison of the different KCS discussed in the previous section. An automobile platform is a vehicle's primary load-bearing assembly and determines a vehicle's size and links the driveline and suspension components (Diem & Kimberley, 2001) The benefits of sharing an automobile platform across different models, while still preserving the marque identity of the models, include potential savings from standardization. For instance, the platform shared between Peugeot and Citroen helped save

€0.4 billion in one project, while using a common platform for Volkswagen helped the company cut costs by €1 billion and speed up development of niche vehicles.

5.1 Simulation Data

This example refers specifically to the Volkswagen small passenger car platform A. A series of mini car models such as VW Golf, Audi A3 and Audi TT are based on this platform (Diem & Kimberley, 2001). Production of platform A is considered as single stage Manufacturing Process (MP) while the two vehicle types resulting from the same production stage refer to VW Golf and Audi TT models. Product type 1 (Audi TT) is the expensive product while product type 2 (VW Golf) is the cheaper product. The demand arrival rate for product type 1, λ_1 , is assumed to be 500 units per month while that for product type 2 (the inexpensive model) λ_2 , is 1200 units per month. This assumption is based on the Volkswagen platform production in 2000 where the production for VW Golf was far greater than Audi TT (Diem & Kimberley, 2001). Being the more economical car, the sales forecast for VW Golf was higher than for Audi TT; therefore we assume that the demand arrival rate for VW Golf is higher than Audi TT.

Next, the processing (MP) rate for product type 1, μ_1 , is set at 1,800 units per month, while the rate for product type 2, μ_2 , is 2,000 units per month. The values of $\lambda_1, \lambda_2, \mu_1, \mu_2$ are chosen so that the queuing theory assumptions of Section 4.1 hold.

The holding cost for product type 1, C_{h1} , is assumed to be \$1,000 per unit per month, while C_{h2} , for product type 2 is set at \$500 per unit per month. Holding cost for the Audi TT is twice that for the VW golf as Audi TT is considerably more expensive due to the cost of electronics used in the Audi TT's engine and transmission system (Diem & Kimberley, 2001). The shortage cost for product type 1, C_{s1} , is assumed to be \$10,000 per unit per month, while shortage cost for product type 2, C_{s2} , is assumed to be \$2,000 per unit per month.

The data used in this study is summarized in Table 1. The MATLAB code for optimization of different KCS and the resulting plots can be found in Ang (2013).

To compare the four KCS (BS, TKCS and De-EKCS and Sh-EKCS) using a common platform and using similar testing conditions, we make use of simulation modeling. We cannot use the closed form solution of their Expected Total Cost (ETC) for performance comparison as expression for each KCS is developed using a different set of parameters.

Table 1: Input parameters for the manufacturing example

Product Type 1 (Audi TT)				Product Type 2 (VW Golf)			
λ_1 (units/ time)	μ_1 (units/ time)	C_{h1} (\$/unit/ time)	C_{s1}, C_{b1} (\$/unit/ time)	λ_2 (units/time)	μ_2 (units/time)	C_{h2} (\$/unit/time)	C_{s2}, C_{b2} (\$/unit/time)
500	1,800	1,000	10,000	1,200	2,000	500	2,000

In the simulation study, the performance of different KCS is measured by Actual total cost (ATC) which comprises of total backorder cost, shortage cost and holding cost. The performance measures (such as the number of backorders and expected shortage time) required for the computation of the three cost components are easily obtained using the model developed in a simulation software.

$$\text{Actual Total Cost (ATC)} = (\text{Average inventory level} \times C_{hi}) + (\text{Number of backorders} \times C_{bi}) + (\text{Expected shortage time} \times C_{si}).$$

In line with the two cases mentioned in Section 4.2, two scenarios are simulated: processing rate of product type 1 slower than product type 2, and vice versa. However, first the average demand arrival rate, λ_A , and the average MP rate, μ_A , have to be calculated. Then, the percentage average utilization (λ_A/μ_A) is used to determine how “busy” the system is. Table 2 shows the simulation parameters for SS/MP/KCS for the two scenarios described. The system is studied only over the 50 to 90% utilization range so as to test it in its ‘busy’ state.

5.2 Simulation Assumptions

The above described manufacturing system operating under control of different KCS is simulated in ARENA 11.0 software on a Windows platform. Assumptions made for simulation modelling of the SS/MP/KCS are:

- Only two product types are processed by the system.
- System consists of a single stage and one MP.
- The MP contains one server.

Table 2: Simulation parameters for SS/MP/KCS (50-90% utilization rate)

2A: Processing rate of product 1 slower than product 2

λ_1	λ_2	μ_1	μ_2	λ_A	μ_A	Utilization (%)
1	2	3	8	3	5	0.58
2	3	6	9	5	8	0.67
3	4	9	10	7	10	0.73
4	5	10	11	9	11	0.85
5	6	11	12	11	12	0.95

2B: Processing rate of product 1 faster than product 2

λ_1	λ_2	μ_1	μ_2	λ_A	μ_A	Utilization (%)
1	2	8	5	3	6	0.53
2	3	9	7	5	8	0.65
3	4	10	9	7	9	0.74
4	5	11	10	9	10	0.86
5	6	12	11	11	11	0.96

- Type 1 (expensive) demand has higher priority.
- Demand arrivals follow a Poisson Process.
- Processing times at MPs are assumed to be exponentially distributed.
- There is no pre-emption of service. If a type 2 demand is being served while a type 1

demand arrives, the type 2 demand completes its processing before type 1 demand is allowed to enter the MP.

- A one-card kanban system is adopted.
- Quality and yield issues are ignored.
- Setup times at the server are ignored as they are implicitly considered in the processing times.
- Server failures are ignored.
- The server can only process one part at a time.
- Transfer times for parts are considered negligible.
- Demand signals and kanbans flow through the system instantaneously.
- Component buffers contain an infinite supply of components.
- The simulation run length is one year, with a warm up period of three months.
- Each simulation is replicated 10 times.

5.3 Simulation Results

Figures 7 and 8 show the Actual Total Costs (ATC) for different Kanban Control Systems (KCS); Figure 7 presents the case ($\mu_1 < \mu_2$) while Figure 8 shows the results for the second case ($\mu_1 > \mu_2$).

Both cases show similar results: BS incurs the highest cost, followed by TKCS and Dedicated and Sh-EKCS. BS tends to keep high stock, resulting in very high total holding cost. Also, as the utilization increases, the total cost (and difference between different systems) increases.

Dedicated and Sh-EKCS outperform TKCS consistently by a gap of about 17% (on average \$1000) in both cases. The optimal number of dispatched kanbans for TKCS is, generally, a unit more than for Dedicated and Sh-EKCS (Ang, 2013). As TKCS consistently holds one more unit of stock, its total cost is higher. But with one extra unit of stock, the average customer waiting time for TKCS is lower. However, lowering the customer waiting time does not reduce ATC as much as lowering the inventory does, which costs \$10 per unit. So even though Dedicated and Sh-EKCS have slightly longer customer waiting times, their undispached kanbans help to lower their total cost. Overall, the results show that Dedicated and Sh-EKCS outperform the other two systems.

Figure 7: Performance comparison of SS/MP/KCS ($\mu_1 < \mu_2$)

Figure 8: Performance comparison of SS/MP/KCS ($\mu_1 > \mu_2$)

The interesting finding here is that the performance of Dedicated and Sh-EKCS is quite similar, with their total costs having a difference of no more than 2.5%. Further comparison of dedicated and shared Extended-KCS is carried out over the range of low server utilization

(10 to 50%): once again no significant difference between the two variations of EKCS is found.

From Figure 4 we see that when a customer order arrives a shared kanban acts as though it is “dedicated,” as the MP can only process one product at a time and the product with the highest priority is served first. Despite the fact that shared kanbans are pooled together in the shared kanban queue, they act as if they have been *pre-assigned* to a particular product. Consider the following:

- (i) Assume that S_1^1 and S_1^2 each have 1 base stock (and an attached kanban) in their respective output buffers B_1^1 and B_1^2 . Also, in order to see the effect of shared kanbans being effectively *dedicated*, let us assume that the kanban queue K_0 is empty and the MP is processing a part.
- (ii) Assume now that one customer demand for product type 2 arrives followed shortly (but before MP finishes its processing) by a demand for product type 1. Instantaneously, each demand is satisfied with the products on hand, while each of their kanban is detached and sent back to the shared kanban queue K_0 . Take note the kanbans are not *dedicated*, but can be shared by any product.
- (iii) However, upon entering queue K_0 , these two kanbans are immediately attached to a respective component part, and wait for processing by the MP (in order of priority).
- (iv) Since the priority rule states that product 1 has precedence over product 2, it is processed first. Hence, despite the fact that the two kanbans are *shared*, the priority rule ensures that the customer demand arrivals result in a kanban *dedicated* to a type.

This scenario shows that in a single stage manufacturing system even if the kanbans are shared, the priority rule ensures that the kanbans are effectively dedicated in the ratio of demand arrivals.

6 CONCLUSION AND FUTURE WORK

In this research, the performance of different types of Single Stage, Multiple Product Kanban Control Systems is compared. We first discuss the operations of different KCS with the help of their schematics. We also present algorithms to optimize the parameters of the control systems. The algorithms are coded in MATLAB to obtain optimal parameters for the different kanban control systems, namely S^* for BS, K^* for TKCS and S^* and K^* for EKCS.

Finally, in order to make a comprehensive and fair comparison of the different KCS, we develop simulation models and compute actual total cost for each system by simulating its operations. Data used for simulation modeling is based on a real-life case of Volkswagen 'Platform A' manufacturing.

Simulation experiments shows that dedicated and shared EKCS outperform the rest, with BS performing the worst, whereas the performance of TKCS lies in the middle. The most interesting finding is that performance of dedicated and shared EKCS does not differ much in the single-stage system. Extensive simulation experiments have shown that their operating characteristics are similar inspite of slight differences in their schematics. This is an intriguing insight from our study.

This research can be further extended to case of multiple stages, similar to the Simultaneous EKCS (Chaouiya et al., 2000); it is likely that in the multiple stage case the difference between the performance of dedicated and shared EKCS may come to life.

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APPENDIX A

Expected Total Cost for SS/MP/TKCS

Askin et al. (1993) first optimized a Kanban control system, deriving the expression for the Expected Total Cost (ETC) using Markov Chains and then finding the lowest ETC by exhaustively searching over K .

$$\underset{k}{\text{Minimize}} ETC = \sum_{j=1}^m \left\{ C_{hj} \sum_{x=0}^{k_j} x p_j(x) + C_{sj} \sum_{x=-\infty}^{-1} p_j(x) \right\} \quad (A1)$$

ETC comprises of two components: expected holding cost and expected shortage cost. Their method is computationally intensive as expected total shortage cost (ETSC) is based on the sum of the steady state probabilities of backorders

$$ETSC = \sum_{j=1}^m \left[C_{sj} \sum_{x=-\infty}^{-1} p_j(x) \right] \quad (A2)$$

The computation of the shortage cost requires the long run probability, $\pi_i(x)$, of different number of backorders. In order to simplify the computation, we replace the sum of the backorder probabilities by the long run probability of a stock out, since in kanban systems the shortage cost per unit time is more meaningful than the backorder cost per unit (Nori & Sarker, 1998; Wang & Hsu-Pin, 1991).

$$ETSC = \sum_{j=1}^m \left[s_j \pi_j(0) \right] \quad (A3)$$

In addition, the original Markov chain used by Askin et al. (1993) has been shortened, increasing the computational speed. The modified ETC equation for a MP/ TKCS can thus be written as

$$\underset{k}{\text{Minimize}} ETC = \sum_{j=1}^m \left\{ C_{sj} \pi_j(0) + C_{hj} \sum_{x=0}^{k_j} x \pi_j(x) \right\} \quad (A4)$$

As noted by Askin et al. (1993) each k_i can be solved for separately (as it is dedicated), and the subscript j omitted. The optimal number of kanbans for each product type is found by optimizing ETC. For a specific product type, the ETC optimization can be expressed as:

$$\text{Minimize}_{\mathbf{k}} ETC = C_s \pi_0 + C_h \sum_{x=1}^k x \pi_x \quad (\text{A5})$$

To obtain the optimal number of kanbans, K^* , first the output buffer of the particular product type is modelled as a Markov chain.

$$\mu_A = \frac{\sum_{j=1}^m \lambda_j}{\sum_{j=1}^m \lambda_j t_j} \quad (\text{A6})$$

The total number of jobs in process (or total WIP for all product types, $j = 1, 2, \dots, L$, for an M/G/1 model (Askin et al., 1993; Ross, 2007) is expressed as

$$L = \frac{D^2 / \mu_A^2}{(1 - D / \mu_A)} + \frac{D}{\mu_A} \quad (\text{A7})$$

To compute π_0 and π_x , we look at how the system transitions between states. Figures A1 (a) to (c) show the state space transition diagrams for the output buffer of a SS/MP/TKCS. They reflect the system transitions from state $\pi(x)$ to $\pi(x-1)$ at the rate λ (demand from successors). The system changes from state $\pi(x)$ to $\pi(x+1)$ whenever a job finishes at the MP. There are L jobs in process, service completions occur at the rate μ_A , and the probability a completion is of type 'j' is equal to the proportion of jobs that are of type 'j'. If x is the actual on-hand inventory, this proportion is $(k - x) / L$ and the corresponding processing rate is $(k - x) / L * \mu_A$.

Generalization leads to the denominator of π_0 becoming

$$\sum_{x=0}^k \frac{k!}{(k-x)!} \lambda^{k-x} \rho^x \quad (\text{A8})$$

Figure A1 (a): Left side of Markov chain for MP/TKCS

Figure A1 (b): Middle Markov chain for MP/TKCS

Figure A1 (c): Right side of Markov chain for MP/TKCS

Finally, after applying induction and substituting the relevant equations into (A5), we can write the cost optimization expression as

$$\underset{k}{\text{Minimize}} ETC(k) = \frac{C_s(\lambda^k) + C_h \left[\sum_{x=1}^k x \left(\frac{k!}{(k-x)!} \lambda^{k-x} \rho^x \right) \right]}{\sum_{x=0}^k \frac{k!}{(k-x)!} \lambda^{k-x} \rho^x} \quad (\text{A9})$$

APPENDIX B

Expected Total Cost for SS/MP/De-EKCS

Equation (B1) shows the expected total cost, ETC (S_i, K_i), for MP/De-EKCS. It is the sum of the total expected inventory holding and shortage costs.

$$\begin{aligned} ETC(S_i, K_i) &= \text{Total Inventory Holding Cost} + \text{Total Shortage Cost} \\ &= \sum_{i=1}^m \left[C_{h_i} (I[S_i, K_i]) + C_{s_i} (E\{t_{stockout_i}\}) \right] \end{aligned} \quad (B1)$$

As the kanbans are dedicated, each k_i can be solved separately (Askin et al., 1993), and the subscript ‘i’ omitted. The optimal S^* and K^* for each product type can be found by obtaining the lowest ETC separately. Hence, ETC expression for one specific product type can be written as

$$ETC(S, K) = C_h (I[S, K]) + C_s (E\{t_{stockout}\}) \quad (B2)$$

B1 Expected Inventory Level, $I[S, K]$

The expected inventory level, $I[S, K]$, of MP/De-EKCS represents the expected number of parts, of that particular type, in the MP as well as in the output buffer. In EKCS, kanbans can only be present in one of three places: the undispached kanban queue, K_i , in MP, or attached to stock in output buffer, B_i . Thus,

$$I[S, K] = (S+K) - E[K] \quad (B3)$$

$$E[K] = K - \frac{\rho(K+S)}{K+S+1-\rho(K+S)} + \frac{\left(\rho \left[\frac{K+S}{K+S+1} \right]\right)^{K+S+1}}{1-\rho \left[\frac{K+S}{K+S+1} \right]}, \text{ is the expected number of}$$

undispached kanbans in the kanban queue for the particular product type (Ang, 2013).

As the two-product Dedicated EKCS behaves similar to the single product case, it is possible to split the system into two parts and optimize each part separately.

B2 Expected Time Value of Stock-out, $E\{t_{\text{stock-out}}\}$

In EKCS $E\{t_{\text{stock-out}}\}$ represents the expected time value of stock-out in the output buffer, B_1 of a particular product. $E\{t_{\text{stock-out}}\}$ can be denoted by π_0 , which is the long run average probability of time spent in state '0'.

The state space of the Markov chain is developed around the output buffer of the particular product type. Figure B1 shows the state space transition diagrams for the output buffer of SS/MP/De-EKCS. It reflects the system transitions from state $\pi(x)$ to $\pi(x-1)$ at the rate λ (demand from successors). The system changes from state $\pi(x)$ to $\pi(x+1)$ whenever a product finishes processing at the MP. The assumption is that L jobs are in process, service completions occur at the rate μ_A and the probability a completion is of type j is equal to the proportion of in-process jobs of type j . If x is the actual on-hand inventory, this proportion is $(S+K - x) / L$ and the processing rate would be $(S+K - x) / L * \mu_A$.

Next, Ramakumar (1993)'s standard technique for stochastic processes is used to develop a coefficient matrix S . The coefficient matrix and Markov differential equations are used to generalize the steady state equations. Finally, the expected long run stock out probability, π_0 , is obtained by means of induction. π_0 , or $E\{t_{\text{stock-out}}\}$, can be expressed as

$$E\{t_{\text{stockout}}\} = \frac{\lambda^{S+K}}{\sum_{x=0}^{S+K} \frac{(S+K)!}{(S+K-x)!} \lambda^{S+K-x} \rho^x} \quad (\text{B4})$$

Both MP/TKCS and De-EKCS have the same expected time value of a stock-out in their output buffers, B_1 . In other words, the Markov chains for both are similar since their arrival and departure rates between states are identical.

B3 Expected Total Cost for SS/MP/De-EKCS

After substituting Eqns. (B3) and (B4) into the expression for ETC, and simplifying, we get

$$\begin{aligned} ETC(S, K) &= C_h (I[S, K]) + C_s (E\{t_{\text{stockout}}\}) \\ &= C_h (S + E[K_1]) + C_s \left(\frac{\lambda^{S+K}}{\sum_{x=0}^{S+K} \frac{(S+K)!}{(S+K-x)!} \lambda^{S+K-x} \rho^x} \right) \end{aligned} \quad (\text{B5})$$

Figure B 1a: Left side of Markov chain for MP/De-EKCS

Figure B 1b: Middle of the Markov chain for MP/De-EKCS

Figure B 1c: Right side of Markov chain for MP/De-EKCS

APPENDIX C

Expected Inventory Level for SS/MP/Sh-EKCS

The ETC formulation for a Sh-EKCS is the same as De-EKCS as shown in equation (B1). Total WIP for each product can be obtained separately ($S_i + K_i$; where $i = 1, 2$) (Askin et al., 1993) and hereafter the subscript ‘i’ is omitted. The optimal S^* and K^* for each product type are found by optimizing ETC for each type.

C1 Expected inventory level, $I [S_i, K_i]$

$I [S_1, S_2, K]$ refers to the total WIP of all the product types, both in the MP and the output buffer, B_1 .

$$I [S_1, S_2, K] = L - E [K_1] \quad (C1)$$

where L is the total WIP for all product types in Sh-EKCS. Thus, $L = S_1 + S_2 + K$, and, $E [K]$ is the expected total number of undispached kanbans in the kanban queue.

If the state space of the Markov Chain is positioned on a kanban queue and the arrival rate into it is the same as the departure rate, the expected average number of kanbans in the queue would be $K/2$. In this case, since both the arrival and departure rates are equal to the average customer demand arrival rate into the shared kanban queue, λ , $E [K] = K/2$ holds.

Thus,

$$\begin{aligned} I [S_1, S_2, K] &= S_1 + S_2 + K - \frac{K}{2} \\ &= S_1 + S_2 + \frac{K}{2} \end{aligned} \quad (C2)$$

Since $K = K_1 + K_2$ (once again noting that K_1 and K_2 are not dedicated kanbans but shared kanbans in the shared kanbans queue K_0),

$$I [S_1, S_2, K] = S_1 + S_2 + \frac{K_1}{2} + \frac{K_2}{2} \quad (C3)$$

Now if $I [S_1, S_2, K]$ is separated according to its product type, then the Expected WIP for each product type can be expressed as

$$I[S_i, K_i] = S_i + \frac{K_i}{2} \quad (\text{C4})$$

Thus the expected inventory level for Sh-EKCS is the same as De-EKCS.

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