

Onyeocha, Chukwunonyelum Emmanuel; Wang, Jiayi; Khoury, Joseph;  
Geraghty, John

## Article

# A comparison of HK-CONWIP and BK-CONWIP control strategies in a multi-product manufacturing system

Operations Research Perspectives

## Provided in Cooperation with:

Elsevier

*Suggested Citation:* Onyeocha, Chukwunonyelum Emmanuel; Wang, Jiayi; Khoury, Joseph; Geraghty, John (2015) : A comparison of HK-CONWIP and BK-CONWIP control strategies in a multi-product manufacturing system, Operations Research Perspectives, ISSN 2214-7160, Elsevier, Amsterdam, Vol. 2, pp. 137-149, <https://doi.org/10.1016/j.orp.2015.07.001>

This Version is available at:

<https://hdl.handle.net/10419/178258>

### Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

### Terms of use:

*Documents in EconStor may be saved and copied for your personal and scholarly purposes.*

*You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.*

*If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.*



<http://creativecommons.org/licenses/by-nc-nd/4.0/>



# A comparison of HK-CONWIP and BK-CONWIP control strategies in a multi-product manufacturing system



Chukwunonyelum Emmanuel Onyeocha<sup>a,\*</sup>, Jiayi Wang<sup>a</sup>, Joseph Khoury<sup>b</sup>, John Geraghty<sup>a</sup>

<sup>a</sup> Enterprise Process Research Centre, School of Mechanical & Manufacturing Engineering, Dublin City University, Dublin 9, Ireland

<sup>b</sup> Methode Electronics International, Germany

## ARTICLE INFO

### Article history:

Available online 29 July 2015

### Keywords:

Production control strategies  
Kanban allocation policies  
Multi-product manufacturing systems  
Hybrid Kanban CONWIP

## ABSTRACT

This paper evaluates the performance of the Hybrid Kanban Constant Work-In-Process control strategy and Basestock Kanban Constant Work-In-Process control strategy operating Shared Kanban Allocation Policy (S-KAP) and Dedicated Kanban Allocation Policy (D-KAP) in a multi-product serial flow line. We explored the effect of an increase of product types on the WIP inventory in the system. A simulation-based optimisation technique was used in determining the optimal settings for the strategies. The strategies were compared via pairwise comparison technique and Nelson's ranking and selection procedure. S-KAP responds quicker to demand than D-KAP. BK-CONWIP outperforms HK-CONWIP in a serial manufacturing system. It was shown that an increase in the number of product-type increases the number of PAC and WIP inventory.

© 2015 The Authors. Published by Elsevier Ltd.

This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

## 1. Introduction

CONWIP control strategy is one of the most studied Pull Production Control Strategies (PCS); Scopus (accessed 14th January 2015), a multi-disciplinary abstracting and indexing database, documents that the paper [1], that introduced CONWIP has been cited 440 times. CONWIP combines the high throughput of a push strategy and the WIP control mechanism of a pull strategy [1–3]. The merits of CONWIP prompted comparisons by researchers to other pull production control strategies. A CONWIP controlled system has been shown by various researchers to be superior to Kanban systems [4–7]. Additionally, CONWIP was reported outperforming other pull control strategies in terms of minimising Work-In-Process (WIP) while maximising the service level [8–11]. However, loose co-ordination between stages in the CONWIP strategy has led some researchers to propose modifications of the CONWIP control strategy.

Bonvik et al. [12] proposed a Pull/Push control strategy called Hybrid Kanban CONWIP (HK-CONWIP) control strategy, which integrates Kanban control mechanism in each of the stages of a traditional CONWIP except for the last stage of the system. The Kanban controls the inventory level at every stage in the production line

except for the final stage while the CONWIP controls the inventory of the entire system. HK-CONWIP was shown to have a reduction in inventory levels at each stage when compared with KCS and CONWIP [10,12]. On the other hand, Wang et al. [13] developed a HK-CONWIP strategy that combines the Theory of Constraints (TOC), which focused on solving bottleneck issues in a production line. The proposed HK-CONWIP with TOC outperformed traditional HK-CONWIP and traditional CONWIP, while the traditional HK-CONWIP outperformed CONWIP. The study of Gaury et al. [14,15] generalised HK-CONWIP and showed that HK-CONWIP outperformed the Kanban and CONWIP strategies. Also, Geraghty and Heavey [16] evaluated the performance of HK-CONWIP and hybrid push/pull systems and showed that the control mechanism of the hybrid push/pull strategy found in Hodgson and Wang [17,18], is the same as that of HK-CONWIP. These studies [12–18] showed that HK-CONWIP is superior to KCS and CONWIP.

A majority of these studies are based on single product manufacturing environments with the assumption that the research findings in single product manufacturing systems are scalable to multi-product manufacturing systems. With this assumption in mind, several studies in multi-product manufacturing systems implemented only D-KAP in their studies because it is the only production authorisation card policy found in single product manufacturing systems [19]. Prior to the findings of Baynat et al. [20], studies in multi-product manufacturing systems gave attention to issues such as planning and scheduling, optimisation of the CONWIP card [21]. Some of these studies proposed techniques for

\* Corresponding author.

E-mail address: [chuks247@gmail.com](mailto:chuks247@gmail.com) (C.E. Onyeocha).

**Table 1**  
Acronyms used in this work.

Acronym	Description	Acronym	Description
PCS	Production Control Strategy	KAP	Kanban Allocation Policy
BK-CONWIP	Basestock Kanban CONWIP control strategy	D-KAP	Dedicated Kanban Allocation Policy
BSCS	Basestock Control Strategy	S-KAP	Shared Kanban Allocation Policy
CONWIP	Constant Work In Process control strategy	PCS + KAP	A specified PCS and specified KAP combination
EKCS	Extended Kanban Control Strategy	Other	Other abbreviations used in paper
GKCS	Generalised Kanban Control Strategy	MPME	Multi-Product Manufacturing Environment
HK-CONWIP	Hybrid Kanban CONWIP control strategy	PAC	Production Authorisation Card
KCS	Kanban Control Strategy	WIP	Work In Process inventory

**Table 2**  
Description of symbols.

Symbol	Description	Symbol	Description
$D_{1,2,\dots}$	Demand card for stage 1, 2, ...	CC	CONWIP card in a S-KAP PCS
$D^{1,2,\dots}$	Demand for product 1, 2, ...	$CC^{1,2,\dots}$	CONWIP card for product 1, 2, ... in a D-KAP PCS
$D_{1,2,\dots}^{1,2,\dots}$	Demand card for product 1, 2, ... at stage 1, 2, ...	$MP_{1,2,\dots}$	Manufacturing process unit at stage 1, 2, ...
$K^{1,2,\dots}$	Kanban card for product 1, 2, ...	$I_{1,2,\dots}^{1,2,\dots}$	Inventory output buffer for product 1, 2, ... at stage 1, 2, ...
$K_{1,2,\dots}^{1,2,\dots}$	Kanban card for product 1, 2, ... at stage 1, 2, ...	$I_0^{1,2,\dots}$	Raw material inventory output buffer for product 1, 2, ...
		$RM^{1,2,\dots}$	Raw material for product 1, 2, ...

solving scheduling issues that arise when production authorisation cards for two or more product types are waiting in a queue and a decision is required to ascertain which product-type should be released first [22–25]. Additionally, a number of studies [26,27] developed mathematical or simulation models for optimisation of production authorisation card in order to minimise the inventory, production and shortage costs in a multi-product system, while certain studies [28–31] evaluated the effect of the WIP cap of CONWIP in multi-product manufacturing systems. To address the issue of selection of an appropriate pull control strategy, researchers compare and rank the performance of various pull control strategies [32–37].

Baynat et al. [20] proposed a shared production authorisation card policy that is applicable only to multi-product systems. The application of S-KAP in GKCS and EKCS improved the WIP control of the strategies [20]. Olaitan and Geraghty [36] implemented D-KAP and S-KAP on five PCS in a two-product, three-stage multi-product manufacturing system with minimal blocking policy to evaluate the performance of five PCS under negligible setup and similar manufacturing processes. The findings of Olaitan and Geraghty [36] agree with that of Baynat et al. [20] that S-KAP outperforms D-KAP, but suggested that under robust conditions D-KAP outperforms S-KAP. KCS, CONWIP, HK-CONWIP and BSCS cannot operate naturally in S-KAP mode [20,21,36]. Onyeocha and Geraghty [21] proposed a modification approach that enables PCS that is not capable of operating S-KAP naturally to operate it. The approach was implemented on HK-CONWIP and they developed a new pull production control strategy called BK-CONWIP. However, the performance of both strategies (HK-CONWIP and BK-CONWIP) in both policies (S-KAP and D-KAP) in a multi-product manufacturing environment is yet to be evaluated.

In this study, we investigate and compare the performance of HK-CONWIP and BK-CONWIP in a multi-product, three-stage manufacturing serial line under high demand variation. The multi-product serial line is similar to the model proposed by Olaitan and Geraghty [36]. However, we introduced no minimal blocking policy in our models. The line is highly automated with negligible setups. The remainder of this paper is organised by first presenting an overview of the production authorisation cards policies and the production control strategies under investigation in Section 2. The research methodology is presented in Section 3. The experimental results are provided in Section 4. The results are discussed in Section 5 and Section 6 provides the conclusion of the study.

## 2. Background

An overview of the multi-product production authorisation card policies and the pull production control strategies being investigated is hitherto presented to guide the reader through the subsequent sections. Table 1 describes the acronyms used in this work for easy readability and comprehension while Table 2 defines the symbols used in this paper.

### 2.1. Description of the production authorisation card policies

A majority of pull production control strategies use a signal card known as production authorisation card (sometimes referred to as Kanban) in order to release a product type into a manufacturing system, while few others such as Basestock Control Strategy (BSCS), use the actual demand to trigger the release of product type into a manufacturing system. In single product manufacturing environments, the production authorisation card is rigid such that it is dedicated to a specific product type. However, in multi-product manufacturing environments, the production authorisation cards could be shared among product types or dedicated to a specific product type [20]. The procedure in which the shared and dedicated production authorisation cards are implemented in a pull production control strategy is considered the production authorisation card policy. The two main production authorisation card policies found in the literature are the D-KAP and S-KAP.

D-KAP is applicable to both single and multi-product systems. Each product type in a system has a designated number of production authorisation cards assigned for releasing of such a product type into a manufacturing system [19–21,36]. Therefore, the total number of production authorisation cards in a stage is given by the summation of the total number of production authorisation cards of all the product types in that stage. This implies that a system having a large number of product types with erratic demand will require planning a large number of production authorisation cards for each of the product types in a stage or a system. The issue of such a large number of PAC in a manufacturing system is that it results in a proliferation of WIP in the system which causes line congestion, long lead times and low throughput [19,21]. Furthermore, optimising the PAC for each product type in multi-product systems is complex in nature and takes a long period of time [36]. The complexity of the optimisation process is more prevalent in

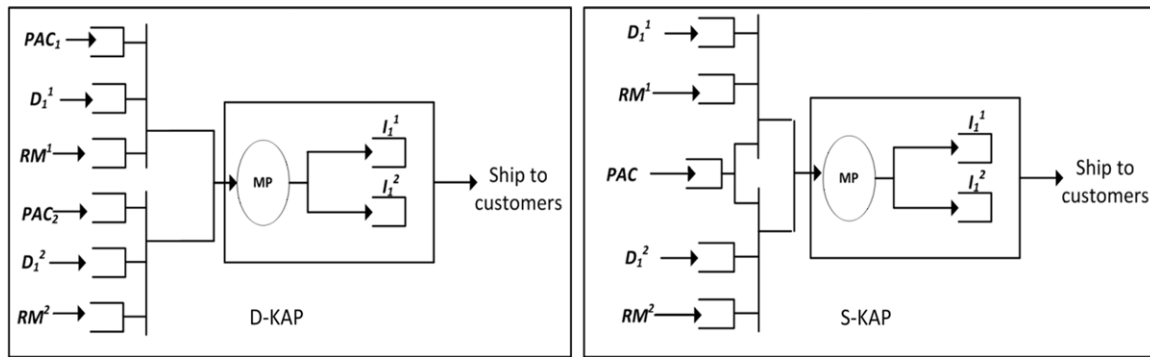


Fig. 1. D-KAP and S-KAP in a multi-product stage.

multi-product manufacturing systems. In multi-product manufacturing systems, D-KAP is extended single product systems [19–21,36].

S-KAP was proposed by Baynat et al. [20], as PAC policy that allocates and distributes its resources among the product types in a system. There is only a single resource pool containing the total number of the PAC that is shared among all product types in a stage or a system. The allocation of PAC to product types in S-KAP in a multi-product system depends on the scheduling policy in the system. Onyeocha and Geraghty [21] suggested that sharing PAC in a multi-product system enables the PCS to rapidly respond to demand variations. Additionally, a decrease in a specific product type with a corresponding demand increase of another product type in the same system can be catered for without alteration or re-configuration of the control parameters [21]. However, in some PCS, S-KAP could also behave as D-KAP such that when a specific PAC is released from a finished product type. The released PAC is used to re-authorise a replacement of the same product type. The control mechanism of D-KAP and S-KAP, as implemented in a multi-product single stage manufacturing system is shown in Fig. 1.

## 2.2. Pull production control strategies under investigation

HK-CONWIP uses CONWIP cards (a global set of cards) to control the inventory of the entire production system and Kanban cards (an individual signal cards) to tightly control the inventory of a stage in a system except for the last stage of the system that is push controlled. A vital feature of the CONWIP is that it sets an upper limit on the inventory of a system, which is referred to as WIP cap. However, CONWIP has a poor control of an individual stage inventory causing large inventory in front of the bottleneck stages in a system. Conversely, HK-CONWIP combines Kanban in its control mechanism in order to control each stage WIP excluding the last stage. The addition of Kanban controls in HK-CONWIP proffers a solution to the problem of a large build-up of inventories and bottleneck issues in a multi-product manufacturing system. The initial state of the final product inventory buffer of HK-CONWIP has a predefined number of basestock with CONWIP cards attached to them. The control mechanism of the D-KAP HK-CONWIP in a multi-product manufacturing system is presented in Fig. 2.

In Fig. 2,  $MP_{1...3}$  denotes the manufacturing process where the subscript signifies the stage number. Also,  $K_1^1 \dots K_2^2$  are the stage Kanbans, the superscript refers to the product type and the subscript represents the stage number.  $CC^{1...2}$  signifies the CONWIP card, while the superscript denotes the product-type that the card authorises.

Finished product types in the final product inventory  $I_3^1$  or  $I_3^2$  have CONWIP cards attached to them. When a demand for a

product-type occurs, a finished product in the finished product inventory corresponding to the product-type is released to satisfy the demand. Simultaneously the attached CONWIP card on the released product is detached and sent back upstream to authorise a replacement of the similar product-type. In the first stage, the CONWIP card  $CC^{1...2}$  is attached to a raw material  $RM^{1...2}$  and a stage Kanban  $K_1^1 \dots K_2^2$  and then transferred to the manufacturing process for production of the replacement product-type in the system. The finished product-type is stored in the output buffer of that stage  $I_1^{1...2}$ . For production to begin in the next stage, the following factors must be available, next stage manufacturing process  $MP_2$ , the next stage Kanban  $K_2^{1...2}$  and a semi-finished product-type with CONWIP card  $CC^{1...2}$  in the current stage output buffer  $I_1^{1...2}$ . These parameters are synchronised together while the current stage Kanban is detached and sent back to its initial position. The synchronised semi-finished product-type is processed in the manufacturing process of the next stage. The finished product is then transferred to the output buffer of that stage  $m + 1$ . When the product-type completes the processes in the next stage, it is then stored in the output buffer of that stage. The process continues in a similar manner until the last stage. If the last stage manufacturing process is available, the semi-finished product-type in the output buffer of the previous stage is transferred into the last stage manufacturing process via a push control mechanism. The finished product is stored in the final product inventory.

Traditional HK-CONWIP does not operate S-KAP. In order to develop HK-CONWIP in S-KAP mode, the modification approach proposed by Onyeocha and Geraghty [21] was implemented on HK-CONWIP. The control mechanism of HK-CONWIP S-KAP is similar to that of HK-CONWIP D-KAP, except for the modification at the last stage of the strategy. The modification is such that the CONWIP card is detached from the finished product, immediately the product-type leaves the manufacturing process of the last stage to enable the sharing of the CONWIP cards. Therefore, the base stock level of the final product inventory is used to trigger off demand information to the first stage of the system. Fig. 3 illustrates the control mechanism of HK-CONWIP S-KAP in a multi-product manufacturing system.

When a demand occurs in HK-CONWIP S-KAP, finished product-type (no CONWIP card attached) is released from the output buffer of the last stage to satisfy the demand. During the process of satisfying a demand, demand information  $D_1$  or  $D_2$  is transmitted to the first stage to authorise a replacement of a product-type.

HK-CONWIP was recently developed by Onyeocha and Geraghty [21]. HK-CONWIP was modified owing to the need for rapid response to demand variability. The choice to modify HK-CONWIP was based on their review that it is a better strategy in comparison to Kanban Control Strategy (KCS), CONWIP and Basestock control strategy [21]. However, it has a tight coupling between demand information and the CONWIP cards such that it does not

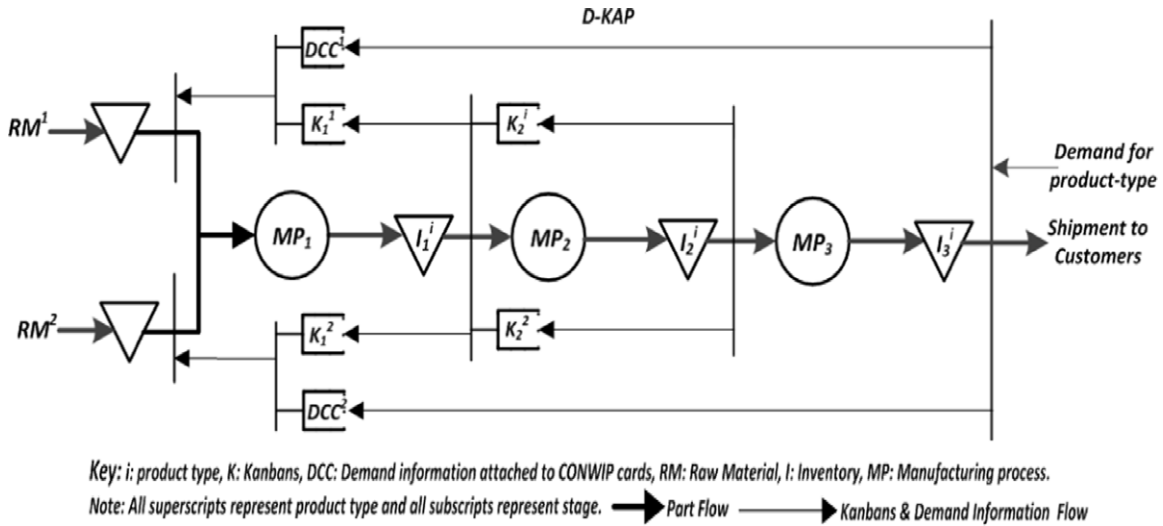


Fig. 2. The control mechanism of HK-CONWIP D-KAP.

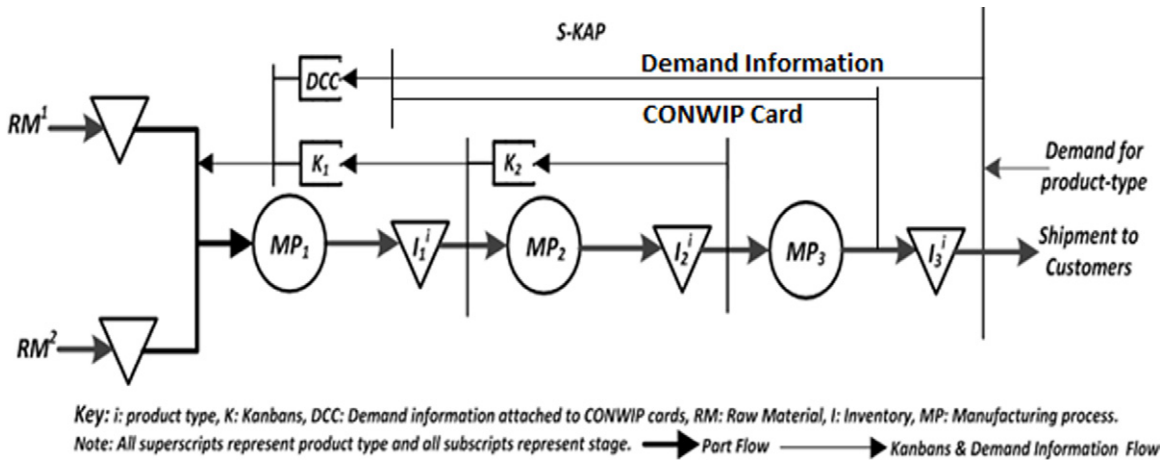


Fig. 3. The control mechanism of HK-CONWIP S-KAP.

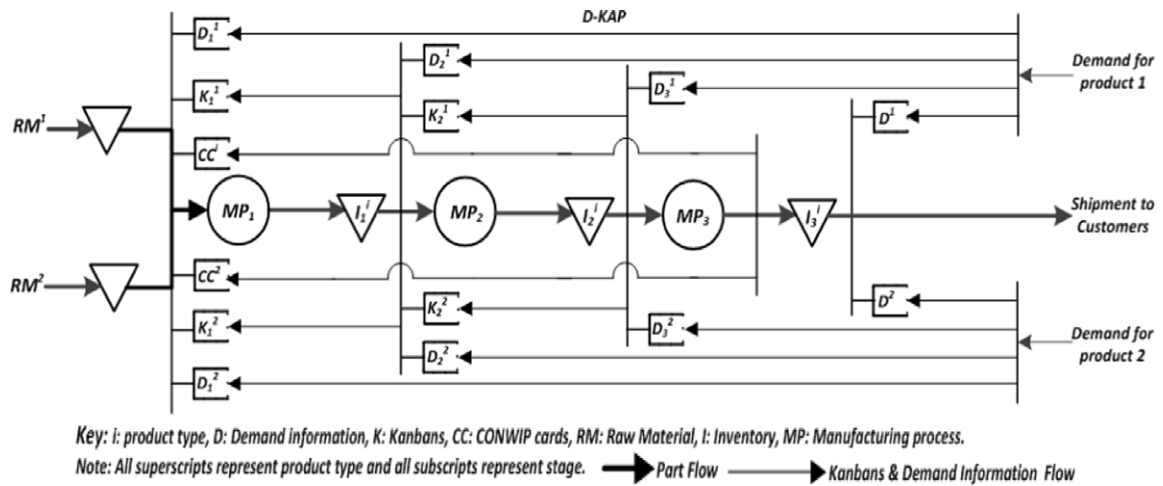


Fig. 4. The control mechanism of BK-CONWIP D-KAP.

operate S-KAP. Also, when a demand occurs, the demand information is transferred from the last stage output buffer to the first stage for replacement of the product-type. The demand information is transferred from the first stage to the subsequent stage until it reaches the last stage. This causes a slow response to demand

in HK-CONWIP. BK-CONWIP combines the merits of BSCS (global transmission of demand information to all stages at the same time), KCS (stage inventory controls) and CONWIP (high throughput rate while maintaining a small quantity of WIP inventory). Figs. 4 and 5 provide descriptions of the control mechanism of the D-KAP and

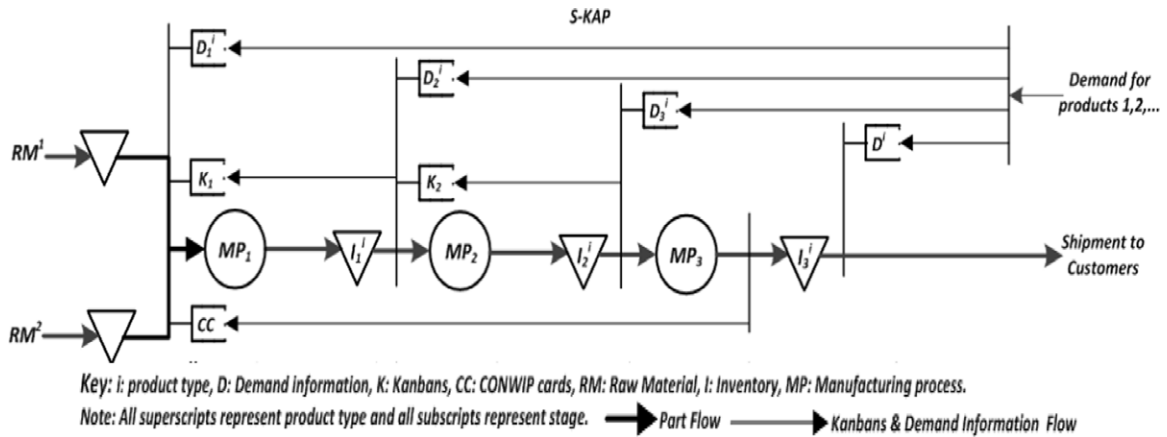


Fig. 5. The control mechanism of BK-CONWIP S-KAP.

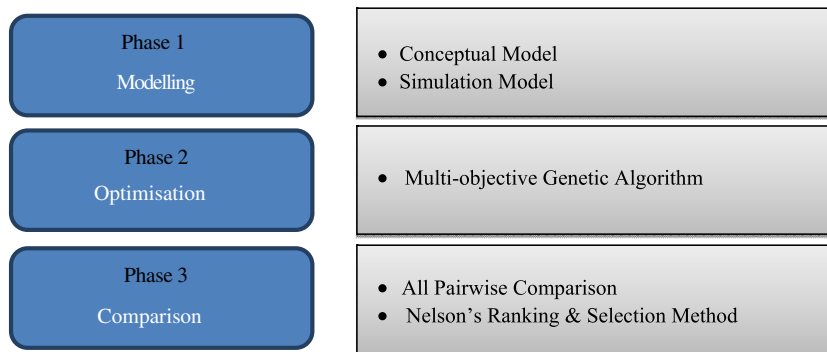


Fig. 6. A pictorial description of the methodology.

S-KAP of BK-CONWIP in a multi-product manufacturing system respectively.

The control mechanism of BK-CONWIP has three parameters (basestock, CONWIP and Kanban). The initial state of BK-CONWIP has a predefined number of basestock with no CONWIP cards and Kanbans attached to them, at the output buffer of the final stage. Also, resource pools of CONWIP cards and Kanbans have a pre-planned number of CONWIP cards and Kanbans. When a demand for a product-type occurs, the demand splits into the total number of stages +1 demand information. The demand information is transmitted to each of the stages while the last demand information is transmitted to the last stage output buffer for the release of a finished product-type in order to satisfy the demand. If the manufacturing processes of the stages are available and the raw material/semi-finished product types are available, production of the product types begins in all of the stages simultaneously. However, if any of the elements are unavailable, the production will be delayed. In the last stage, a push control mechanism controls production and the CONWIP cards are released immediately after the manufacturing process of the last stage.

### 3. Research methodology

In this study, the performance metrics of interest are the level of WIP inventory and the service level achieved by the pull control strategies operating D-KAP or S-KAP. The three fundamental procedures used here are modelling, multi-objective optimisation and comparison techniques. The system entities, their interactions and outcomes were identified in order to model the system. The identified entities were conceptually designed and translated into simulation models. The control parameters (Kanbans and

CONWIP cards) of the simulation models were optimised using a multi-objective optimisation block developed for ExtendSim [38]. The models were simulated and the outcome was compared using all pairwise comparison technique and Nelson’s ranking and selection technique. Fig. 6 shows a pictorial description of the research methodology used in this study. This section provides a description of the system modelled, the modelling assumptions, the verification, the validation of the models, the parameters of the system, the optimisation and comparison techniques.

#### 3.1. A description of the system modelled

The system studied is a two-product three-stage serial flow line described by Olaitan and Geraghty [36]. The flow line was modified to have no minimal blocking policy as shown in Fig. 7. The structure of the flow line was rearranged to produce three products and four products. The two product serial flow line is referred as Case 1 while the three and four product flow lines are referred as Case 2 and Case 3 respectively. The production capacity, loading and the level of variability were considered in selecting the processing times, Mean Time Between Failures (MTBF), and the Mean Time to Repair (MTTR). The models were initially run for 20 replications using a simple push control strategy with infinite demand and 100% manufacturing process availability in order to determine a realistic level of loading of the production capacity. The mean outputs (13593–case 1, 13601–case 2 and 13587–case 3) and the mean time between demands were recorded. The mean time between demands for 100% manufacturing process availability of the push model was used to determine the mean time between demands for 90% manufacturing process availability in each of the cases. For instance, in case-1, the mean time between demands for product 1 is given as 5.61 h and for product 2 as 5.72 h obtained

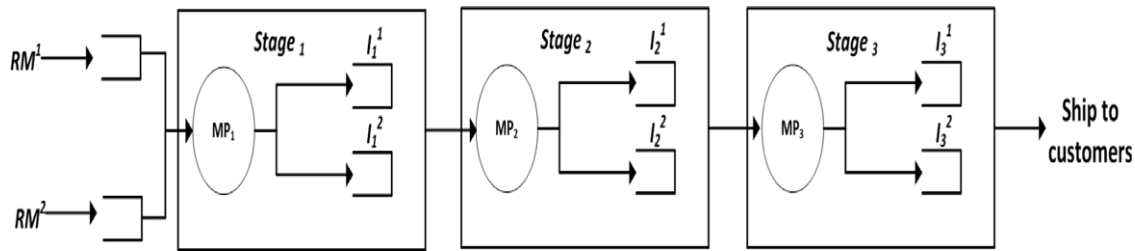


Fig. 7. Case-1 two-product three-stage manufacturing system.

Table 3  
The system configuration.

	Stage	Product 1 processing time (hours)	Product 2 processing time (hours)	Product 3 processing time (hours)	Product 4 processing time (hours)	MTBF exponential distribution mean (hours)	MTTR exponential distribution mean (hours)
Case 1 (2-product system)	1	1.50	3.00	N/A	N/A	90.00	10.00
	2	1.50	3.00	N/A	N/A	90.00	10.00
	3	1.50	3.00	N/A	N/A	90.00	10.00
	Demand	$\sim N(5.61, 2.81)$	$\sim N(5.72, 0.57)$	N/A	N/A		
Case 2 (3-product system)	1	1.50	3.00	1.50	N/A	90.00	10.00
	2	1.50	3.00	1.50	N/A	90.00	10.00
	3	1.50	3.00	1.50	N/A	90.00	10.00
	Demand	$\sim N(8.48, 0.92)$	$\sim N(8.63, 4.63)$	$\sim N(8.38, 6.54)$	N/A		
Case 3 (4-product system)	1	1.50	3.00	1.50	3.00	90.00	10.00
	2	1.50	3.00	1.50	3.00	90.00	10.00
	3	1.50	3.00	1.50	3.00	90.00	10.00
	Demand	$\sim N(11.32, 2.76)$	$\sim N(11.33, 8.43)$	$\sim N(11.28, 1.11)$	$\sim N(11.35, 5.62)$		

from the push model analysis. The standard deviation of product 1 is set at 2.805 h (50% of its mean) while that of product 2 is set to 0.572 h (10% of its mean). This corresponds to 90% capacity loading level of the system. The same method was used for determining the mean and standard deviation of product demands in cases 2 and 3.

The products are set to have low to high demand variability and the system is required to deliver a high service level with the least possible WIP inventory. MTBF and MTTR are exponentially distributed. MTBF with a mean of 90 h and MTTR with a mean of 10 h were modelled such as to represent a 90% manufacturing process availability. A summary of the processing times, demand, MTBF and MTTR is provided in Table 3 for cases 1, 2 and 3.

StatFit ([www.promodel.com](http://www.promodel.com)) application software was used to fit an appropriate distribution to the data. Normal distribution ranked highest under the lower bound condition and was selected. According to Olaitan and Geraghty [36] a normal distribution is suitable for modelling distributions, which combine two or more events. The importance of the use of a normal distribution is because the values of the mean and standard deviation would simply combine to represent various levels of variations in demand. Therefore, values for the standard deviation for the two products were set to correspond to a low and a high level of demand variations. The demand information is provided in Table 3.

### 3.2. Modelling of the system

Modelling in this study is the representation of a system via a logical framework. In manufacturing system analysis studies, simulation is widely used to model systems owing to its advantages over analytic techniques, especially its computation time [39–41]. Simulation modelling uses logical objects (icons) or program instructions (codes) to represent entities of a system and their interactions. These objects are constructed and configured to mimic the behaviour of the system modelled. The accuracy of designing and configuring the model determines the extent to which the model represents the actual system.

In this study, an object-oriented simulation tool (Extendsim) from Imagine That Inc. ([www.extendsim.com](http://www.extendsim.com)) was used to model the manufacturing system. The process followed in modelling the system is (i) the identification of the relevant entities, (ii) the designing of the entities' structure and (iii) the linking of the entities' interactions with each other as the actual system. The system entities modelled include the manufacturing processes, buffers, demands, operators, finished-products, WIP levels, and PAC. The events captured in the modelling are the demand arrival, starting and finishing point of part processing, manufacturing process failure and repair. Owing to the complexity of manufacturing system entities and their interactions, assumptions were made to minimise the challenges in modelling. The complexity of the system was simplified in the model by removing some of the characteristics of the systems that have an insignificant effect on the results of the model. Hence, the following assumptions were made:

- Two to four product types are produced in a three-stage serial-line via the same manufacturing process.
- The demand profile is stochastic in nature and unsatisfied demand within a defined period is logged as backlog and is served in the next period before satisfying the demand of the next period.
- There are three stages in the manufacturing system with each having a similar manufacturing process.
- The three stages are assumed to have negligible setup.
- The manufacturing processes are assumed to have an operation dependent breakdown such that a manufacturing process can only breakdown during processing of a part-type.
- The time for loading and unloading a manufacturing process is negligible.
- The information flow in the system occurs within a negligible time. The demands and the production authorisation cards' information are instantaneous.
- Any negative output generated due to a normal distribution used in representing the demand arrival event will produce arrival of demand.

**Table 4**  
WIP results for model validation.

PCS + KAP	Average total WIP from Olaitan and Geraghty [36], with minimal blocking policy at 95% SL	Average total WIP from current models with minimal blocking policy at 95% SL	Average total WIP from current models with no minimal blocking policy at 95% SL	Confidence interval of differences between average total WIP of columns 2 and 3
CONWIP D-KAP	47.000	47.000	Not applicable	0.000
KCS D-KAP	47.764	47.557	Not applicable	0.207 ± 0.284
EKCS D-KAP	46.835	46.609	Not applicable	0.226 ± 0.272
EKCS S-KAP	46.252	46.112	Not applicable	0.140 ± 0.153
GKCS D-KAP	44.278	44.187	Not applicable	0.091 ± 0.116
GKCS S-KAP	43.832	44.024	Not applicable	−0.192 ± 0.207
HK-CONWIP D-KAP	Not applicable	36.376	32.204	Not applicable
HK-CONWIP S-KAP	Not applicable	36.529	32.101	Not applicable
BK-CONWIP D-KAP	Not applicable	33.877	31.633	Not applicable
BK-CONWIP S-KAP	Not applicable	33.25	30.051	Not applicable

- A warm-up period of 15 000 h, 50 000 h run-length and 30 simulation replications as described by Olaitan and Geraghty [36] were used in carrying out the experiments in this study.

The model was verified to ensure accuracy with the system. A structural walk through and a stage by stage examination of the models were conducted. Corrections were made to the models, wherever errors or inaccuracies were found. The production capacities and the throughput of the models were tested. The validation of the models was based on the study of Olaitan and Geraghty [36], which confirms the accuracy of the models used here. Table 4 shows the comparison of WIP results from models developed by Olaitan and Geraghty [36] and the models used in this work.

### 3.3. Performance measures

The performance measures often used in Pull production control strategy comparison are the average WIP inventory in the system and the average service level that the system achieved after a defined length of time [12,36,39,40]. The use of targeted service level at a minimum WIP inventory level has been widely used in pull production control strategy comparisons [36]. For instance, Geraghty and Heavey [40] based their comparison on the level of WIP inventory of a system that would achieve targeted service levels. In this study, a minimum WIP inventory that would achieve targeted service levels of 95%, 98% and 100% was used as the performance measure for comparison of the pull production control strategies and production authorisation card policies.

### 3.4. Optimisation

The performance of pull control strategies significantly depends on the settings of the parameters. Setting control parameters to their best values before comparing pull control strategies highlights the outcome of the strategies [36,41]. Khojasteh-Ghamari [39], defines the optimal setting of the production authorisation cards of a strategy as a minimum number of production authorisation cards required by the system to achieve maximum or targeted throughput. Additional production authorisation cards to the optimal value will increase the WIP inventory in the system. A majority of real-life manufacturing problem consists of immediate optimisation of numerous objectives that are difficult to measure and at the same time are conflicting. On the other hand, the single objective optimisation has a well-defined single target for the optimal solution such that any good combination in the search space within the targeted objective function is considered a solution, while in multi-objective optimisation, a set of alternative trade-offs, referred to as Pareto-optimal solutions is generated. These solutions are non-dominated such that they are superior to all other solutions within the search space.

The control parameters of the model were optimised to operate in their best performance. A scenario manager block combined

with a multi-objective optimisation block [38] of ExtendSim were used in the optimisation. The Extendsim optimisation searches for a solution via genetic algorithms. The mutation rate, the crossover, the number of generations, the number of replications, the production authorisation cards and the basestock level of the strategy are the variables that affect the percentage of the search space and the number of solutions produced. The aim of the multi-objective is to establish a trade-off between conflicting objectives such that a set of non-dominated solutions would become a guide or support a decision process for managers or production personnel to co-ordinate production authorisations and manage inventory in a multi-product system while maintaining targeted or higher service levels.

In this work, the multi-objective optimisation block developed by Kernan and Geraghty [38] for Extendsim was used. The multi-objective optimisation method is iterative and requires a check by the user in order to express preferences of iterations based on the user's defined interest (e.g. a low WIP level, while achieving a high service level) for a solution. The steps followed are (i) a pre-defined mutation rate (0%–20%) and crossover rate (0%–100%) expected to achieve a high service level with the lowest WIP inventory was determined by varying the settings, (ii) the search was set to termination after 150 generations if the search failed to find optimal solutions, (iii) the number of PAC and the basestock level are defined, (iv) the Extendsim multi-objective optimisation block is simulated and the solutions were recorded.

The parameters of the multi-objective optimisation block were configured as follows: (i) the mutation rate of 10% was selected for the experiments after testing various mutation rates ranging from 0% to 20% on the HK-CONWIP D-KAP and BK-CONWIP S-KAP models. During the trial test for the selection of a mutation rate, it was observed that higher mutation rates of up to 15% reduced the outcome with respect to the number of generations obtained. (ii) The crossover rate of 70% was selected after testing a range of crossover rates of 0%–100% at 10% mutation rate. (iii) The number of specific generation before termination of the search is 150 generations. According to Kernan and Geraghty [38], a generation of 150 is significantly large enough to achieve a good solution search. (iv) The number of replications is 30. 30 replications were found to have statistically a high confidence level from similar and relevant experiments [12,36].

### 3.5. Comparison techniques

To understand the difference between the strategies, the pairwise comparison analysis and Nelson's ranking and selection technique were adopted in this study. The performances (minimum WIP required to achieve targeted 95%, 98% and 100% service levels) of the strategies for cases 1–3 were screened and ranked.

Pairwise comparison is useful for evaluating the criteria of systems. It is used where differences between systems are



subjective and unclear [36]. The technique matches the mean of each system to the mean of each of the alternatives. A system is awarded a point for outperforming an alternative in each one-on-one comparison. A system is awarded half of a point for a tie with an alternative. The system with the highest total points is the superior system to its alternatives. Pairwise comparison satisfies the Condorcet (fairness) criterion in selecting a superior system. A pairwise comparison was used in this study to screen the strategies for an overall 95% confidence level for nine sets. The Bonferroni Approximation was used such that an individual confidence level is adjusted to 99.17% confidence level. The difference of means of the samples ( $t$ -statistics) and the confidence interval for the  $t$ -statistics was determined.

Nelson's ranking and selection technique [42] authorises the removal of poorer performing PCS + KAP during screening without additional simulations. Survivors of the screening are gathered into a set for further comparison based on additional simulations. However, if the survivors' set contains only one survivor, it is selected as the superior PCS + KAP. In this study, the two-stage ranking and selection (combined) procedure for systems proposed by Nelson et al. [42], was used to select the superior strategy. The parameters of Nelson's combined procedure used in this work are as follows:  $k = 4$ , where  $k$  is the number of systems for screening and selection. The initial number of replication is denoted as  $n_0$  such that  $n_0 = 30$ . An additional number of simulation replications in cases of further screening is  $N_i$ .  $\bar{Y}_i$  is the mean of the sample data. The variance of the sample data is represented as  $S_i^2$ , the overall confidence level ( $\alpha$ ) is 90% for the combined procedure, that is  $\alpha = 0.1$ , also confidence level of 95% for each of the two-stage sampling procedures is given as  $\alpha_0 = \alpha_1 = \frac{\alpha}{2} = 0.05$ . A practical significant difference of 0.2 unit quantities is reasonable [36]. Rinott's integral  $h$  is given as  $h = h(1 - \alpha_1, n_0, k) = 3.129$ .  $W_{ij} = t(\frac{S_i^2}{n_0} + \frac{S_j^2}{n_0})^{0.5}$ , where  $t = t_{1 - (1 - \alpha_0)^{\frac{1}{k-1}}, n_0 - 1}$ ,  $t = 2.5336$ .

## 4. Experimental results

In this section, the outcome of the simulation-based optimisation experiments is presented. Also, the analysis of the performance of the strategies in terms of the WIP inventory and service levels achieved is provided.

### 4.1. Optimal solution

In this study, the main optimisation parameter with significant influence on the performance metrics of the system is the production authorisation cards (CONWIP and Kanban cards). The search range for the optimal parameters is 1–90. The result of the decision setting obtained at 95% service level while maintaining minimum WIP inventory is presented in Table 5.

The result of the search solution shows the decision set that achieves the 95% service level. Table 5 shows that strategies combined with S-KAP have the least number of production authorisation cards. BK-CONWIP has a smaller proportion of production authorisation cards and basestock levels than HK-CONWIP. Similarly, BK-CONWIP combined with S-KAP has the least proportion of production authorisation cards and basestock levels in the system.

### 4.2. WIP inventory and service level

The simulation results of the average total WIP inventory at 95%, 98% and 100% average service levels of the strategies are presented in Table 6 for case-1, while the results of the average total WIP inventory of the strategies for cases 2 and 3 are presented in Tables 7 and 8 respectively.

An observation of the data presented in Table 5 (PAC and basestock level optimal values) and Tables 6–8 (average total WIP) indicates that BK-CONWIP S-KAP has the least production authorisation cards and maintained the least WIP inventory in the experiments. BK-CONWIP S-KAP was observed to outperform its alternatives. Similarly, HK-CONWIP S-KAP outperformed HK-CONWIP D-KAP in terms of WIP control. In contrast, HK-CONWIP D-KAP has the highest level of WIP inventory in the system. BK-CONWIP D-KAP has better WIP control than both HK-CONWIP S-KAP and HK-CONWIP D-KAP. In general, BK-CONWIP outperformed HK-CONWIP while S-KAP outperformed D-KAP.

Furthermore, the WIP inventory, production authorisation cards and throughput of the strategies at varying number of product types were investigated. The outcome of the WIP inventory and the throughput (total finished product output) of the strategies in cases 1–3 are presented in Table 9.

The result (Table 9) shows that the number of product types has similar throughput (mean output) with different proportions of production authorisation cards and WIP inventory levels. Also, the WIP inventory level varies across strategies. For instance, strategies have the least production authorisation cards and WIP inventory levels when the system produces two product types. The proportion of production authorisation cards and WIP inventory levels is at the highest level when the system produced four product types. Again, BK-CONWIP S-KAP has the least production authorisation cards and it is the best performer. BK-CONWIP outperformed HK-CONWIP while S-KAP outperformed D-KAP.

### 4.3. Selection of the superior strategy

The result of the pairwise comparison is presented in Table 10. Any positive confidence interval without zero between the upper and lower bounds indicates the strategy on the row-level has significantly a smaller number of WIP inventory (better performer) than the strategy on the column-level. However, a negative confidence interval without zero between the upper and lower bounds shows that the strategy on the column-level has statistically a smaller proportion of WIP inventory than the strategy on the row-level. If zero exists between the lower and upper bounds, the two strategies have no significant difference (ties).

Table 10 shows the outcome of the pairwise comparison analysis of the WIP inventory level achieved by the strategies at different service levels. From the table, there are no zeros between the upper and lower bounds of the confidence intervals for all the tests. In each comparison, a point is awarded to the best performer and the strategy with the total highest points is the superior. The strategy with the total highest points is ranked 1 (the best performer) and the strategy with the least points is ranked 4 (the worst performer). BK-CONWIP S-KAP has a total of 27 points (9 in each case), followed by BK-CONWIP D-KAP with 18 points (6 in each case), and next is HK-CONWIP S-KAP with 9 points (3 in each case). HK-CONWIP did not win any comparison test and has zero points. A summary of the ranking of the strategies owing to the confidence intervals is presented in Table 11. BK-CONWIP S-KAP is superior to its alternatives in terms of maintaining the least average total WIP inventory in the system.

The outcome of the application of Nelson's combined procedure is presented in Tables 12–14. Table 12 shows the result of the best strategy at 100% service level for case-1, while Tables 13 and 14 show the results of the best strategy at 100% service level for cases 2 and 3 respectively.

The results of the application of Nelson's combined procedure of the sampled data (WIP at 100% service level for the three cases—Tables 12–14) show that only one strategy (BK-CONWIP S-KAP)

**Table 5**  
Cases 1–3 Pareto optimal values of PCS + KAP at 95% service level.

Stage			1	2	3	CONWIP	Kanban	Basestock
PCS	KAP	Product	CONWIP	Kanbans		Basestock	Total	Total
Case 1	D-KAP	1	21	8	14	21	41	38
		2	20	8	8	20		
HK-CONWIP	S-KAP	1	40	12	16	21	40	28
		2				19		
Case 1	D-KAP	1	20	8	7	19	35	27
		2	15	6	6	14		
BK-CONWIP	S-KAP	1	32	13	13	16	32	26
		2				14		
Case 2	D-KAP	1	23	9	15	17	68	65
		2	23	9	13	16		
		3	22	8	11	17		
HK-CONWIP	S-KAP	1	59	23	34	16	59	57
		2				16		
		3				15		
Case 2	D-KAP	1	21	8	7	16	58	46
		2	18	7	8	16		
		3	19	8	8	15		
BK-CONWIP	S-KAP	1	48	21	20	16	48	41
		2				15		
		3				15		
Case 3	D-KAP	1	26	9	15	18	98	83
		2	25	9	13	16		
		3	23	8	11	17		
		4	24	8	10	16		
HK-CONWIP	S-KAP	1	86	27	38	17	86	65
		2				16		
		3				16		
		4				16		
Case 3	D-KAP	1	23	7	7	15	86	55
		2	21	6	7	14		
		3	22	6	7	13		
		4	20	7	8	11		
BK-CONWIP	S-KAP	1	65	23	26	14	65	49
		2				13		
		3				12		
		4				12		

CONWIP cards loop the entire system, Kanbans are not applicable to stage 3, Basestock levels for stages 1 and 2 are zeros.

**Table 6**  
Case-1 optimisation results of PCS + KAP for average total WIP with 95% confidence interval half widths at targeted service levels (SL).

PCS KAP	HK-CONWIP		BK-CONWIP	
	D-KAP	S-KAP	D-KAP	S-KAP
Average total WIP at 95% SL	32.20 ± 0.263	32.10 ± 0.248	31.63 ± 0.242	30.05 ± 0.229
Average total WIP at 98% SL	41.57 ± 0.266	39.30 ± 0.254	37.37 ± 0.248	36.54 ± 0.242
Average total WIP at 100% SL	54.57 ± 0.291	54.02 ± 0.273	52.30 ± 0.263	51.40 ± 0.251

**Table 7**  
Case-2 optimisation results of PCS + KAP for average total WIP with 95% confidence interval half widths at targeted service levels (SL).

PCS KAP	HK-CONWIP		BK-CONWIP	
	D-KAP	S-KAP	D-KAP	S-KAP
Average total WIP at 95% SL	44.25 ± 0.371	42.63 ± 0.315	40.75 ± 0.418	39.654 ± 0.338
Average total WIP at 98% SL	54.56 ± 0.465	50.55 ± 0.413	47.06 ± 0.376	45.79 ± 0.321
Average total WIP at 100% SL	67.88 ± 0.574	65.74 ± 0.389	63.49 ± 0.454	61.14 ± 0.385

survived the screening procedure and was selected as best strategy over its alternatives. This verifies the observation (Tables 6–8) that BK-CONWIP outperforms HK-CONWIP while a strategy combined with S-KAP outperforms the same strategy combined with D-KAP. It validates the pairwise comparisons (Tables 10 and 11) that

BK-CONWIP S-KAP has the highest number of points (in pairwise comparison) and the only strategy that survived all the screening (in Nelson’s combined procedure). BK-CONWIP S-KAP is selected as the best performer in terms of minimisation of WIP inventory in a multi-product serial flow line.

**Table 8**

Case-3 optimisation results of PCS + KAP for average total WIP with 95% confidence interval half widths at targeted service levels (SL).

PCS KAP	HK-CONWIP		BK-CONWIP	
	D-KAP	S-KAP	D-KAP	S-KAP
Average total WIP at 95% SL	55.03 ± 0.507	53.16 ± 0.359	49.87 ± 0.405	46.26 ± 0.387
Average total WIP at 98% SL	67.54 ± 0.353	61.80 ± 0.437	56.76 ± 0.452	54.05 ± 0.411
Average total WIP at 100% SL	83.14 ± 0.496	79.46 ± 0.433	75.67 ± 0.362	73.88 ± 0.378

**Table 9**

Result for multi-product HK-CONWIP and BK-CONWIP at 100% service level.

PCS + KAP	Number of product types	(MTBF, MTTR) Exponentially distributed	Total PAC count	Total basestock count	Mean output	Standard deviation output	Average total WIP
HK-CONWIP D-KAP	2	(90, 10)	98	44	12 357	129	55
HK-CONWIP S-KAP	2	(90, 10)	92	43	12 352	154	54
BK-CONWIP D-KAP	2	(90, 10)	88	39	12 360	122	52
BK-CONWIP S-KAP	2	(90, 10)	84	35	12 359	103	51
HK-CONWIP D-KAP	3	(90, 10)	112	52	12 360	253	68
HK-CONWIP S-KAP	3	(90, 10)	106	50	12 355	248	66
BK-CONWIP D-KAP	3	(90, 10)	102	45	12 361	232	63
BK-CONWIP S-KAP	3	(90, 10)	97	41	12 357	211	61
HK-CONWIP D-KAP	4	(90, 10)	131	58	12 359	287	83
HK-CONWIP S-KAP	4	(90, 10)	123	55	12 357	256	79
BK-CONWIP D-KAP	4	(90, 10)	116	51	12 358	249	75
BK-CONWIP S-KAP	4	(90, 10)	112	46	12 360	235	74

**Table 10**

Confidence interval of differences between average total WIP of PCS + KAP.

Case 1	PCS + KAP	HK-CONWIP S-KAP	BK-CONWIP D-KAP	BK-CONWIP S-KAP
WIP at 95% SL	HK-CONWIP D-KAP	-0.0992 ± 0.0208	-0.5689 ± 0.0291	-2.1483 ± 0.0458
	HK-CONWIP S-KAP	-	-0.4697 ± 0.0083	-2.0491 ± 0.0250
	BK-CONWIP D-KAP	-	-	-1.5794 ± 0.0167
WIP at 98% SL	HK-CONWIP D-KAP	-2.2694 ± 0.0167	-4.1991 ± 0.0250	-5.0287 ± 0.0333
	HK-CONWIP S-KAP	-	-1.9297 ± 0.0083	-2.7594 ± 0.0167
	BK-CONWIP D-KAP	-	-	-0.8297 ± 0.0083
WIP at 100% SL	HK-CONWIP D-KAP	-0.5491 ± 0.0250	-2.2686 ± 0.0375	-3.1680 ± 0.0541
	HK-CONWIP S-KAP	-	-1.7195 ± 0.0125	-2.6189 ± 0.0291
	BK-CONWIP D-KAP	-	-	-0.8994 ± 0.0167
Case 2	PCS + KAP	HK-CONWIP S-KAP	BK-CONWIP D-KAP	BK-CONWIP S-KAP
WIP at 95% SL	HK-CONWIP D-KAP	-1.62 ± 0.0601	-3.49 ± 0.0245	-4.60 ± 0.0311
	HK-CONWIP S-KAP	-	-1.89 ± 0.0501	-2.98 ± 0.0184
	BK-CONWIP D-KAP	-	-	-1.11 ± 0.0163
WIP at 98% SL	HK-CONWIP D-KAP	-4.01 ± 0.0092	-7.50 ± 0.0106	-8.77 ± 0.0187
	HK-CONWIP S-KAP	-	-3.49 ± 0.0264	-4.76 ± 0.0229
	BK-CONWIP D-KAP	-	-	-1.27 ± 0.1328
WIP at 100% SL	HK-CONWIP D-KAP	-2.14 ± 0.0187	-4.39 ± 0.0229	-6.74 ± 0.0324
	HK-CONWIP S-KAP	-	-2.25 ± 0.0265	-4.60 ± 0.0187
	BK-CONWIP D-KAP	-	-	-2.35 ± 0.0132
Case 3	PCS + KAP	HK-CONWIP S-KAP	BK-CONWIP D-KAP	BK-CONWIP S-KAP
WIP at 95% SL	HK-CONWIP D-KAP	-1.87 ± 0.0350	-5.16 ± 0.0748	-8.77 ± 0.0262
	HK-CONWIP S-KAP	-	-3.29 ± 0.0494	-6.90 ± 0.0418
	BK-CONWIP D-KAP	-	-	-3.61 ± 0.0229
WIP at 98% SL	HK-CONWIP D-KAP	-5.74 ± 0.0804	-10.78 ± 0.793	-13.49 ± 0.0561
	HK-CONWIP S-KAP	-	-5.04 ± 0.0296	-7.75 ± 0.0208
	BK-CONWIP D-KAP	-	-	-2.71 ± 0.0374
WIP at 100% SL	HK-CONWIP D-KAP	-3.68 ± 0.0477	-7.47 ± 0.0804	-9.26 ± 0.0276
	HK-CONWIP S-KAP	-	-3.79 ± 0.0418	-5.58 ± 0.0396
	BK-CONWIP D-KAP	-	-	-1.79 ± 0.0561

**Table 11**  
The ranking summary of the pairwise comparison.

Case 1	HK-CONWIP D-KAP	HK-CONWIP S-KAP	BK-CONWIP D-KAP	BK-CONWIP S-KAP
WIP at 95% SL	4	3	2	1
WIP at 98% SL	4	3	2	1
WIP at 100% SL	4	3	2	1
Case 2	HK-CONWIP D-KAP	HK-CONWIP S-KAP	BK-CONWIP D-KAP	BK-CONWIP S-KAP
WIP at 95% SL	4	3	2	1
WIP at 98% SL	4	3	2	1
WIP at 100% SL	4	3	2	1
Case 3	HK-CONWIP D-KAP	HK-CONWIP S-KAP	BK-CONWIP D-KAP	BK-CONWIP S-KAP
WIP at 95% SL	4	3	2	1
WIP at 98% SL	4	3	2	1
WIP at 100% SL	4	3	2	1

**Table 12**  
Case-1 application of Nelson’s combined procedure for the best strategy (WIP at 100% SL).

PCS + KAP	<i>i</i>	<i>n<sub>o</sub></i>	$\bar{Y}_i$	$S_i^2$	<i>j</i>	$W_{ij}$	$\bar{Y}_j + \max(0, W_{ij} - \epsilon)$	Keep/Eliminate	<i>N<sub>i</sub></i>
HK-CONWIP D-KAP	1	30	54.57	4.16	2	0.695	54.516	Eliminate	1154
					3	1.028	53.516		
					4	0.921	52.125		
HK-CONWIP S-KAP	2	30	54.02	3.56	1	0.695	55.067	Eliminate	972
					3	0.819	52.920		
					4	0.622	51.825		
BK-CONWIP D-KAP	3	30	52.30	3.43	1	1.028	55.400	Eliminate	936
					2	0.819	54.640		
					4	0.988	52.192		
BK-CONWIP S-KAP	4	30	51.40	1.81	1	0.921	55.294	Keep	494
					2	0.622	54.443		
					3	0.988	53.090		

**Table 13**  
Case-2 application of Nelson’s combined procedure for the best strategy (WIP at 100% SL).

PCS + KAP	<i>i</i>	<i>n<sub>o</sub></i>	$\bar{Y}_i$	$S_i^2$	<i>j</i>	$W_{ij}$	$\bar{Y}_j + \max(0, W_{ij} - \epsilon)$	Keep/Eliminate	<i>N<sub>i</sub></i>
HK-CONWIP D-KAP	1	30	67.88	5.72	2	1.808	67.348	Eliminate	1833
					3	1.579	64.869		
					4	1.546	62.486		
HK-CONWIP S-KAP	2	30	65.74	6.31	1	1.808	69.488	Eliminate	2080
					3	1.629	64.919		
					4	1.597	62.537		
BK-CONWIP D-KAP	3	30	63.49	3.46	1	1.579	69.259	Eliminate	710
					2	1.629	67.169		
					4	1.333	62.273		
BK-CONWIP S-KAP	4	30	61.14	3.08	1	1.546	69.226	Keep	567
					2	1.597	67.137		
					3	1.333	64.623		

**Table 14**  
Case-3 application of Nelson’s combined procedure for the best strategy (WIP at 100% SL).

PCS + KAP	<i>i</i>	<i>n<sub>o</sub></i>	$\bar{Y}_i$	$S_i^2$	<i>j</i>	$W_{ij}$	$\bar{Y}_j + \max(0, W_{ij} - \epsilon)$	Keep/Eliminate	<i>N<sub>i</sub></i>
HK-CONWIP D-KAP	1	30	83.14	7.23	2	1.999	81.259	Eliminate	1972
					3	1.845	77.315		
					4	1.805	75.485		
HK-CONWIP S-KAP	2	30	79.46	7.48	1	1.999	84.939	Eliminate	2041
					3	1.863	77.333		
					4	1.824	75.504		
BK-CONWIP D-KAP	3	30	75.67	5.29	1	1.845	84.785	Eliminate	1444
					2	1.863	81.123		
					4	1.653	75.333		
BK-CONWIP S-KAP	4	30	73.88	4.77	1	1.805	84.745	Keep	1301
					2	1.824	81.084		
					3	1.653	77.123		

## 5. Discussion

The result of the multi-objective optimisation (Table 5) shows that BK-CONWIP requires the least production authorisation cards and basestock levels to achieve a targeted service level in cases 1–3. A low proportion of basestock and production authorisation cards in a system will result in a low WIP inventory level. The low proportion of production authorisation cards and basestock in BK-CONWIP is largely attributed to the mode of demand information flow. The delay of information in HK-CONWIP results in the untimely response to demand. Therefore, to meet a targeted service level, higher proportions of basestock and production authorisation cards are required in HK-CONWIP. Similarly, the table shows that strategies operating S-KAP have a lower proportion of production authorisation cards and basestock level than when the same strategies operate D-KAP. This is attributed to the way in which cards are shared in S-KAP such that a single pool of cards is used to release part-types.

The effect of the low proportion of basestock levels and production authorisation cards is evident in the WIP inventory results (Tables 6–8). The table shows that BK-CONWIP outperformed HK-CONWIP in cases 1–3 at different service levels. Direct observation from Tables 6–8 shows that BK-CONWIP in both S-KAP and D-KAP modes consistently outperformed HK-CONWIP. However, the differences between WIP inventories of the strategies are relatively small. Therefore, it is worthwhile to investigate if there is any significant difference between WIP inventories of the strategies. Also, it was observed that a strategy combined with S-KAP consistently maintained a fewer quantity of WIP inventory in the system when compared to the same strategy combined with D-KAP. Again, the difference in WIP inventories is relatively small and requires statistical confirmation.

The result of the application of the pairwise comparison (Table 10) in cases 1–3, shows statistical evidence of differences in the WIP inventories of the strategies. The result indicates that BK-CONWIP outperformed HK-CONWIP in all the comparisons. Similarly, a strategy combined with S-KAP outperforms the same strategy combined with D-KAP. For instance, HK-CONWIP S-KAP outperformed HK-CONWIP D-KAP in cases 1–3. The ranking of the performance of the strategies based on pairwise comparison (Table 11) shows that BK-CONWIP S-KAP is superior to its alternatives. Therefore, BK-CONWIP is a better performer than HK-CONWIP while S-KAP outperformed D-KAP. Furthermore, the result of the application of Nelson's combined procedure in cases 1–3 affirms the superiority of the performance of BK-CONWIP over HK-CONWIP in terms of WIP inventory. BK-CONWIP S-KAP is the lone survivor of all the screening conducted and it is selected as the superior strategy.

The number of product types influenced the WIP inventory (Table 9) in the system. The proportion of the WIP inventory is increased with an increase in the number of product types. The table shows that the two product system (case 1) maintained the least WIP inventory level in all the targeted service levels, the three product system (case 2) had the second least WIP inventory levels while the four product system (case 3) had the highest WIP inventory level. Similarly, the results in Table 9 show that a higher total number of basestock level and production authorisation cards are required with an increase in the number of product types, resulting in proliferation of WIP in the system. This is attributed to the need to maintain a sufficient number of production authorisation cards and basestock level that will respond to the demand of those product types. Additionally, it is postulated that the number of stages in a multi-product flow-line would influence the proportion of the production authorisation card and basestock levels. In general, BK-CONWIP S-KAP consistently maintained the least basestock level, PAC and WIP inventory levels in all the cases.

The superior performance of BK-CONWIP in terms of WIP control, over its alternatives is attributed to its ability to maintain low PAC and basestock levels in a system.

## 6. Conclusion and future research

We examined two strategies and policies in three cases (2-product, 3-product and 4-product systems). The findings are consistent throughout this study. It was shown that (i) an increase in the number of product types in a serial flow line will increase the WIP inventory, (ii) a strategy combined with S-KAP requires a smaller number of control parameters and it will achieve a fewer proportion of WIP inventory than the same strategy combined with D-KAP, (iii) BK-CONWIP requires the least control parameters and it is more effective in WIP inventory control than HK-CONWIP.

The outcomes of the pairwise comparison analysis and the application of Nelson's combined screening and selection procedure validates the superiority of S-KAP over D-KAP and the superiority of BK-CONWIP over HK-CONWIP. It was shown that when minimisation of the average total WIP for targeted service levels is a concern to the decision makers; S-KAP combined with BK-CONWIP is recommended because it responds quicker to demand variability than D-KAP. BK-CONWIP S-KAP is selected as the overall best strategy.

Practical implications of this study are mainly to multi-product manufacturing flow lines. The multi-objective optimisation provides support for a selection of the control parameters to achieve a targeted or a new service level without additional optimisations. Similarly, implementation of BK-CONWIP S-KAP will improve the service level of the system while minimising WIP.

Further studies are required to provide clearer guidance to operation managements in selection and implementation of PCS under robust conditions and system instabilities, such studies could include an increase in the manufacturing stages to understand the effect of the flowline length to the WIP inventory, also complex manufacturing system (parallel/serial flow line, an increase in the number of products, non-similar manufacturing processes and different product-families with complex changeover times).

## References

- [1] Spearman ML, Woodruff D, Hopp W. CONWIP: a pull alternative to Kanban. *Int J Prod Res* 1990;28:879–94.
- [2] Park CW, Lee HS. Performance evaluation of a multi-product CONWIP assembly system with correlated external demands. *Int J Prod Econ* 2013;144:334–44.
- [3] Duri C, Frein Y, Di-Mascolo M. Comparison among three pull control policies: Kanban, base stock, and generalized Kanban. *Ann Oper Res* 2000;93:41–69.
- [4] Spearman ML. Customer service in pull production system. *Oper Res* 1992;40:948–58.
- [5] Spearman ML, Zazanis MA. Push and pull production systems: issues and comparisons. *Oper Res* 1992;40:521–32.
- [6] Mustadt JA, Tayur SR. A comparison of alternative Kanban control mechanisms. I. Background and structural results. *IIE Trans* 1995;27:140–50.
- [7] Mustadt JA, Tayur SR. A comparison of alternative Kanban control mechanisms. II. Experiment results. *IIE Trans* 1995;27:151–61.
- [8] Pettersen JA, Segerstedt A. Restricted work-in-process: a study of differences between Kanban and CONWIP. *Int J Prod Econ* 2009;118:199–207.
- [9] Takahashi K, Myreshka D, Hirovani. Comparing CONWIP, synchronized CONWIP, and Kanban in complex supply chains. *Int J Prod Econ* 2005;93–94:25–40.
- [10] Bonvik AM, Dallery Y, Gershwin SB. Approximate analysis of production systems operated by a CONWIP/finite buffer hybrid control policy. *Int J Prod Res* 2000;38:2845–69.
- [11] Buzacott JA, Shanthikumar JG. A general approach for coordinating production in multiple-cell manufacturing systems. *Prod Oper Manage* 1992;1:34–52.
- [12] Bonvik AM, Christopher C, Gershwin SB. A comparison of production line control mechanisms. *Int J Prod Res* 1997;35:789–804.
- [13] Wang Y., Cao J., Kong L. Hybrid Kanban/CONWIP control system simulation and optimization based on theory of constraints. In: Conference proceedings on intelligent computing and intelligent systems, IEEE international conference, Shanghai, Vol. 2. 2009. p. 666–70.

- [14] Gaury EGA, Pierrel H, Kleijnen JPC. An evolutionary approach to select a pull system among Kanban, CONWIP and hybrid. *J Intell Manuf* 2000;11:157–67.
- [15] Gaury EGA, Kleijnen JPC, Pierrel H. A methodology to customize pull control systems. *J Oper Res Soc* 2001;52:789–99.
- [16] Geraghty J, Heavey C. A comparison of hybrid push/pull and CONWIP/pull production inventory control policies. *Int J Prod Econ* 2004;91:75–90.
- [17] Hodgson TJ, Wang D. Optimal hybrid push/pull control strategies for a parallel multi-stage system: Part I. *Int J Prod Res* 1991;29:1279–87.
- [18] Hodgson TJ, Wang D. Optimal hybrid push/pull control strategies for a parallel multi-stage system: Part II. *Int J Prod Res* 1991;29:1453–60.
- [19] Onyeocha C.E., Khoury J., Geraghty J.. Evaluation of the effect of erratic demand on a multi-product Basestock Kanban-CONWIP control strategy. In: Proceedings of the 9th conference on stochastic models of manufacturing and service operations, Kloster Seon. 2013.
- [20] Baynat B, Buzacott JA, Dallery Y. Multi-product Kanban-like control systems. *Int J Prod Res* 2002;40:4225–55.
- [21] Onyeocha C.E., Geraghty J.. A modification of the hybrid Kanban CONWIP production control strategy for multi-product manufacturing systems. In: IMC29: International manufacturing conference proceedings, University of Ulster, Belfast, UK. 2012.
- [22] Akturk MS, Erhun F. An overview of design and operational issues of Kanban systems. *Int J Prod Res* 1999;37:3859–81.
- [23] Hum SH, Lee CK. JIT scheduling rules: a simulation evaluation. *Omega* 1998;26:381–95.
- [24] Feng W, Zheng L, Li J. Scheduling policies in multi-product manufacturing systems with sequence-dependent setup times and finite buffers. *Int J Prod Res* 2012;50:7479–92.
- [25] Renna P, Magrino L, Zaffina R. Dynamic card control strategy in pull manufacturing systems. *Int J Comput Integr Manuf* 2013;26:881–94.
- [26] Bard JF, Golany B. Determining the number of Kanbans in a multi-product, multi-stage production system. *Int J Prod Res* 1991;29:881–95.
- [27] Ajorlou S, Shams I. Artificial bee colony algorithm for CONWIP production control system in a multi-product multi-manufacturing process manufacturing environment. *J Intell Manuf* 2013;24:1145–56.
- [28] Satyam K, Krishnamurthy A. Performance evaluation of a multi-product system under CONWIP control. *IIE Trans* 2008;40:252–64.
- [29] Duenyas I. A simple release policy for networks of queues with controllable inputs. *Oper Res* 1994;42:1162–71.
- [30] Ryan SM, Baynat B, Choobineh F. Determining inventory levels in a CONWIP controlled job shop. *IIE Trans* 2000;32:105–14.
- [31] Ryan SM, Vorasayan J. Allocating work in process in multi-product CONWIP system with lost sales. *Int J Prod Res* 2005;43:223–46.
- [32] Khojasteh Y, Sato R. Selection of a pull production control system in multi-stage production processes. *Int J Prod Res* 2015; <http://dx.doi.org/10.1080/00207543.2014.1001530>.
- [33] Huang G, Chen J, Wang X, Shi Y. A simulation study of CONWIP assembly with multi-loop in mass production, multi-products and low volume and OKP environments. *Int J Prod Res* 2014; <http://dx.doi.org/10.1080/00207543.2014.980458>.
- [34] Onyeocha CE. An investigation of pull control strategies and production authorisation cards in a multi-product plant in the presence of environmental variability. *Comput Sci Appl* 2014;1:67–84.
- [35] Onyeocha CE, Khoury J, Geraghty J. A comparison of Kanban-like control strategies in a multi-product manufacturing system under erratic demand. In: Pasupathy R, Kim S-H, Tolk A, Hill R, Kuhl ME, editors. Proceedings of the winter simulation conference. Washington (DC, USA): IEEE; 2013. p. 2730–41.
- [36] Olaitan OA, Geraghty J. Evaluation of production control strategies for negligible-setup, multi-product, serial lines with consideration for robustness. *J Manuf Technol Manage* 2013;24:331–57.
- [37] Krishnamurthy A, Suri R, Vernon M. Re-examining the performance of MRP and Kanban material control strategies for multi-product flexible manufacturing systems. *Int J Flex Manuf Syst* 2004;16:123–50.
- [38] Kernan B., Geraghty J.. A multi-objective genetic algorithm for extend. In: Proceedings of the first Irish workshop on simulation in manufacturing, services and logistics, Limerick. 2004. p. 83–92.
- [39] Khojasteh-Ghamari Y. A performance comparison between Kanban and CONWIP controlled assembly systems. *J Intell Manuf* 2009;20:751–60.
- [40] Geraghty J, Heavey C. A review and comparison of hybrid and pull-type production control strategies. *OR Spectrum* 2005;27:435–57.
- [41] Koulouriotis DE, Xanthopoulos AS, Tourassis VD. Simulation optimisation of pull control policies for serial manufacturing lines and assembly manufacturing systems using genetic algorithms'. *Int J Prod Res* 2010;48:2887–912.
- [42] Nelson BL, Swann J, Goldsman D, Song W. Simple procedures for selecting the best simulated system when the number of alternatives is large. *Oper Res* 2001;49:950–63.