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# Performance comparison of multiple product kanban control systems

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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 procedures for optimising multiple product kanban control systems, namely 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 in spite 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 authorisation 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 batch is sent to the customer/downstream station, its kanban is detached and transferred upstream to reinitiate the production process. Kanbans thus become the only way to control work-in-process (WIP) and to authorise upstream stations to initiate production of a new batch to replenish the downstream stock.

Several empirical studies have documented the potential of kanban control to significantly improve operations (White, Pearson, and Wilson 1999; Fullerton and McWatters 2001). 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 and Shanthikumar 1993; Gershwin 2000; Liberopoulos and Dallery 2002). For the sake of simplicity most researchers analyse kanban systems with one product (Diaz and Ardalan 2010; Moran and Brayer 2011; Aghajani, Keramati, and Javadi 2012). A number of analytical procedures have also been proposed but they are all for systems processing a single product either at a single stage (So and Pinault 1988; Wang and Hsu-Pin 1991; Di Mascolo 1996; Kim and Tang 1997; Nori and Sarker 1998), or at multiple stages (So and Pinault 1988; Deleersnyder et al. 1992; Buzacott and Shanthikumar 1993; Tayur 1993; Siha 1994; Di Mascolo 1996; Gstettner and Kuhn 1996; Fujiwara et al. 1998; Bonvik, Dallery, and Gershwin 2000). Despite the fact that kanban systems in industry control the production of several products in a single manufacturing facility (Anupindi and Tayur 1998; Krieg and Kuhn 2002), only a couple of researchers have discussed different forms of Multiple Product Kanban Control Systems (Baynat, Buzacott, and Dallery 2002; Onyeocha et al. 2015). In addition, hardly any approaches exist to guide the control of a Single Stage, Multiple Product Kanban System (Askin, Mitwasi, and Goldberg 1993; Krieg and Kuhn 2002, 2004).

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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, Woodruff, and Hopp 1990)
3. Generalised 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, Al-Turki, and Perry 1999)
7. Adaptive Kanban System (AKS) (Tardif and Maaseidvaag 2001)
8. Reactive Kanban System (RKS) (Takahashi, Morikawa, and Nakamura 2004)
9. Knowledge Kanban (KK) (Lin, Chen, and Chen 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) is the first to propose this system but only discusses a single product version; Baynat, Buzacott, and Dallery (2002) then introduce the multi-product version.

A more recent body of literature (Faccio, Gamberi, and Persona 2013; Faccio et al. 2013; and Lolli et al. 2016) looks at the framework and optimisation of kanban control systems in a mixed-model assembly facility, using a supermarket warehouse and tow trains (or forklifts) to feed the assembly lines. In this body of research, the focus is on designing the control system, including the number of kanbans and tow truck operators, so as to minimise the system wide costs, including inventory, holding and handling costs, while using a basic kanban control system. In comparison, the focus in this research is on determining the best (optimally designed) version of kanban control system to manage a manufacturing system producing multiple products.

Ang (2015) conducts a performance comparison of Single Stage, Single Product Kanban Control Systems (SS/SP/KCS) including EKCS. Using simulation, he shows that Extended-KCS outperforms Traditional KCS and Base-stock, but only under specific conditions of low utilisation rate and low backorder and shortage costs. TKCS still performs very well, whereas BS performs the worst. Deokar (2004) also performs a simulation-based comparison of different types of KCS for a multi-stage manufacturing system producing multiple products, but the comparison is done simplistically, by varying key parameters (such as number of kanbans) over a chosen range. More recently, Onyeocha et al. (2015) compare two variations of CONWIP policy on a 3-stage serial manufacturing system producing multiple products. The authors find that the base-stock Kanban CONWIP policy (BK-CONWIP) performs better when coupled with shared kanbans. While, this work does an excellent job of developing a detailed simulation model and comparing the two variations of the CONWIP policy, like most hybrid policies, the results may not be extendable to a more general set of conditions. In addition, the hybrid policies are more difficult to implement in practice, explaining the shortage of real-life applications.

These are the only works to date to have conducted a comprehensive study of kanban control systems using simulation. In this research, we first carry out an optimal design of the following control systems:

- 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).

This is followed by a detailed comparison study, based on actual total cost of operating the policy; the total cost also quantifies the cost of backorders. The Kanban control systems are used to control manufacturing systems modelled as a single-stage, but producing multiple products. In the literature, two kinds of MP/TKCS have been proposed: dedicated and shared; however, they have proven to be equivalent (Baynat, Buzacott, and Dallery 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 organised as follows: 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 optimisation procedures for optimising the four systems, which is followed by a simulation study in Section 5 compare 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 a SS/MP/BS system for two 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

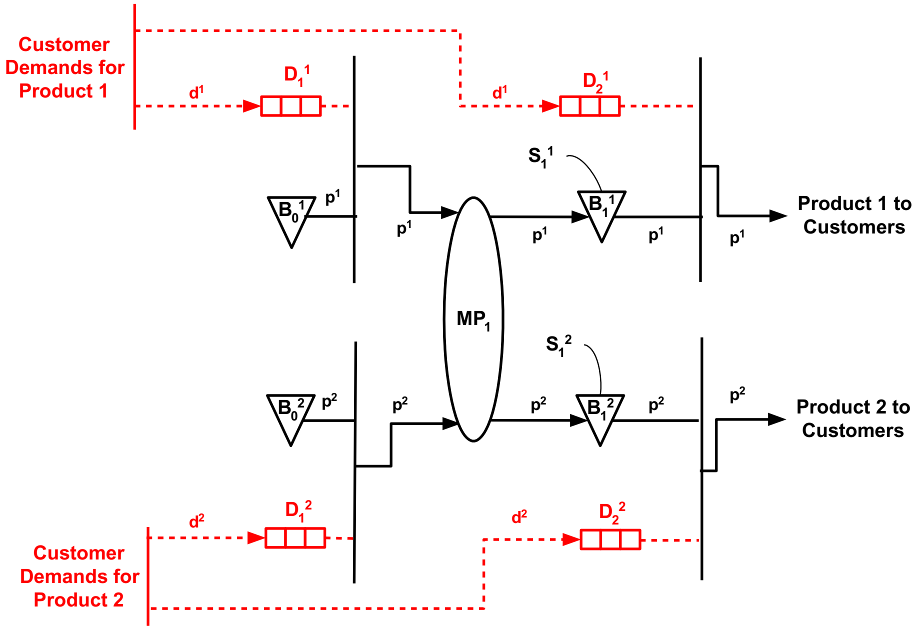

Figure 1. Single Stage, Multiple Product Base Stock (SS/MP/BS) System. Adopted from (Baynat, Buzacott, and Dallery 2002).

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 $D_i^j$. The last one joins the Queue $D_2^j$ requesting the release of a finished product from $B_1^j$ for 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 buffer $B_0^j$ which is assumed to contain infinite number of components. Thus, the system operates on a one-for-one lot replacement basis, continuously striving to maintain the base-stock in buffers $B_1$.

## 3. Single stage, multiple product, Kanban control systems (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) A part is available in $B_1^j$ (which is initially the case), is released to the customer and its kanban is detached. The detached kanban is moved upstream to $K^j$, where it authorises the production of a new part by pulling a component from buffer $B_0^j$.

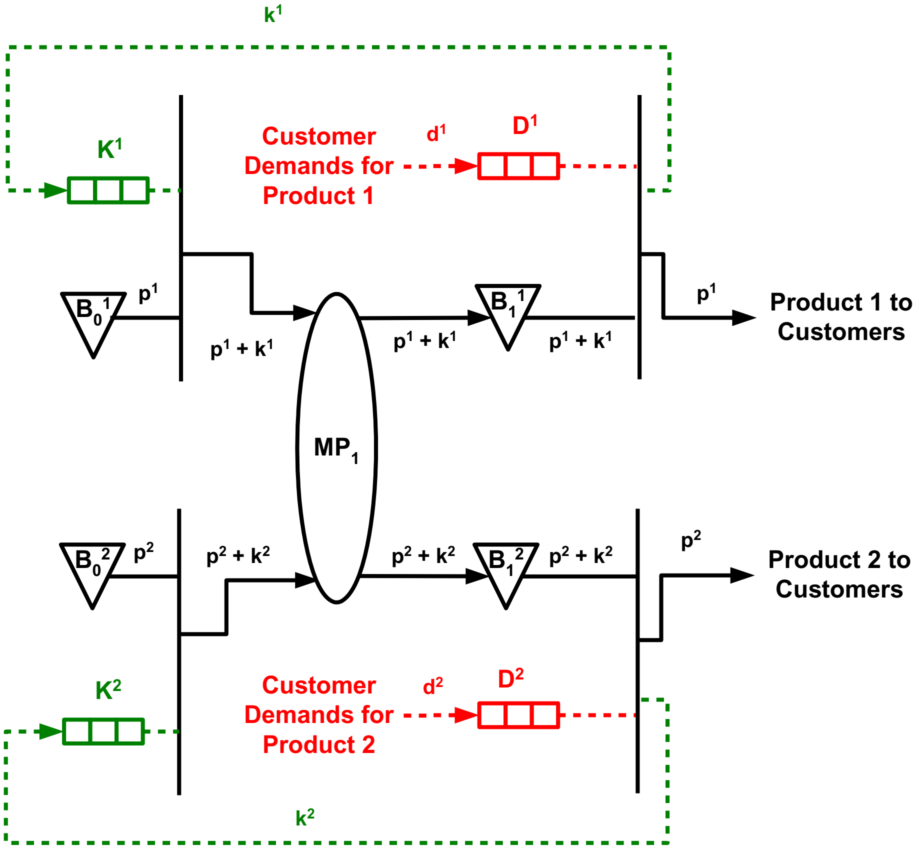

Figure 2. Single Stage, Multiple Product, Traditional Kanban Control System (Adopted from SS/MP/TKCS) (Baynat, Buzacott, and Dallery 2002).

(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 its 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 undispatched kanbans. De-EKCS depends on two parameters per stage: number of undispatched 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 $K^j$ undispatched 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 its dedicated Kanban, which is transferred upstream to the undispatched kanban queue $K_1^j$; otherwise the demand is backordered.

(2) The duplicated demand signal that joins the demand queue $D_1$ results in the un-dispatched kanban from queue $K_1^j$ being attached to a component from component buffer $B_0^j$.

A part is then released into the MP since all three, a component (infinite supply), demand signal and a Kanban, are available. However, if no un-dispatched kanbans are 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 $K_1^j$.

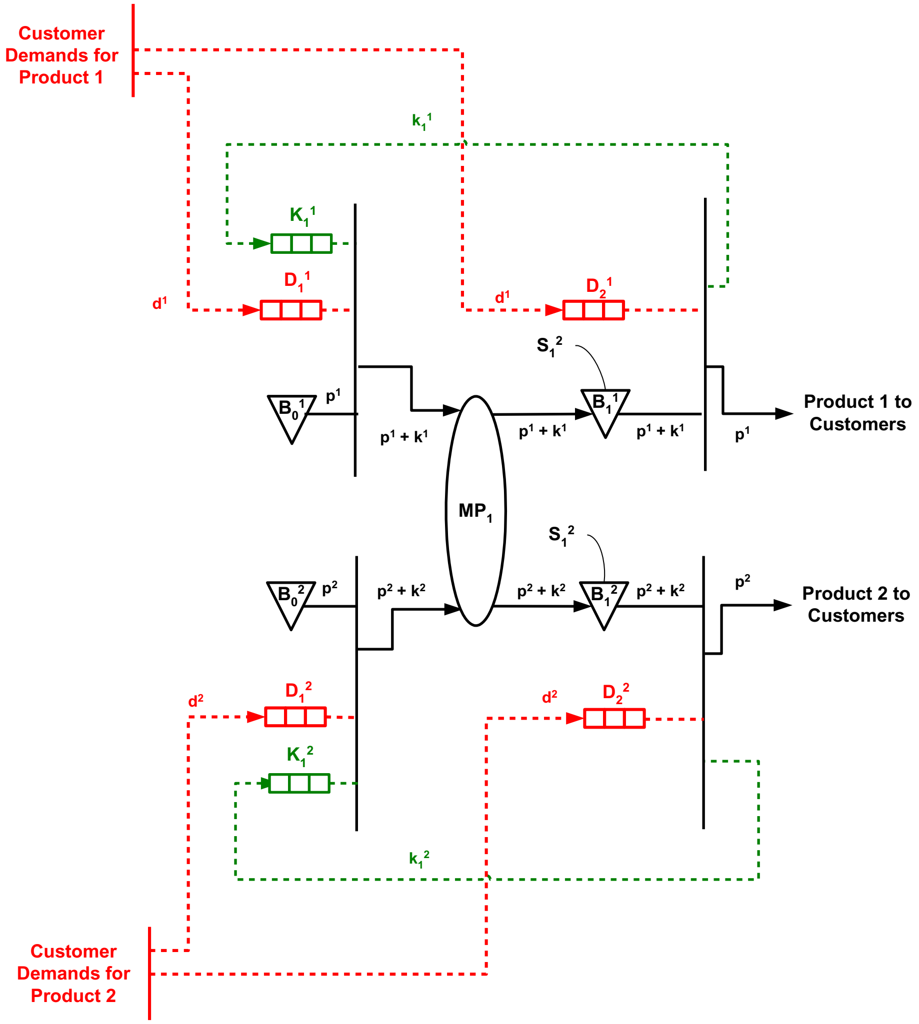

Figure 3. Single Stage, Multiple Product, Dedicated-Extended Kanban Control System (Adopted from SS/MP/De-EKCS) (Baynat, Buzacott, and Dallery 2002).

### 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 $D_i^j$ contains the incoming customer demand and queue $K_0$ contains the shared kanbans. Sh-EKCS depends on two parameters per stage: number of shared, undispatched kanbans, $K$ and base-stock level $S_i^j$. The operation of shared-EKCS is similar to De-EKCS, except that the kanbans are shared and wait in a single queue $K_0$.

## 4. Optimisation of kanban control systems (single stage, multiple products)

For sake of tractability, we assume that the kanban control systems 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, Buzacott, and Dallery (2002) who made no assumption about the internal processing of parts; the focus, instead, was on external routeing. However, for a detailed simulation of the control systems, an understanding of the internal mechanism at the MP is also necessary.

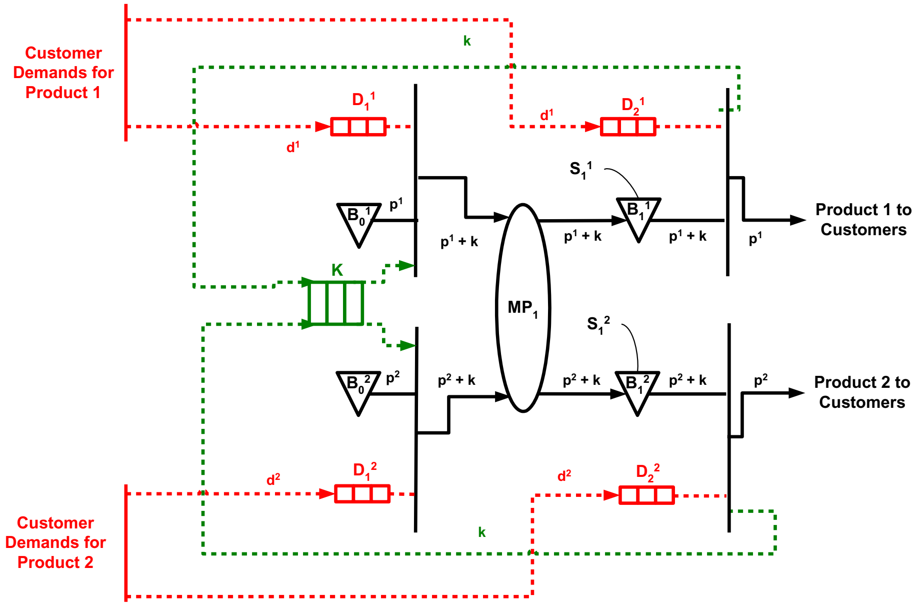

Figure 4. Single Stage, Multiple Product, Shared-Extended Kanban Control System (Adopted from SS/MP/Sh-EKCS) (Baynat, Buzacott, and Dallery 2002).

### 4.2 *M/M/1 with priority queues*

Figure 5 shows the detailed arrival and processing operations at the server of an MP/KCS, modelled as an M/M/1 queue.

The single server operates as per the following assumptions:

- Types 1 and 2 demands have Poisson arrival rates of $\lambda_1$ and $\lambda_2$, respectively.
- Type 1 demand arrivals have higher priority.
- Types 1 and 2 demands have Exponential service rates with mean $\mu_1$ and $\mu_2$, 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 products 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.

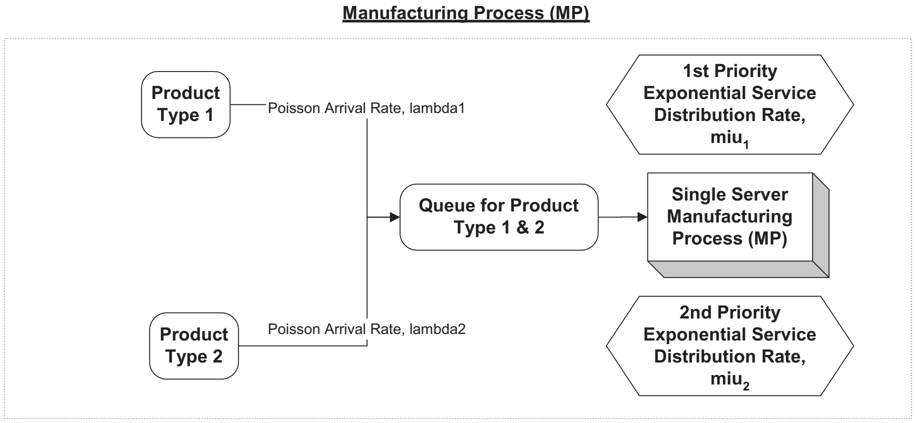

Figure 5. Manufacturing Process (MP) as an M/M/1 queue serving two product types with different arrival rates and priorities.

- $\lambda_2 < \mu_1$: 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, the system would overflow 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, $\lambda_A$, be lower than average service rate, $\mu_A$, 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 optimisation of MP/KCS. Ross (2007) uses a general service time to compute the average arrival rate $\lambda_A$ and the distribution of arrivals as follows:

$$\lambda_A = \lambda_1 + \lambda_2 \tag{1}$$

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

Equation (1) defines 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:

$$\mu_A = \frac{\lambda_A \mu_1 \mu_2}{\lambda_1 \mu_2 + \lambda_2 \mu_1} \tag{3}$$

### 4.4 *SS/MP/BS optimisation*

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 optimisation 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 $\lambda_i$, and holding and backorder costs, $C_{hi}$ and $C_{bi}$.

### 4.5 *SS/MP/TKCS optimisation*

Askin, Mitwasi, and Goldberg (1993) optimised the SS/MP/TKCS using Markov chains. In this research, we modify their technique for improved computational efficiency.

$$\text{Minimise ETC } (k) = \frac{C_s(\lambda^k) + C_h[\sum_{x=1}^{k} x(\frac{k!}{(k-x)!} \lambda^{k-x} \rho^x)]}{\sum_{x=0}^{k} \frac{k!}{(k-x)!} \lambda^{k-x} \rho^x} \tag{4}$$

Equation 4 is the expression for the Expected Total Cost (ETC) for a MP/TKCS; the reader is referred to Appendix A for its development. To find the minimum cost, exhaustive enumeration can be used where ETC is minimised over the feasible range of $K$.

### 4.6 *SS/MP/De-EKCS optimisation*

This section details a method to determine the optimal size 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):

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

To optimise Equation (5) with respect to $S$ and $K$ we again resort to exhaustive enumeration. However, optimisation of MP/De-EKCS entails optimising two parameters, $S$ and $K$. Total holding cost (first term in Equation (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 Equation (5)). We again adopt the exhaustive enumeration strategy to determine the optimal parameters. Firstly, treating $(S + K)$ as the total WIP, we search for the optimum value that minimises 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 minimises the total cost, leading to the optimal $S^*$ and $K^*$ combination.

### 4.7 *SS/MP/Sh-EKCS optimisation*

In dedicated kanban systems, for minimising 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 optimise the SS/MP/Sh-EKCS: the heuristic effectively partitions the shared Queue $K_0$ into two parts, each to serve one of the two product types separately.

Total WIP in 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, Mitwasi, and Goldberg (1993) and Ross (2007) discuss total number of jobs in process (or total WIP for all product types, $i = 1, \ldots, m$) '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 utilisation rate of MP for product type 'i' can be written as, $\lambda_i/\mu$. Next, $L$ is apportioned as per the utilisation rates 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 un-dispatched kanbans in the kanban queue $K_0$. However, they are assigned the subscript 'i' as they represent the number of un-dispatched kanbans (in steady state) 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 optimising Sh/EKCS is shown in Figure 6. The development of expected inventory level for MP/Sh-EKCS can be found in Appendix C.

## 5. Simulation study

Motivated by the practice of automobile platform sharing we next discuss a manufacturing system which forms the basis for comparison of the different KCS discussed in the previous section. An automobile platform is a vehicle's primary load-bearing assembly, determines a vehicle's size and links the driveline and suspension components (Diem and 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 standardisation. 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.

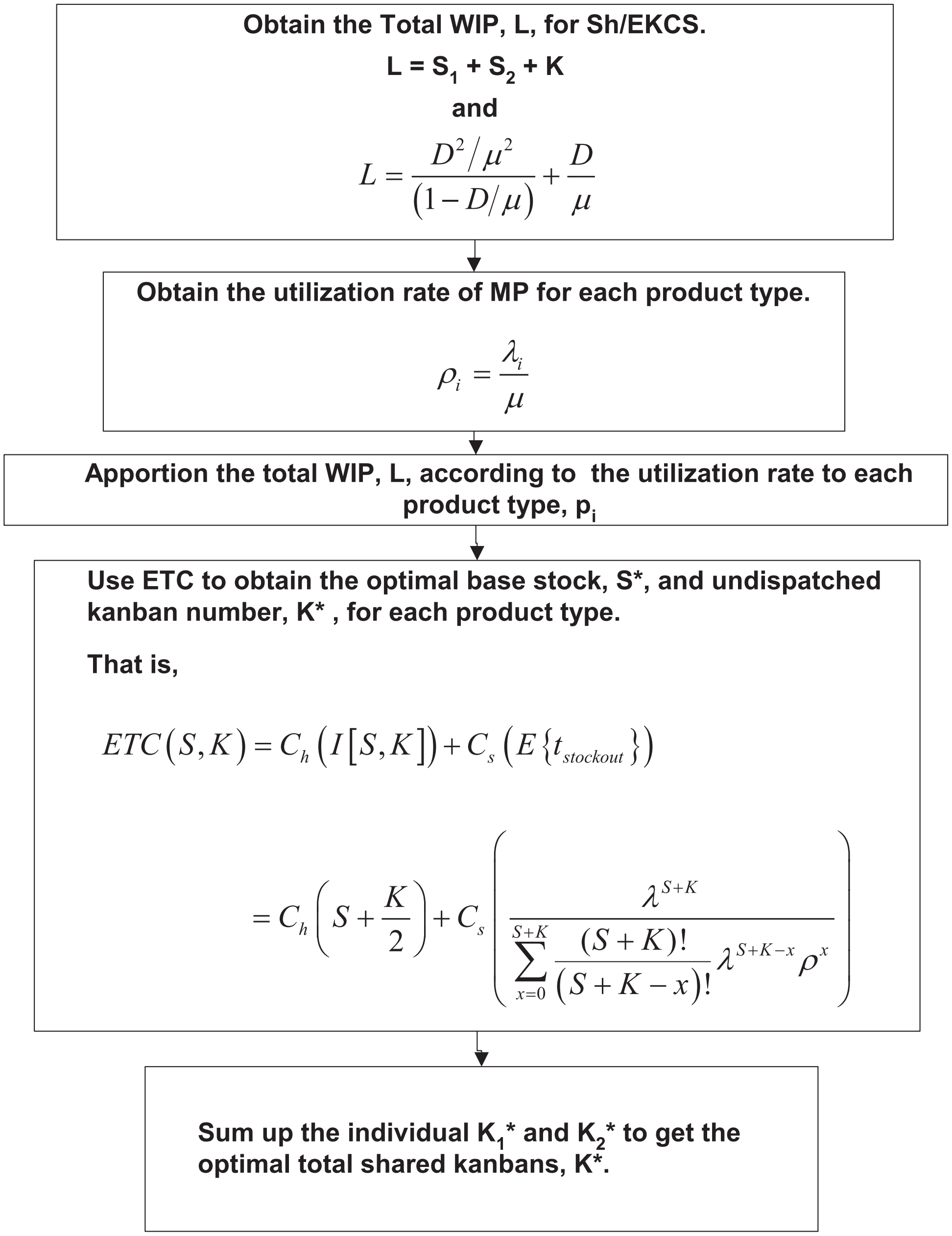

Figure 6. Algorithm for optimising SS/MP/Sh-EKCS.

### 5.1 *Simulation data*

The data used in the simulation study is derived from the case of Volkswagen small passenger car platform A. A series of mini car models such as VW Golf, Audi A3 and Audi TT are based on platform A (Diem and 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, $\lambda_1$, is assumed to be 500 units per month, while that for product-type 2 (the inexpensive model) $\lambda_2$, 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 and Kimberley 2001). Being the more economical car, the sales forecast for VW Golf was higher than for Audi TT, leading to our assumption that the demand arrival rate for VW Golf be higher than Audi TT.

Next, the processing (MP) rate for product type 1, $\mu_1$, is set at 1800 units per month, while the rate for product type 2, $\mu_2$, is 2000 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 \$1000 per unit per month, while $C_{h2}$, 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 Audit TT's engine and transmission system (Diem and 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 \$2000 per unit per month.

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

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

Instead we measure the performance of different KCS by Actual total cost (ATC) comprising 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 developed simulation model.

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

In line with the two cases mentioned at the end of Section 4.2, we simulate two scenarios: processing rate of product-type 1 slower than product-type 2, and vice versa. However, first we need to compute the average demand arrival rate, $\lambda_A$ and the average MP rate, $\mu_A$. Then, the percentage average utilisation ($\lambda_A/\mu_A$) can be used to determine how 'busy' the system is. Table 2 lists the simulation parameters for SS/MP/KCS for the two scenarios described. The system is studied only over the 50–90% utilisation range (its busy state).

### 5.2 *Simulation assumptions*

Using ARENA 11.0 software on a Windows platform, we next simulate the above-described manufacturing system under control of the various KCS. The following assumptions are made for simulation modelling of the SS/MP/KCS:

- Only two product types are processed by the system.
- System consists of a single stage and a single MP, represented by a single server.
- 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, as are server failures
- Setup times at the server are ignored as they are implicitly considered in the processing times.
- The server can only process one part at a time.
- Transfer times for parts are negligible.
- Demand signals and kanbans flow through the system instantaneously.
- Component buffers contain an infinite supply of components.

Table 1. Input parameters for the manufacturing example.

| Product-type 1 (Audi TT) | | | | Product-type 2 (VW Golf) | | | |
|---|---|---|---|---|---|---|---|
| $\lambda_1$ (units/time) | $\mu_1$ (units/time) | $C_{h1}$ (\$/unit/time) | $C_{s1}$, $C_{b1}$ (\$/unit/time) | $\lambda_2$ (units/time) | $\mu_2$ (units/time) | $C_{h2}$ (\$/unit/time) | $C_{s2}$, $C_{b2}$ (\$/unit/time) |
| 500 | 1800 | 1000 | 10,000 | 1200 | 2000 | 500 | 2000 |

Table 2. Simulation parameters for SS/MP/KCS (50–90% utilisation rate).

Processing rate of product 1 slower than product 2

| $\lambda_1$ | $\lambda_2$ | $\mu_1$ | $\mu_2$ | $\lambda_A$ | $\mu_A$ | Utilisation (%) |
|---|---|---|---|---|---|---|
| 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 |

Processing rate of product 1 faster than product 2

| $\lambda_1$ | $\lambda_2$ | $\mu_1$ | $\mu_2$ | $\lambda_A$ | $\mu_A$ | Utilisation (%) |
|---|---|---|---|---|---|---|
| 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 |

- The simulation run length is one year, with a warm up period of three months.
- Each simulation run is replicated 30 times.

### 5.3 *Simulation results*

Figures 7 ($\mu_1 < \mu_2$) and 8 ($\mu_1 > \mu_2$) show the Actual Total Costs (ATC) for different Kanban Control Systems (KCS). Both cases exhibit 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 utilisation increases, the total cost (and the difference between the systems) increases.

Dedicated and Sh-EKCS outperform TKCS consistently by a difference of about 17% ($1000 on average) in both the cases. The optimal number of dispatched kanbans for TKCS is, in general, a unit more than that for Dedicated and Sh-EKCS (Ang 2013). As TKCS holds (on average) one additional 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 un-dispatched kanbans help to lower the total cost. Overall, the results show that Dedicated and Sh-EKCS outperform the other two systems.

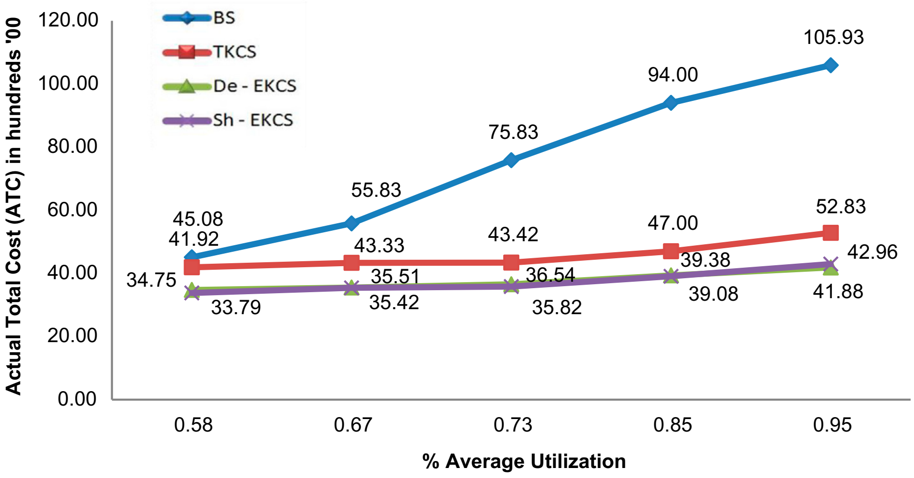

Figure 7. Performance comparison of SS/MP/KCS ($\mu_1 < \mu_2$).

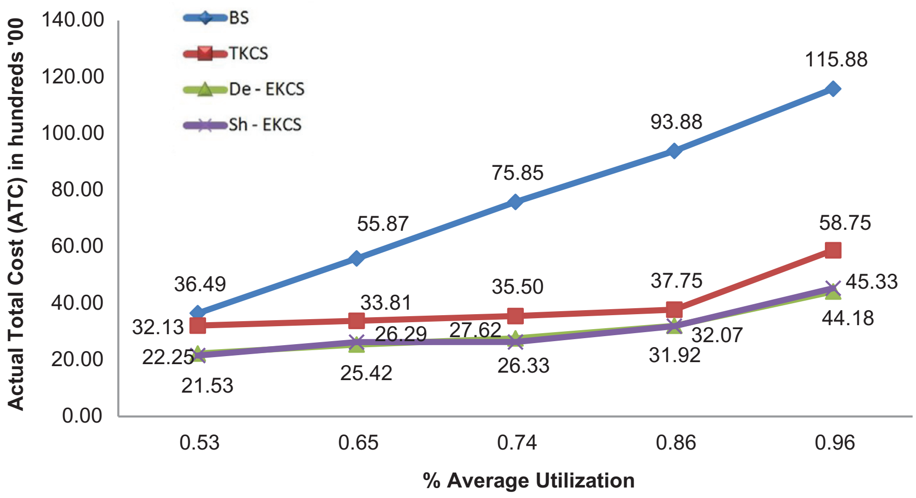

Figure 8. Performance comparison of SS/MP/KCS ($\mu_1 > \mu_2$).

We also conduct 20 hypothesis tests at 95% confidence level on the simulation results (discussed in detail in Appendix D) which confirm the finding that EKCS outperforms TKCS and BS.

One interesting finding here is that the performance of Dedicated and Sh-EKCS is quite similar their total costs being within 2.5% of each other. Further comparison of dedicated and shared-extended-KCS is carried out over the range of low server utilisation (10–50%), with no significant difference between the two variations of EKCS.

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 scenario:

(i) $S_1^1$ 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. Thus, despite the fact that the two kanbans are *shared*, the priority rule ensures that the customer demand arrivals result in a kanban *dedicated* to the arriving type.

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

## 6. Conclusions 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 detailed schematics. We also present algorithms to optimise 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 modelling is based on a real-life case of Volkswagen 'Platform A' manufacturing.

Simulation experiments show 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 a single-stage system. Extensive simulation experiments have shown that their operating characteristics are similar inspite of slight differences in their schematics.

This research can be further extended to the case of multiple stages, similar to the Simultaneous EKCS (Chaouiya, Liberopoulos, and Dallery 2000); it is likely that the multiple stage case may highlight the difference between the dedicated and shared EKCS.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Supplemental data

Supplemental data for this article can be accessed here [https://doi.org/10.1080/00207543.2017.1332436].

## References

Aghajani, M., A. Keramati, and B. Javadi. 2012. "Determination of Number of Kanban in a Cellular Manufacturing System with Considering Rework Process." *The International Journal of Advanced Manufacturing Technology* 63 (9–12): 1177–1189.

Al-Hawari, T., and F. Aqlan. 2012. "A Software Application for E-Kanban-based WIP Control in the Aluminium Industry." *International Journal of Modelling in Operations Management* 2 (2): 119–137.

Ang, A. 2013. "An Investigation into the Extended Kanban Control System (EKCS)." PhD Thesis, Nanyang Technological University (NTU), Lee Wee Nam Library.

Ang, A. 2015. "A Performance Comparison of Single Product Kanban Control Systems." *International Journal of Production Management and Engineering* 3 (1): 57–74.

Anupindi, R., and S. Tayur. 1998. "Managing Stochastic Multiproduct Systems: Model, Measures, and Analysis." *Operations Research* 46 (3-supplement-3): S98–S111. doi:10.1287/opre.46.3.S98.

Askin, R. G., M. G. Mitwasi, and J. B. Goldberg. 1993. "Determining the Number of Kanbans in Multi-item Jun-in-time System." *IIE Transactions* 25 (1): 89–98.

Baynat, B., J. A. Buzacott, and Y. Dallery. 2002. "Multiproduct Kanban-like Control Systems." *International Journal of Production Research* 40 (16): 4225–4255.

Bonvik, A. M., Y. Dallery, and S. B. Gershwin. 2000. "Approximate Analysis of Production Systems Operated by a CONWIP/Finite Buffer Hybrid Control Policy." *International Journal of Production Research* 38 (13): 2845–2869.

Boonlertvanich, K. 2005. "Extended-CONWIP-Kanban System: Control and Performance Analysis." PhD, Georgia Tech, USA.

Buzacott, J. A. 1989. "Queueing Models of Kanban and MRP Controlled Production Systems." *Engineering Costs and Production Economics* 17 (1–4): 3–20.

Buzacott, J. A., and J. G. Shanthikumar. 1993. *Stochastic Models of Manufacturing Systems*. Englewood Cliffs, NJ: Prentice Hall.

Chaouiya, C., G. Liberopoulos, and Y. Dallery. 2000. "The Extended Kanban Control System for Production Coordination of Assembly Manufacturing Systems." *IIE Transactions (Institute of Industrial Engineers)* 32 (10): 999–1012.

Dallery, Y. 2000. "Extended Kanban Control System: Combining Kanban and Base Stock." *IIE Transactions* 32 (4): 369–386.

Deleersnyder, J.-L., T. J. Hodgson, R. E. King, P. J. O'Grady, and A. Savva. 1992. "Integrating Kanban Type Pull Systems and MRP Type Push Systems: Insights from a Markovian Model." *IIE Transactions* 24 (3): 43–56.

Deokar, S. S. 2004. "Performanc Evaluation of Multi-product Kanban-like Control Systems." Unpublished Masters Thesis (MSIE), University of South Florida.

Di Mascolo, M. 1996. "Analysis of a Synchronization Station for the Performance Evaluation of a Kanban System with a General Arrival Process of Demands." *European Journal of Operational Research* 89 (1): 147–163.

Diaz, R., and A. Ardalan. 2010. "An Analysis of Dual-Kanban Just-in-time Systems in a Non-repetitive Environment." *Production and Operations Management* 19 (2): 233–245.

Diem, W., and W. Kimberley. 2001. "The Same Only Different." *Automotive Engineer* 26 (5): 46.

Faccio, M., M. Gamberi, and A. Persona. 2013. "Kanban Number Optimisation in a Supermarket Warehouse Feeding a Mixed-model Assembly System." *International Journal of Production Research* 51 (10): 2997–3017.

Faccio, M., Mauro Gamberi, A. Persona, A. Regattieri, and F. Sgarbossa. 2013. "Design and Simulation of Assembly Line Feeding Systems in the Automotive Sector Using Supermarket, Kanbans and Tow Trains: A General Framework." *Journal of Management Control* 24 (2): 187–208.

Fujiwara, O., X. Yue, K. Sangaradas, and H. T. Luong. 1998. "Evaluation of Performance Measures for Multi-part, Single-product Kanban Controlled Assembly Systems with Stochastic Acquisition and Production Lead times." *International Journal of Production Research* 36 (5): 1427–1444.

Fullerton, R. R., and C. S. McWatters. 2001. "The Production Performance Benefits from JIT Implementation." *Journal of Operations Management* 19 (1): 81–96.

Gershwin, S. B. 2000. "Design and Operation of Manufacturing Systems: The Control-point Policy." *IIE Transactions (Institute of Industrial Engineers)* 32 (10): 891–906.

Gstettner, S., and H. Kuhn. 1996. "Analysis of Production Control Systems Kanban and CONWIP." *International Journal of Production Research* 34 (11): 3253–3273.

Gupta, S. M., Y. A. Y. Al-Turki, and R. F. Perry. 1999. "Flexible Kanban System." *International Journal of Operations & Production Management* 19 (10): 1065–1093. doi:10.1108/01443579910271700.

Hopp, W. J., and M. L. Spearman. 2008. *Factory Physics*. 3rd ed. New York: McGraw-Hill/Irwin/Irwin.

Kim, I., and C. S. Tang. 1997. "Lead Time and Response Time in a Pull Production Control System." *European Journal of Operational Research* 101 (3): 474–485.

Krieg, G. N., and H. Kuhn. 2002. "A Decomposition Method for Multi-product Kanban Systems with Setup times and Lost Sales." *IIE Transactions* 34 (7): 613–625.

Krieg, G. N., and H. Kuhn. 2004. "Analysis of Multi-product Kanban Systems with State-dependent Setups and Lost Sales." *Annals of Operations Research* 125 (1–4): 141–166.

Liberopoulos, G., and Y. Dallery. 2002. "Base Stock versus WIP Cap in Single-stage Make-to-stock Production-inventory Systems." *IIE Transactions* 34 (7): 627.

Lin, C. J., F. F. Chen, and Y. M. Chen. 2013. "Knowledge Kanban System for Virtual Research and Development." *Robotics and Computer-Integrated Manufacturing* 29 (3): 119–134.

Lolli, F., R. Gamberini, C. Giberti, B. Rimini, and F. Bondi. 2016. "A Simulative Approach for Evaluating Alternative Feeding Scenarios in a Kanban System." *International Journal of Production Research* 54 (14): 4228–4239.

Monden, Y. 1998. *Toyota Production System : An Integrated Approach to Just-in-time*. 3rd ed. Norcross, GA: Engineering & Management Press.

Moran, T. J., and K. Brayer. 2011. "A Simulation Study of Economic Production Quantity Lot Size to Kanban for a Single Line Production System under Various Setup times with Annual Setup Cost as Performance Metric." *International Journal of Management and Information Systems* 15 (2): 23–30.

Nori, V. S., and B. R. Sarker. 1998. "Optimum Number of Kanbans between Two Adjacent Stations." *Production Planning & Control* 9 (1): 60–65.

Onyeocha, C. E., J. Wang, J. Khoury, and J. Geraghty. 2015. "A Comparison of HK-CONWIP and BK-CONWIP Control Strategies in a Multi-product Manufacturing System." *Operations Research Perspectives* 2: 137–149.

Ross, S. M. 2007. *Introduction to Probability Models*. 9th ed. Amsterdam: Academic Press.

Siha, S. 1994. "The Pull Production System: Modelling and Characteristics." *International Journal of Production Research* 32 (4): 933–949.

So, K. C., and S. C. Pinault. 1988. "Allocating Buffer Storages in a Pull System." *International Journal of Production Research* 26 (12): 1959–1980.

Spearman, M. L., D. L. Woodruff, and W. J. Hopp. 1990. "CONWIP: A Pull Alternative to Kanban." *International Journal of Production Research* 28 (5): 879–894.

Sugimori, Y., K. Kusunoki, F. Cho, and S. Uchikawa. 1977. "Toyota Production System and Kanban System Materialization of Just-in-time and Respect-for-human System." *International Journal of Production Research* 15 (6): 553–564.

Takahashi, K., K. Morikawa, and N. Nakamura. 2004. "Reactive JIT Ordering System for Changes in the Mean and Variance of Demand." *International Journal of Production Economics* 92 (2): 181–196.

Tardif, V., and L. Maaseidvaag. 2001. "An Adaptive Approach to Controlling Kanban Systems." *European Journal of Operational Research* 132 (2): 411–424.

Tayur, S. R. 1993. "Structural Properties and a Heuristic for Kanban-controlled Serial Lines." *Management Science* 39 (11): 1347–1368.

Wang, H., and W. Hsu-Pin. 1991. "Optimum Number of Kanbans between Two Adjacent Workstations in a JIT System." *International Journal of Production Economics* 22 (3): 179–188.

White, R. E., J. N. Pearson, and J. R. Wilson. 1999. "JIT Manufacturing: A Survey of Implementations in Small and Large US Manufacturers." *Management Science* 45 (1): 1–15. doi:10.1287/mnsc.45.1.1.

Zipkin, P. H. 2000. *Foundations of Inventory Management*. Boston, MA: McGraw-Hill.