

Development and evaluation of a Basestock-CONWIP pull production control strategy in balanced assembly systems

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ABSTRACT

In this study, a new pull production control strategy called Basestock-Constant Work-in-Process (B-CONWIP) is proposed. It is used to control the flow of materials and information in balanced assembly production systems. This proposed control strategy uses one type of authorization cards called CONWIP card that limits the work-in-process (WIP) in the whole system. It has been applied in a single-product and a mixed-product assembly system balanced by two efficient Genetic algorithms introduced in literature. The performance of this control strategy is compared with another pull production control strategy called Basestock Kanban CONWIP (BK-CONWIP), which is a very promising production control strategy found in literature. The proposed strategy has two control parameters, CONWIP authorization cards and basestock levels while BK-CONWIP has three control parameters Kanban authorization cards, CONWIP authorization cards and basestock levels. The comparison is based on three performance measures average system WIP, percentage of satisfied customer demand (service level) and WIP variation between workstations. The performance of the proposed strategy B-CONWIP and BK-CONWIP is mainly similar in both types of assembly systems when mean demand rates are low with respect to mean service rates with the proposed strategy being easier to control and optimize. On the other hand, when mean demand rates are high with respect to mean service rates; B-CONWIP is preferable if service level is more important, while BK-CONWIP is preferable if WIP level is more important. Regarding WIP variation, it mainly depends on the efficiency of the balancing approach. The more efficient the balancing approach, the less WIP variation. Treating demand as lost instead of backordered results in decreased average system WIP and does not affect service levels in both PCSs. It is also shown that S-KDP is more flexible in dealing with situations of variable product mixes than D-KDP because control parameters can be used by any product which minimizes the effect of the unbalanced systems.

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1. Introduction and literature review

In serial production systems the manufacturing of parts passes through several stages. Each stage has a workstation to perform a manufacturing process and a buffer space for inventory. During the passage of a part from upstream stages to downstream stages, raw material is converted to finished products. Production systems can be classified according to the flow of parts, information and release of orders into push, pull and hybrid systems. The difference between pull and

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push systems is in the mechanism used to control the flow of materials and information through the production system. A push production system releases parts based on forecasted demand and raw materials availability. In contrast, a pull system releases parts based on actual demand and the availability of the raw materials and production authorization cards which give permission to workstations to start production. Hybrid systems integrate merits of different pull systems, or different push systems, or both [9].

Pull production systems which are referred to as just-in-time (JIT), use authorization cards (Kanban or CONWIP) to authorize the release of parts into a system. Several mechanisms called production control strategies (PCS) are used to regulate and control the flow of materials and information in pull systems; such as, Kanban Control Strategy (KCS) [26], Base Stock Control Strategy (BSCS) [13], Constant Work-In-Process Control Strategy (CONWIP) [25], Hybrid Kanban CONWIP Control Strategy (HK-CONWIP) [3]. These strategies limit the WIP in the system using a specific number of authorization cards in order to achieve specific goals such as improving customer satisfaction level or minimizing WIP. The advantages of these pull PCS lie in their ability to eliminate waste, reduce WIP and improve customer service levels [13].

According to previous studies on PCS that were performed in single product systems [7,8,14,24]; it is shown that pull control strategies (KCS, BSCS, CONWIP and HK-CONWIP), achieved high service levels and low WIP levels which led to a reduction in production cost, inventory, lead time and an increase productivity and fill rate.

In multi-product systems, pull PCS can be operated by two different policies called Kanban Distribution Policies (KDP); Shared Kanban Distribution Policy (S-KDP) or Dedicated Kanban Distribution Policy (D-KDP) (Bayant et al. [2], Faccio et al. [6] and Lolli et al. [16]). In D-KDP, an authorization card is used for a specific product type and cannot be used to authorize other product types so the part cannot be released into a system when that specific authorization card for that part is not available. On the other hand, in S-KDP presented by Bayant et al. [2], an authorization card can be shared among product-types, and can be used to release any available part type, depending only on the availability of demand information and raw material. Sharing of authorization cards among product types leads to quick response to any change in demand volume or product mix and reduces WIP in multi-product systems.

Unfortunately, the results of Bayant et al. [2] showed that pull PCS, such as KCS, BSCS, CONWIP and HK-CONWIP, can be operated only with D-KDP and cannot be operated with S-KDP as a result of the coupling between authorization cards, demand information and parts. This coupling means that the authorization card is attached to a specific product type from the beginning and cannot be shared among different products which prevents the usage of S-KDP [19]. Therefore, a large number of authorization cards for every product are required which leads to an increase in WIP in each stage for every product type in the system. This also leads to long lead times, poor service levels and high waste and production cost [27]. This is not compatible with the concept and objectives of pull production systems. In addition, these control strategies have drawbacks such as, long delays, high response times to high demand volume and product mix variation [17,28].

These drawbacks of pull PCS in multi-product systems led researchers to develop new pull PCS, which can separate demand information from authorization cards to operate S-KDP in addition to D-KDP, with the objective of minimizing WIP and improving service levels. Several pull PCS which have the ability to operate S-KDP were developed such as, Extended Kanban control strategies (EKCS) [5], Generalized Kanban Control Strategy (GKCS) [4], Basestock Kanban CONWIP Control Strategy (BK-CONWIP) [19], Modified Hybrid Kanban CONWIP Control Strategy (MHK-CONWIP) [20]. In these strategies, the authorization cards are not coupled to demand information which allows for the implementation of both S-KDP and D-KDP policies.

The results of Baynat et al., [2] proved that, S-KDP outperformed D-KDP when using the same pull PCS, in terms of WIP and service levels. In another study performed by Olaitan and Geraghty [18], S-KDP and D-KDP were applied in multi-product systems with several pull PCS (BSCS, CONWIP, GKCS, EKCS, KCS). The study found that, PCS that can apply both S-KDP and D-KDP (EKCS, GKCS) perform better with S-KDP. It also found that control strategies that can only apply D-KDP (BSCS, CONWIP, KCS) are found to perform poorly with respect to strategies that can apply both. Piplani and Ang [22] made a comparison between KCS, BSCS and EKCS (both D-KDP and S-KDP) that control multi-product systems in terms of a total cost measure. It was proved that the both types of EKCS perform better than the other two control strategies. On the other hand, there was no a big difference in the performance of dedicated and shared EKCS.

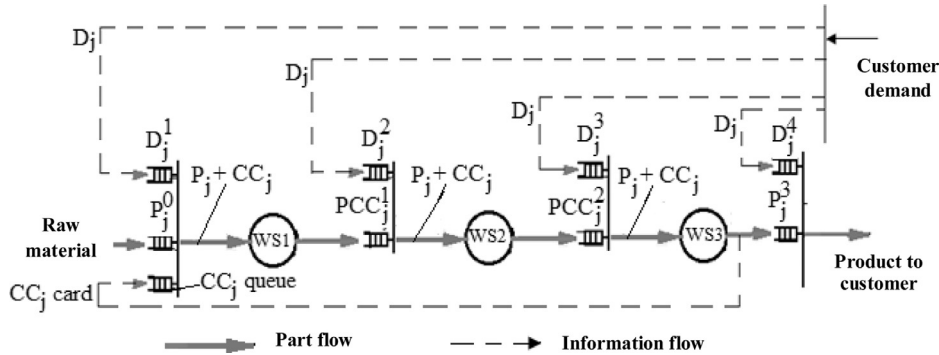
Onyeocha et al. [20,21] studied the performance of BK-CONWIP strategy with S-KDP and D-KDP in a multi-product system. The performance of this strategy was checked and compared with other strategies (EKCS, GKCS, HK-CONWIP) under several factors; erratic demand, product mix variation, significant setup time and demand volume variation. The performance of BK-CONWIP combined with S-KDP was found to be the best for all the examined production conditions when WIP level is the priority for selection, but when customer satisfaction (service level) is the priority; BK-CONWIP combined with D-KDP was found to be the best strategy for all examined production conditions.

In this study, a new pull PCS called Basestock-Constant Work-in-Process (B-CONWIP) is presented. This strategy is a hybrid of BSCS and CONWIP. It has been applied in a single-product and a mixed-product assembly system balanced by two efficient Genetic algorithms (GA). The two (GAs) are the Priority-based Genetic Algorithm (PriGA) presented by Hwang et al. [10], and the Multiple Assignment Genetic Algorithm (MA-GA) presented by Al-Hawari et al. [1], which are used to assign tasks to workstations and perform assembly line balancing. The performance of this control strategy is compared with BK-CONWIP [19], which outperformed other pull PCS. The proposed strategy uses two of the three control parameters used by BK-CONWIP namely; Basestock and CONWIP cards and excludes Kanban cards. The basestock level is the minimum inventory for a stage that is needed to satisfy any unanticipated demand. CONWIP card is similar to a Kanban card, it is used to limit WIP in the whole system while a Kanban card is used to limit WIP only in one stage in the system.

Table 1

Symbol description.

Symbol	Description	Symbol	Description
$S^{1,2, \dots}$	Stage 1, 2, i, ..., m	$P_{1,2, \dots}$	Product 1, 2, j, ..., n
$WS^{1,2, \dots}$	Workstation at stage 1, 2, ..., m	P_j^i	Queue of part j at buffer space of stage i
P_j^0	Raw material for product j	D_j	Demand card for product j
D_j^i	Queue of demand card for product j at stage i	K_j^i	Kanban card for product j at stage i
A_j^i	Queue of Kanban card dedicated to product j at stage i	PA_j^i	Queue of kanban attached with part j at stage i
DA_j^i	Queue of demand card attached with Kanban card for product j at stage i	CC_j	CONWIP Card for product j in a system
PCC_j^i	Queue of product j attached with CONWIP card	DCC_j	Queue of demand card attached with CONWIP card for product j in a system

**Fig. 1.** Queuing model of B-CONWIP control strategy with three stages.

The comparison is based on three performance measures which are service level, WIP level and WIP variation. The performance of the proposed strategy in a balanced assembly system is studied and compared with BK-CONWIP using both D-KDP and S-KDP mode. Both control strategies are applied to assembly systems balanced by the two Genetic algorithms. The effect of these balancing algorithms is examined in both cases. Also, the effect of demand rate change on the performance of these strategies is studied.

2. The proposed B-CONWIP control strategy

The strategy introduced in this study is a hybrid of BSCS PCS and CONWIP PCS. It uses two control parameters; Basestock level and CONWIP authorization cards. These control parameters are set to perform specific objectives such as, minimizing WIP and achieving specific service levels. This control strategy has been developed to control the flow of information and materials in balanced assembly systems. In most assembly systems, different algorithms are used to balance the system, optimize line efficiency, minimize workload variation among workstations and eliminate bottleneck workstations. Therefore, line balancing will be used in the suggested Pull PCS; B-CONWIP, as an alternative to Kanban authorization cards which would have a similar effect of controlling WIP between stations as Kanbans because of the reduced variation in WIP between stations. This makes this control strategy easier to control than BK-CONWIP because of excluding Kanban cards.

To explain how parts and information flow in B-CONWIP, a queuing model is used. The queuing model consists of a synchronization station and a queuing network [15]. The synchronization station consists of a server with zero time that performs synchronization between parts, demand cards and authorization cards.

Some common symbols used in the queuing model of B-CONWIP strategy are shown in Table 1. Superscript (i) refers to the stage number S^i ($i = 1, \dots, m$). A subscript (j) refers to the product number P_j ($j = 1, \dots, n$). (Note: when there is only one product in a system, the subscript is removed).

Fig. 1 shows the queuing model of B-CONWIP. As shown, the demand information in B-CONWIP is transferred globally simultaneously into all workstations in the system once demand occurs. As an illustration, when the customer demand for product j (D_j) arrives to the system, then the following happens: (a) the demand information are separated into $m + 1$ signals, where m is the number of stages, these signals join their respective demand information queues D_j^i , (b) for the first stage, if raw material is present in P_j^0 queue prior to the first stage as well as a CONWIP card CC_j in CC_j queue and demand information in D_j^1 queue, the CONWIP card is attached to the raw material and transferred to WS^1 for processing. Once the processing starts in WS^1 the demand information D_j is eliminated from D_j^1 queue. After processing is finished, the processed part with CONWIP card ($P_j + CC_j$) enters PCC_j^1 queue as a couple. It waits for the presence of the demand information for stage 2 (D_j) in D_j^2 queue. If present, the couple ($P_j + CC_j$) is transferred to WS^2 for processing, and the demand information

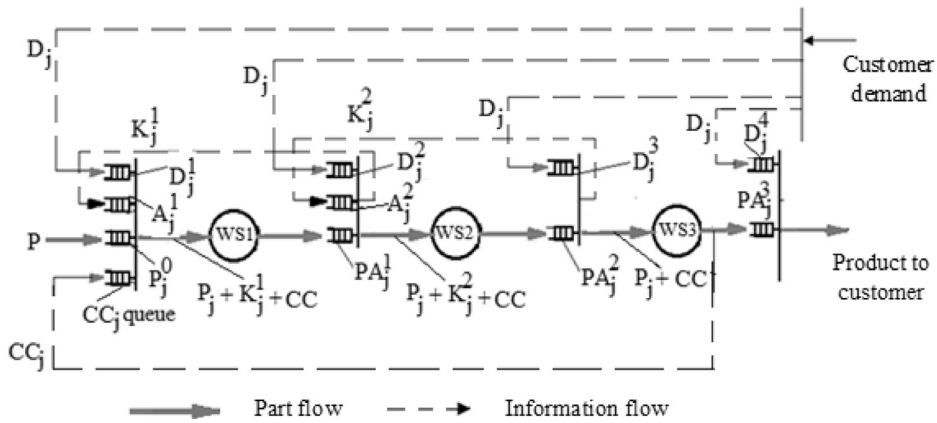


Fig. 2. Queuing model of BK-CONWIP control strategy with three stages.

D_j is eliminated from D_j^2 queue once the processing starts. When the couple $(P_j + CC_j)$ reaches the final workstation (WS^3), it is processed. Similarly, the couple leaves the final workstation, the CONWIP card CC_j is detached from the part P_j , and sent upstream to CC_j queue in front of the first stage, simultaneously part P_j is sent downstream and stored in P_j^3 queue. As soon as the demand information D_j is present in D_j^4 queue the part P_j is sent to a customer and demand is satisfied. As shown, the CONWIP card is separated from the part before the part enters the last buffer space, and it is sent back to the CC queue in front of the first stage to prevent coupling between demand information and authorization cards. B-CONWIP control strategy can be operated by S-KDP and D-KDP. In D-KDP, a specific number of CONWIP cards are assigned to each product in order to give production authorization, while in S-KDP, a specific number of CONWIP cards are assigned to give production authorization for any product type.

On the other hand, the BK-CONWIP strategy presented by Onyeocha and Geraghty [19] is a hybrid of BSCS, KCS and CONWIP control strategies, and is controlled by three parameters, Kanban cards to control WIP level between stages, CONWIP cards to limit WIP level in the whole system, and basestock to satisfy unanticipated demand. Fig. 2 shows the queuing model of the BK-CONWIP strategy. Once demand arrives to the system, it is transferred instantaneously into all stages in the system. If a part is present in the buffer space of the last stage, it is sent to the customer and the demand is satisfied. As shown, there is no Kanban for the last stage and the CONWIP card is separated from parts before the part enters the last buffer space and sent back to CONWIP queue in front of the first stage.

3. Experimental setup

3.1. System description

In this research, two assembly systems are used as case studies. The first is a single model assembly system taken from literature. The second, is a real-life mixed model assembly system that assembles two products. The following subsections present a detailed explanation of each system.

3.1.1. Single model assembly system

Two pull PCS are applied in the single model assembly system that consists of multi-workstations and produces one homogeneous product. The total assembly workload needed to assemble a product is divided into small tasks. A task is defined as the smallest work unit that can be done independently in a workstation, and the time needed to accomplish it is called task time. This system is defined by the number of tasks, task times, precedence relations which is a diagram that determines the relations between tasks and how the tasks are ordered on an assembly line; and a theoretical cycle time that is determined based on a desired production rate. The tasks are assigned to workstations while the precedence relations and predetermined cycle time constraints are maintained.

This system described by [23] has the following characteristics:

- The system assembles one homogenous product in mass quantities.
- The workstations are arranged in a serial sequence, and there are no parallel subassembly lines or feeders.
- The tasks have deterministic processing times
- A task must be performed only in one workstation and cannot be divided among two or more workstations.
- Any task can be processed in any workstation, where associated costs of all workstations are the same.
- The number of machines or workers are the same for all workstations.
- The task processing time is independent of the workstation.

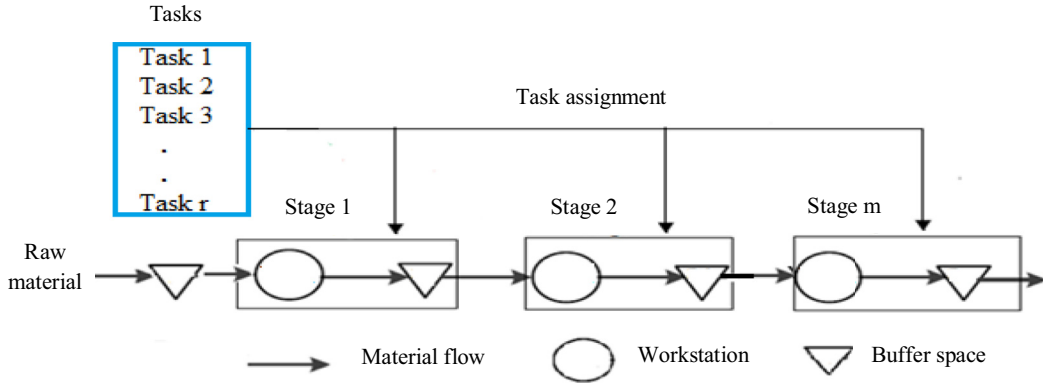


Fig. 3. Single model assembly system.

- The system is 100% reliable and no failures were considered.

Fig. 3 shows the single model assembly system. As shown, the GAs are used to balance the system and assign tasks to workstations in order to optimize certain objectives such as minimizing the number of workstations and cycle time, and optimizing system performance measures such as work load variation (W_v) and balanced line efficiency (E). The workload variation measures the variation or dispersion around the average utilization of workstations, while the balanced line efficiency measures the ability of a system to produce a product with the lowest idle time. They can be calculated using the following equations:

$$W_v = \sqrt{\frac{\sum_{i=1}^m (U_i - \bar{U})^2}{m}} \quad (1)$$

$$E = \frac{\text{Sum of task times} \times 100\%}{\text{number of workstations (m)} \times \text{cycle time (C)}} \quad (2)$$

Where:

U_i : Utilization of the workstation i , $i = 1, \dots, m$

$\bar{U}$: is the average utilization of workstations

3.1.2. Mixed model assembly system

The second system is a real-life case study taken from Classic Fashion Apparel Company located at Al-Hasan Industrial City in Irbid, Jordan. The production environment consists of a mixed assembly system which assembles two product types; jeans trousers and jackets. This assembly system consists of multi-workstations arranged sequentially and operated by manual workers using sewing machines with each sewer performing specific tasks. The following characteristics describe this system.

- The system assembles two product types in mass quantities.
- The tasks have deterministic processing times.
- The tasks performed to produce both product types are mainly the same while the task times may be different from one product type to another.
- A task must be performed only in one workstation and cannot be divided among two or more workstations.
- Any task can be processed in any workstation, where associated costs of all workstations are the same.
- The number of machines or workers are the same for all workstations.
- The task processing time is independent of the workstation.
- This system operates two 8-hour shifts, five days a week and workers have thirty- minute breaks.
- The system is 100% reliable and no failures were considered.

Fig. 4 shows the mixed assembly system for jeans trousers and jackets. According to customer demands, the assembly process is started. At first, a set of tasks are performed to assemble the back and front parts of the product. Then other parts such as pockets, zippers and labels are attached. The tasks, task times and precedence relations of the products are given in Appendix A. After completion of the assembly process, the final assembled product is transferred into a storage area where the demands for the final products arrive. The system receives daily Poisson distributed demands with a mean of 240 units per day for trousers and 230 units per day for jackets. The Poisson distribution was selected through demand data collected from the actual system and the input analyzer in Arena simulation software was used to find the appropriate distribution.

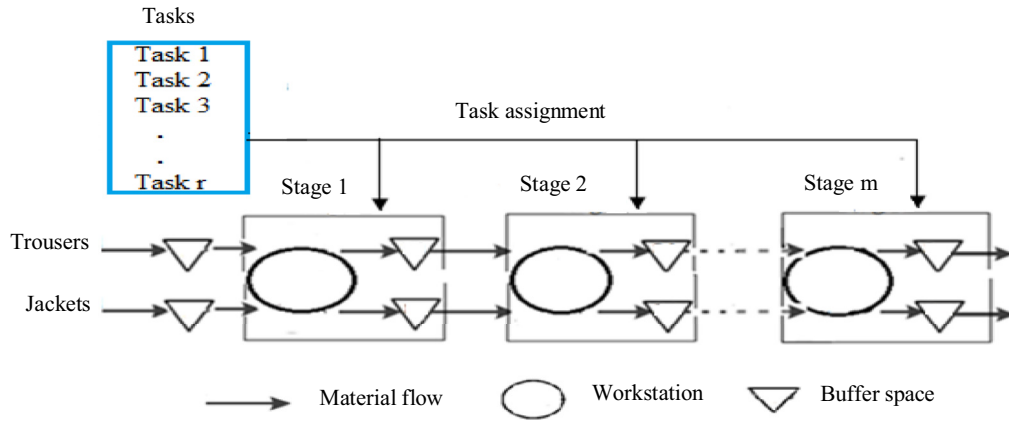


Fig. 4. Mixed model assembly system.

Table 2

Task times of two products A and B.

Task (k)	Task time product A	Successor task (k)	Task time product B	Successor task (k)
1	12	2,3	15	2,3
2	8	4	13	5
3	10	4,5	11	5
4	10	6	–	–
5	8	6	9	6
6	7	–	10	–

When the demand arrives to the system, the storage area is checked, if the final assembled products are available the demand is satisfied; otherwise, the demand is not satisfied and is dealt with as backlog.

To solve the balancing problem in the mixed assembly system, the concept used by Thomopoulos [29] will be applied. Typically, the products assembled by mixed assembly systems have several tasks in common with similar precedence relations. Thomopoulos concept replaces all products precedence diagrams by one combined precedence diagram and transfers a mixed assembly system into an equivalent single assembly system. The following steps will illustrate how the balancing problem is performed in mixed assembly systems:

Step 1: Precedence diagram for all products is drawn.

Step 2: The combined precedence diagram is constructed.

Step 3: A weighted average time required for each task in all products is calculated according to this formula.

$$T_k = \sum_{j=1}^n Pr_j * t_{kj} \quad (3)$$

Step 3: Where n is the number of products; Pr_j is the weighted average or proportion of the product j produced in a system, and t_{kj} is the time of task k in product j . The proportion of each product can be calculated as follows: $Pr_j = \frac{PR_j}{TPR}$, where PR_j is the desired production rate of product j in a specific period and TPR is the total desired production rate for all products in the same period.

Step 4: A new total production rate (TPR) for an equivalent single assembly system is calculated by summing production rates of all products.

Step 5: A new cycle time (C_n) for an equivalent single assembly system is calculated.

$$C_n = \frac{\text{Total available time per shift}}{TPR} = \frac{\text{shift time} * \text{system efficiency}}{TPR} \quad (4)$$

Step 6: Tasks are assigned to workstations by any balancing algorithm used in a single assembly system.

Numerical Example

To illustrate the steps mentioned above an example problem is solved. In this example, two products A and B with production rates 8 units/h and 12 units/h, respectively are assembled in a mixed assembly system. Most of the tasks are common between the two product types, in some cases task times are different from one product to another. Table 2 gives the task times of the two product types and precedence relations among the tasks.

Solution:

Step 1: The precedence diagram for products A and B are drawn as shown in Fig. 5.

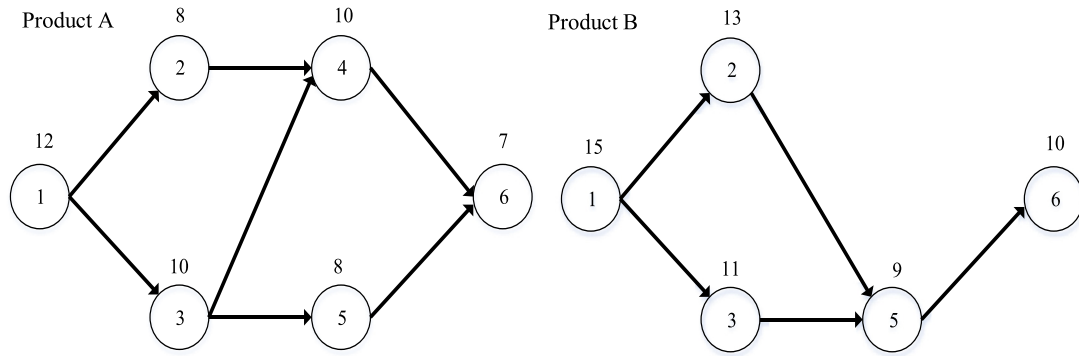


Fig. 5. Precedence diagram for products A and B.

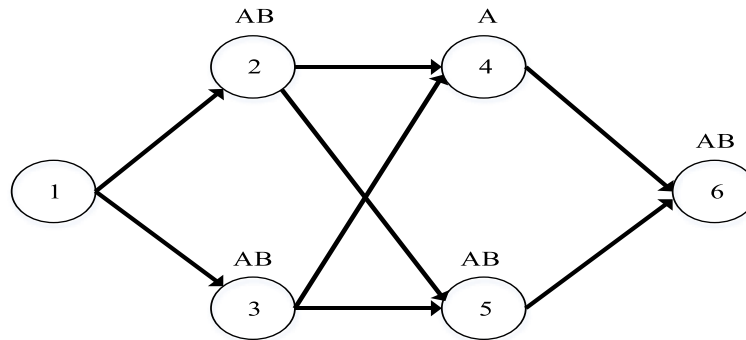


Fig. 6. Combined precedence diagram for Products A and B.

Table 3

Weighted average times required for tasks in products A and B.

Task (k)	$Pr_1 * t_{k1}$	$Pr_2 * t_{k2}$	$\sum_{j=1}^n Pr_j * t_{kj}$
1	$0.4 * 12 = 4.8$	$0.6 * 15 = 9$	13.4
2	$0.4 * 8 = 3.2$	$0.6 * 13 = 7.8$	11
3	$0.4 * 10 = 4$	$0.6 * 11 = 6.6$	10.6
4	$0.4 * 10 = 4$	–	4
5	$0.4 * 8 = 3.2$	$0.6 * 9 = 5.4$	8.6
6	$0.4 * 7 = 2.8$	$0.6 * 10 = 6$	8.8

Step 2: The combined precedence diagram is constructed as shown in Fig. 6.

Step 3: Total time required for each task in all products is calculated as shown in Table 3.

Step 4: A new total production rate (TPR) for an equivalent single assembly system is calculated.

Step 5: $PR = PR_1 + PR_2 = 8 + 12 = 20$ units/hour = 160 units/8 h shift.

Step 6: A new cycle time (C_n) for an equivalent single assembly system is calculated using Eq. (4):

$$C_n = \frac{480 * 0.95 \text{ min/shift}}{160 \text{ unit/shift}} = 2.85 \text{ min/unit}$$

Finally, the GAs used to balance the single product assembly system are used to balance this combined system.

3.1.3. Genetic balancing algorithms

Two GAs are used to solve the balancing problem in both assembly systems. The first algorithm is called Priority Genetic Algorithm (Pri-GA) presented by Hwang et al. [10], the second is the Multiple Assignment Genetic Algorithm (MA-GA) presented by Al-Hawari et al. [1]. These algorithms are developed to solve line balancing problems and assign tasks in straight and U-shaped assembly systems while trying to optimize three objectives; number of workstations, workload variation and line efficiency. The difference between Pri-GA and MA-GA is in the approach used to assign tasks to workstations. Three approaches, forward, backward and bidirectional assignment, are used to assign tasks. In the forward approach, tasks are assigned sequentially one by one into workstations from first to last until all tasks are assigned while the cycle time constraint is considered. In contrast, in the backward approach, tasks are assigned sequentially one by one into workstations from last to first. On the other hand, the bidirectional approach assigns tasks in both directions, forward and backward,

Table 4
Parameters configuration.

Parameter	Value
Population size	200
Maximum generation	1000
Crossover probability	0.7
Mutation probability	0.3
Selection size	$0.5 * \text{PopSize}$

from the first and the last workstations simultaneously. In Pri-GA, The forward assignment approach is used while MA-GA combines the three assignment approaches simultaneously, which increases the chance of discovering the optimal solution by increasing the number of feasible solutions.

Both genetic algorithms are coded using MATLAB R2008. Both are configured with the same parameters shown in Table 4 for the purpose of performing a meaningful comparison between the two algorithms.

The GAs use an elitism size of 20% in which the best 20% of the current population chromosomes are transferred to the next generation. Three terminating conditions were implemented if any one occurs the GAs are terminated which are:

- Optimal perfect line balance occurs i.e. Line efficiency $E = 100\%$ and workload variation $W_V = 0$.
- No improvement in the workload variation W_V is found in 200 generations.
- The maximum number of generations (MaxGen = 1000) is reached.

3.2. System modeling

3.2.1. Assumptions

In order to reduce the complexity in simulation modeling, many assumptions were made and taken into account while modeling both single and mixed assembly systems. These assumptions can be summarized in the following points:

- The demand quantity for products in both systems is equal to one unit per customer.
- There is no constraint on the availability of raw materials, so they are always available.
- Two cases were considered when insufficient inventory of finished products is available in the final buffer space; the first case in which demands are backordered. These backordered demands have priority over current demand by being satisfied first when inventory of finished products becomes sufficiently available. The second case considers lost demand with no backorders.
- The priority rule used in both systems is First in First out (FIFO). Which means that the oldest entity in the system is served or processed first.
- The set-up time is not taken into account in all workstations of both systems.
- The transfer time of parts and information in both systems is negligible.
- The total simulation period is 50,000 h.
- A warm-up period is estimated to be 10,000 hours for the single product assembly system and 13,500 h for the mixed product assembly system.
- The results of all simulation models are the average of thirty independent replicates.

3.2.2. Modeling

Simulation models are built using Rockwell Arena simulation software package version 14.5. The models are developed to evaluate the performance of pull PCS in assembly systems. They are also used to investigate the effect of various control parameters on the performance of assembly systems and to select the parameter values that optimize certain performance measures. The modeling of assembly systems controlled by BK-CONWIP and B-CONWIP control strategies can be divided into four main steps: (a) creating, transferring and satisfying customer demands, (b) creating and synchronizing the movement of authorization cards (CONWIP and Kanban) with parts, (c) part processing, (d) inventory replenishment. Fig 7 shows general modeling steps of the assembly system controlled by BK-CONWIP PCS and B-CONWIP PCS. The procedure of modeling is the same for both control strategies, except that, in B-CONWIP, there are no Kanban cards.

3.2.3. Validation

Validation is an approach for ensuring that the simulation model is correctly constructed, and the results are valid. To ensure that the simulation models, built in this work, are valid, the model of a system described by [20] and modeled by a simulation software called ExtentSim is reconstructed by Arena software in which the same conditions and assumptions were applied. The entities that enter the model were tracked step by step to ensure that the construction of the model is logically correct. Then, the Arena model was optimized under the same conditions and control parameters that were used in the ExtentSim model. Afterwards, WIP statistics obtained from the Arena model were compared to WIP statistics obtained from the ExtentSim model. Table 5 shows WIP statistics for both models. As shown, the difference between models is very small.

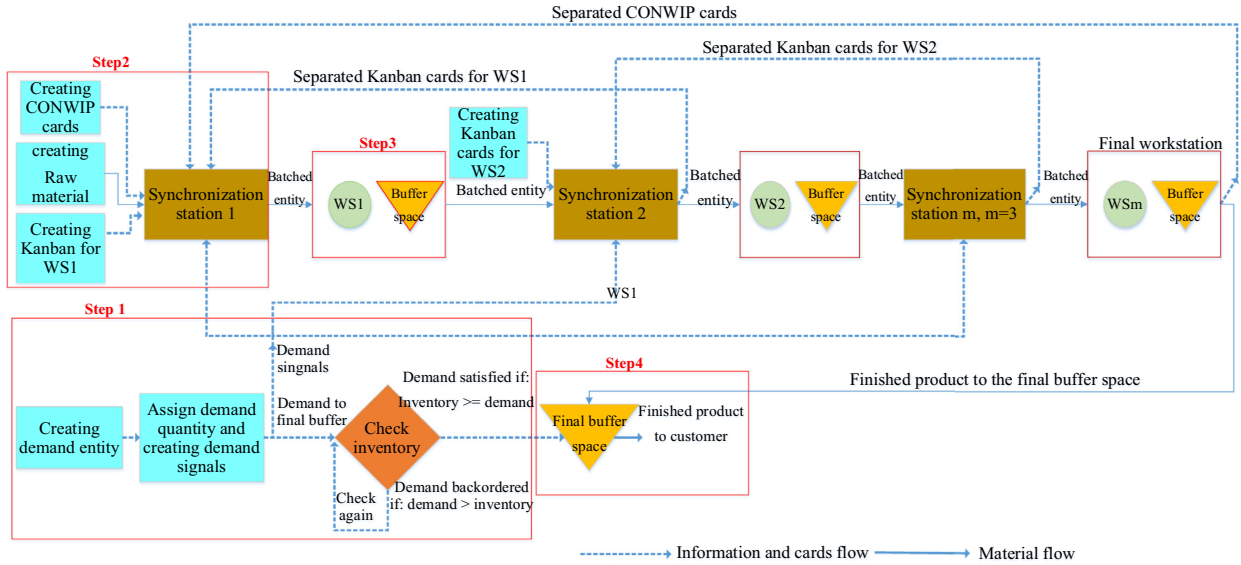


Fig. 7. Modeling steps of an assembly system controlled by BK-CONWIP or B-CONWIP Control strategy.

Table 5

Comparison of average WIP for the Arena model and the ExtendSim model.

Pull PCS	Avg system WIP of ExtendSim model with 100% service level	Avg system WIP of Arena model with 100% service level	Percentage difference
BK-CONWIP with S-KDP	63.34	63.7	0.56%
BK-CONWIP with D-KDP	72.86	72.80	0.082%

3.2.4. Performance measures and optimization

The performance of B-CONWIP and BK-CONWIP PCS applied in single and mixed balanced assembly systems are evaluated based on WIP levels, achieved service levels and WIP variation. WIP level is one of the most important performance measures used in the comparison of pull PCS because it has an essentially direct effect on other performance measures such as productivity, cost and lead time. Therefore, if it is under control, other measures become much easier to control. Another vital measure in the comparison of PCS is service level which represents the percentage of satisfied customer demands. It can be calculated as follows:

$$\text{Service level} = \frac{\text{Satisfied demand}}{\text{Total demand}} * 100\% \quad (5)$$

Another performance measure used is WIP variation which measures the variation or dispersion around the average system WIP of all workstations. This measure is used to evaluate the effect of using various assembly balancing algorithms on the performance of pull PCS. The smaller the WIP variation, the better performance of PCS. It can be calculated using the following formula:

$$WIP_v = \sqrt{\frac{\sum_{i=1}^m \left(\overline{WIP}_i - \overline{WIP} \right)^2}{m}} \quad (6)$$

Where:

$\overline{WIP}_i$ is the WIP average of workstation i over the simulation time period.

$\overline{WIP}$ is the grand average of WIP of all workstations $= \sum_{i=1}^m \frac{\overline{WIP}_i}{m}$.

To obtain the optimal values of these performance measures, the simulation models are optimized. A built-in tool in Arena software called OptQuest is used to perform the optimization process. The following steps are implemented to achieve the optimization process:

- Control parameters determined are CONWIP cards, Kanban cards and basestock levels in BK-CONWIP; and CONWIP cards and basestock levels in B-CONWIP.
- These parameters are determined based on maximizing service levels and minimizing WIP. Their values represent the minimum number of authorization cards (Kanban, CONWIP) and minimum basestock level to achieve optimal service and WIP level. Extra authorization cards and basestock will only lead to increase in WIP levels [12].

Table 6
Characteristics of single product assembly problems.

Problem	Number of tasks (r)	Total task times (min)
Heskia	28	1024
Tonge	70	3510
Arcus2	111	150,399

Table 7
Results from balancing algorithms.

Problem	Number of tasks	Cycle time	PriGA			MA-GA		
			m	E %	W_v	m	E %	W_v
Heskia	28	324	4	87.4	0.153	4	100	0.00
Tonge	70	468	8	94.2	0.014	8	96.7	0.007
Arcus2	111	17,067	9	97.9	0.006	9	99.6	0.001

The optimization problem is constructed as a trade-off between the minimization of WIP levels and the maximization of service levels. The specific service levels (e.g. 95%, 100%) are achieved while the average system WIP is maintained at the lowest level.

4. Experimental results and discussion

Several experiments are performed in order to evaluate the performance of BK-CONWIP and B-CONWIP PCS. The computational results of these experiments are presented. The main objective of this section is to show the difference between these PCS and to determine which PCS is better for balanced assembly systems.

4.1. Single product assembly system results

The experiments conducted to evaluate the performance of pull PCS in a single product assembly system use the data sets for assembly system problems (precedence relations and task times) presented in the website of Scholl and Klein [23]. These data sets were used to test the performance of various balancing algorithms in several studies. Three problem sizes were selected, a small size problem with 28 tasks, a medium size problem with 70 tasks and a large problem with 111 tasks which are shown in Table 6.

4.1.1. Assembly systems balancing

Initially, PriGA and MA-GA are used to solve the balancing problem of the assembly systems controlled by BK-CONWIP and B-CONWIP. The problem inputs are task times, precedence relations and cycle times while the outputs are the number of workstations, assignment of tasks to workstations, line efficiency (E) and workload variation (W_v). Table 7 summarizes the inputs and outputs of the problems balanced by PriGA and MA-GA.

4.1.2. Simulation model inputs

Next, the results from balancing; number of workstations and assignment of tasks, are used as inputs for simulations models. Another important input is the mean demand inter arrival time which is determined according to the service time of the bottleneck station. As a rule, to keep a system in a stable state, the mean demand inter arrival time has to remain greater than the service time of the bottleneck station [11]. For assembly problems studied here, the mean demand inter arrival time is selected to be slightly greater than the bottleneck station service time.

The simulation models are then optimized to select the control parameters which minimize the average system WIP and maximize the service level. Demand inter arrival times are assumed to be exponentially distributed (to be consistent with the Poisson distribution for demand arrivals) with a mean value greater than the value of the bottleneck station service time by 15% (all times are in minutes). Table 8 shows the values of the bottleneck station service times. Tables 9–11 summarize the best values obtained for the control parameters, which achieve minimum average system WIP and 100% service level. Afterwards, the sensitivity of system performance measures to demand rate change for each assembly problem is studied while keeping the control parameters fixed. Several values for the mean demand inter arrival times are selected which are greater than the bottleneck station service times by 10% and 5%, respectively. The smaller the percentage, the smaller the demand inter arrival time, the higher the demand rate becomes.

Both strategies, BK-CONWIP and B-CONWIP, are compared based on the average system WIP and WIP variation. From Tables 9–11 and Fig. 8, the following observations are noted:

- The basestock levels in a system controlled by either PCS and balanced by MA-GA are less than those in a system balanced by PriGA because of the superior efficiency of MA-GA.

Table 8
Bottleneck station service times.

Balancing algorithm	Problem	Service time (min)
Pri-GA	Heskia	262
	Tonge	463
	Arcus2	17,052
MA-GA	Heskia	256
	Tonge	443
	Arcus2	16,837

Table 9

Optimal values of control parameters at 100% service level for Heskia problem.

Problem	PCS	Number of CONWIP	Number of Kanbans for WS ⁱ			Basestock
			K1	K2	K3	
Heskia balanced by PriGA	BK-CONWIP	10	7	6	6	28
	B-CONWIP	10	Without Kanban			28
Heskia balanced by MA-GA	BK-CONWIP	8	6	5	6	22
	B-CONWIP	8	Without Kanban			22

Table 10

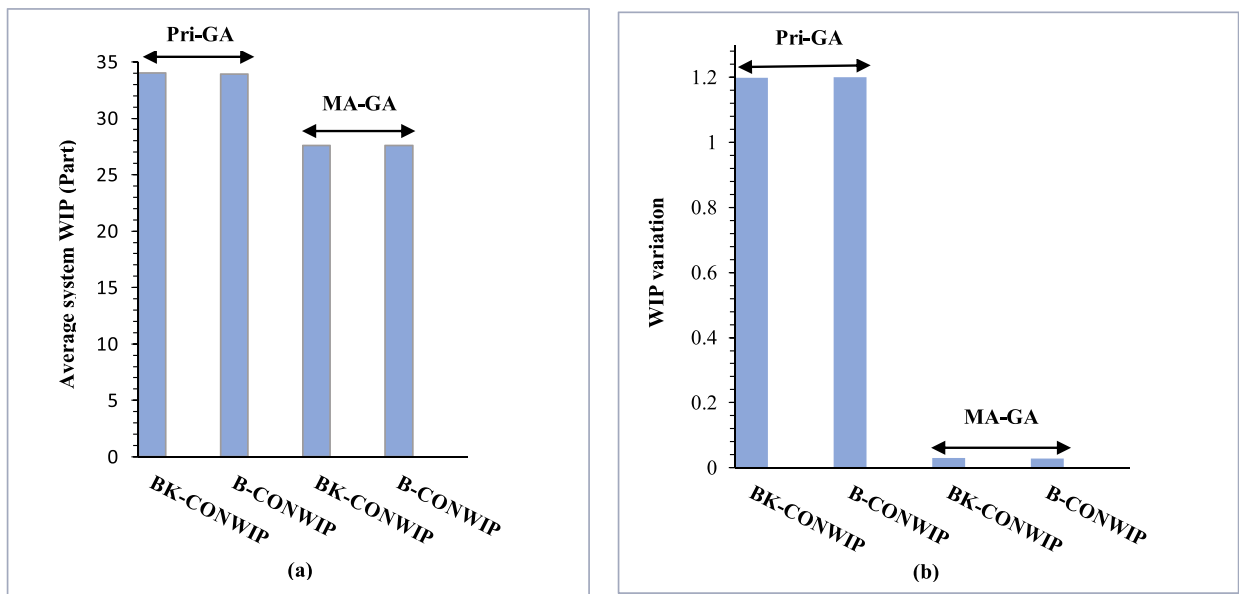
Optimal values of control parameters at 100% service level for Tonge problem.

Problem	PCS	Number of CONWIP	Number of Kanbans for WS ⁱ							Basestock
			K1	K2	K3	K4	K5	K6	K7	
Tonge balanced by PriGA	BK-CONWIP	9	6	6	8	7	10	5	6	35
	B-CONWIP	9	Without Kanban							35
Tonge balanced by MA-GA	BK-CONWIP	9	6	6	6	7	7	7	6	28
	B-CONWIP	9	Without Kanban							28

Table 11

Optimal values of control parameters at 100% service level of Arcus2 problem.

Problem	PCS	Number of CONWIP	Number of Kanbans for WS ⁱ								Basestock
			K1	K2	K3	K4	K5	K6	K7	K8	
Arcus2 balanced by PriGA	BK-CONWIP	10	6	5	6	6	6	5	7	8	25
	B-CONWIP	10	Without Kanban								25
Arcus2 balanced by MA-GA	BK-CONWIP	9	6	5	6	6	6	5	6	6	22
	B-CONWIP	10	Without Kanban								22

**Fig. 8.** Average system WIP and WIP variation of Heskia assembly problem.

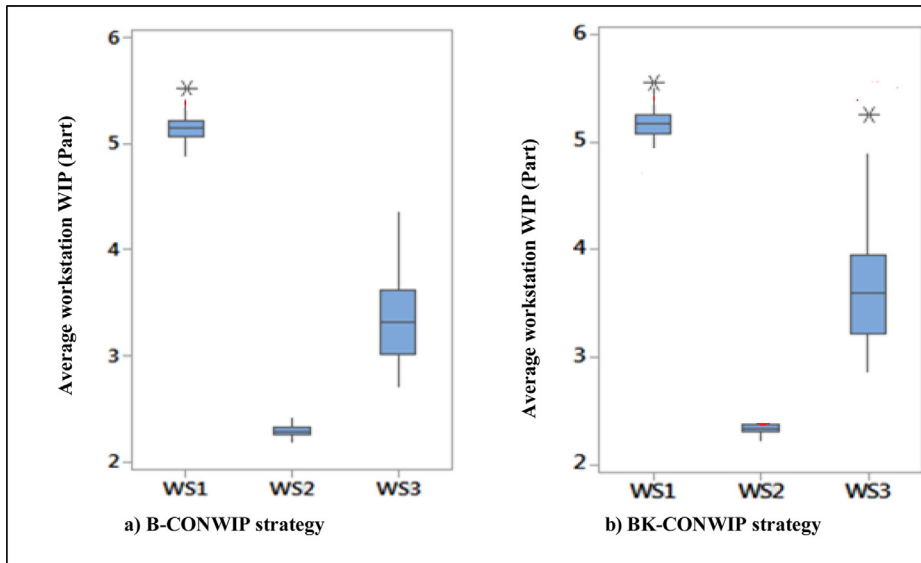


Fig. 9. Box plot for the average workstation WIP of Heskia problem balanced by Pri-GA.

- There is increased complexity in the optimizing process of a system controlled by BK-CONWIP, especially a system with a large number of workstations, since an optimal number of Kanban cards has to be determined for each station which in turn control the level of WIP among workstations. Every time a change happens in the environmental production factors such as processing times and demand rates, a new optimizing process is required. Which makes the application of BK-CONWIP in flexible production systems a more complex process.
- Balancing algorithms try to eliminate bottlenecks and balance WIP among workstations, which eliminate the need for Kanban cards. This means that balanced assembly systems can be operated under pull disciplines without the need for Kanban cards. Only, CONWIP cards are set for the whole system to control system WIP levels.
- Fig. 8 shows that B-CONWIP and BK-CONWIP achieve largely similar performance in terms of average system WIP and WIP variation, when the same balancing algorithm is used. For example, in Heskia problem balanced by Pri-GA, the average system WIP in both strategies is similar (about 32 parts) as shown in Fig. 8a. Also WIP variation is almost the same for both strategies (about 1.2) as shown in Fig. 8b. This similarity in performance makes B-CONWIP superior to BK-CONWIP since B-CONWIP is easier to implement. Similar results are obtained in the other problems.
- The performance of an assembly system also depends on the efficiency of the balancing approach used. As an example, the efficiency of MA-GA in Heskia problem is higher than that of PriGA as was shown in Table 7. Thus, the average system WIP and WIP variation accompanied with MA-GA are lower than those accompanied with Pri-GA as shown in Fig. 8. The more efficient the balancing approach, the better control on WIP among workstations. Therefore, Kanban cards can be eliminated, and B-CONWIP can be applied instead of BK-CONWIP in assembly systems that are balanced.

4.1.3. Effect of Kanban cards

The effect of Kanban cards on WIP levels among workstations is discussed. As an illustration, Heskia problem is taken as an example where all other problems have similar results. Figs. 9 and 10 show the box plots for the average workstation WIP for Heskia problem. These averages are obtained from 30 replicates. In addition, Figs. 11 and 12 show the box plots of the maximum workstation WIP for Heskia problem. These values are also obtained from 30 replicates.

Figs. 9a and b show the average workstation WIP of the problem balanced by Pri-GA. The WIP averages in workstations 1, 2 and 3 are largely similar in both strategies; B-CONWIP and BK-CONWIP, when the same balancing algorithm is used. Additionally, in B-CONWIP, the maximum values of WIP averages are 5.5, 2.5 and 4.5 parts for workstations 1, 2 and 3, respectively. These values do not exceed the number of Kanban cards, 7, 6 and 6, accompanied with BK-CONWIP, for the same workstations. Based on the values of average workstation WIP, it can be concluded that the workstation WIP levels can be limited without needing Kanban cards when a system is balanced by an efficient approach.

Fig. 10a and b show average workstation WIP levels in Heskia problem balanced by MA-GA. As shown, average workstation WIP levels are less than those balanced by Pri-GA because of MA-GA's superior efficiency; furthermore the maximum values of WIP averages do not exceed the number of Kanban cards.

Fig. 11 shows that when Pri-GA is used as a balancing algorithm and B-CONWIP is used to control the system, the maximum WIP for some workstations in some replicates may exceed the number of Kanban cards. This depends on the efficiency of the balancing algorithm. As shown in Fig. 11a, when the system is balanced by Pri-GA, the values of maximum WIP in workstation 1 reaches 9 parts in some replicates. This value exceeds the number of Kanban cards specified for

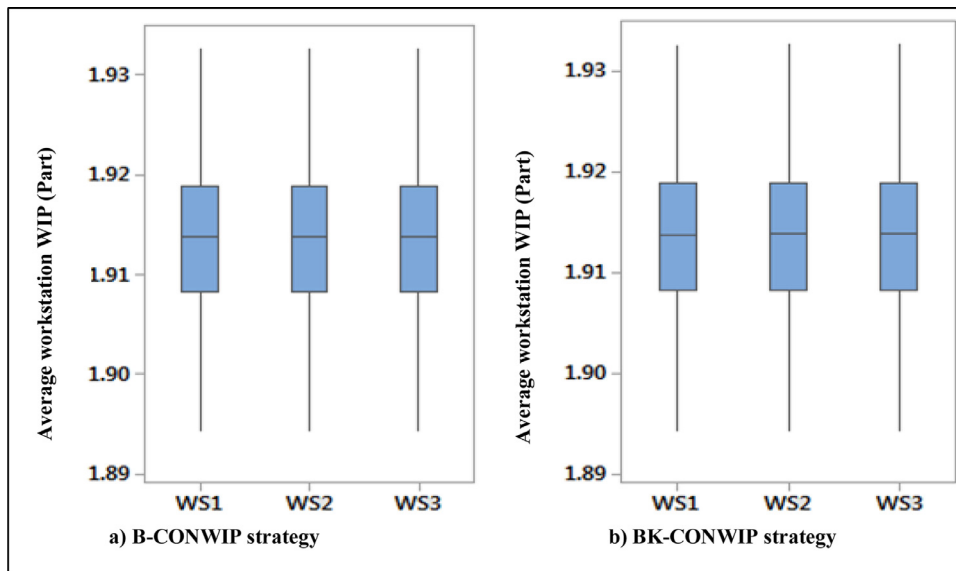


Fig. 10. Box plot for the average workstation WIP of Heskia problem balanced by MA-GA.

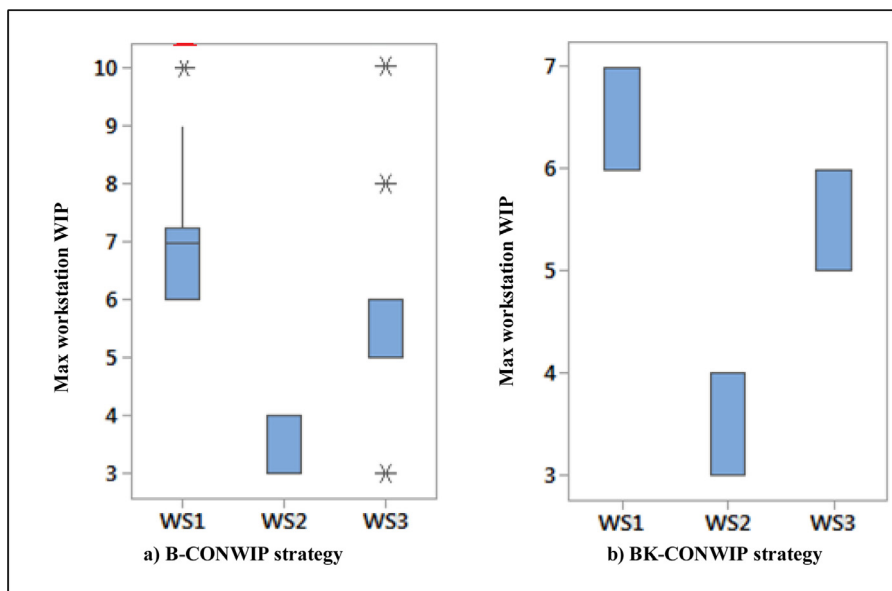


Fig. 11. Box plot for the maximum workstation WIP of Heskia problem balanced by Pri-GA.

workstation 1, which is 7. While the maximum workstation WIP in the system do not exceed the number of Kanban cards when BK-CONWIP is used to control the system because of Kanban existence as shown in Fig. 11b.

In contrast, as shown in Fig. 12 when the problem is balanced by MA-GA, the values of maximum workstation WIP do not exceed the number of Kanban cards regardless of the control strategy used to control the system. Based on the values of maximum workstation WIP, it can be concluded that Kanban cards are necessary to limit the WIP levels of workstations when a system is balanced using an inefficient approach. For the other problems, similar results were obtained. None of the maximum workstation WIP exceeded the limit on Kanban with MA-GA. In contrast, when the system is balanced by Pri-GA, the values of maximum workstation WIP exceed the number of Kanban cards if it is controlled by B-CONWIP while not exceeding if the system is controlled by BK-CONWIP.

4.1.4. Effect of demand rate change

To study the impact of change in demand arrival rates, the demand arrivals (mean demand inter arrival times) are varied, while other control parameters, determined previously for the assembly problems at 100% service level, are fixed. Three

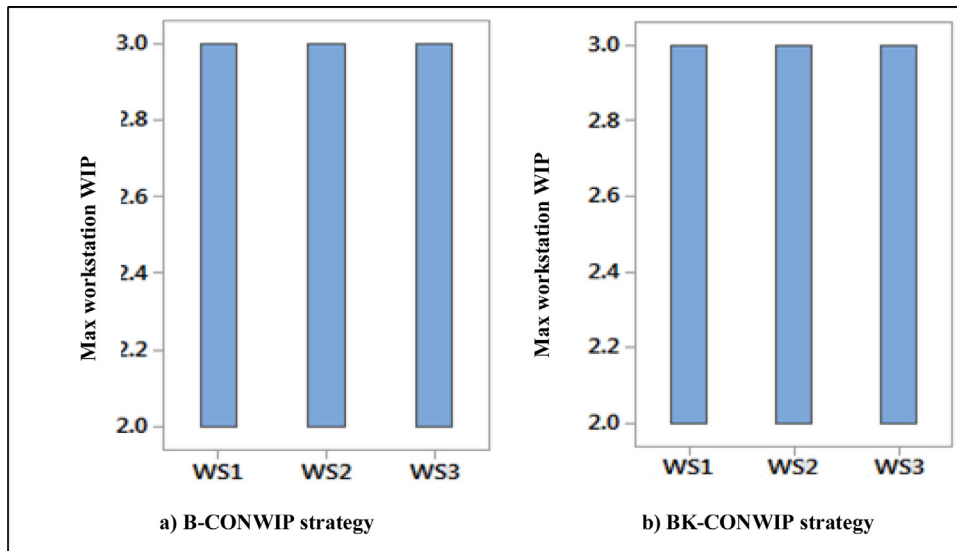


Fig. 12. Box plot for the maximum workstation WIP of Heskia problem balanced by MA-GA.

Table 12

Impact of change of demand arrival rates on system performance measures.

Percentage increase in mean inter arrival times	Problem	PCS	Service level (%)	Δ Service level %	P- Value	Average system WIP(parts)	Δ WIP%	P- Value	WIP variation
15%	Heskia	BK-CONWIP	100	–	–	24	–	–	0.025
		B-CONWIP	100	–	–	24	–	–	0.024
	Tonge	BK-CONWIP	100	–	–	27.3	–	–	0.200
		B-CONWIP	100	–	–	27.3	–	–	0.197
	Arcus2	BK-CONWIP	100	–	–	22	–	–	0.134
		B-CONWIP	100	–	–	22	–	–	0.133
10%	Heskia	BK-CONWIP	93	5	0.01	24	3.3	0.025	0.015
		B-CONWIP	97.7	–	–	24.8	–	–	0.013
	Tonge	BK-CONWIP	94.6	5.1	0.005	27	8.5	0.025	0.055
		B-CONWIP	99.4	–	–	29.3	–	–	0.055
	Arcus2	BK-CONWIP	93.2	6.6	0.005	21.8	12.8	0.025	0.037
		B-CONWIP	99.4	–	–	24.6	–	–	0.035
5%	Heskia	BK-CONWIP	85	9.1	0.001	23.9	12.9	0.01	0.078
		B-CONWIP	92.7	–	–	27	–	–	0.078
	Tonge	BK-CONWIP	88	11.5	>0.001	27.2	13.9	0.005	0.083
		B-CONWIP	98.1	–	–	31	–	–	0.083
	Arcus2	BK-CONWIP	86.7	13.6	0.0005	21	25.2	0.005	0.029
		B-CONWIP	98.5	–	–	26.3	–	–	0.029

mean demand inter arrival times are taken that are greater than the bottleneck station service time by 15%, 10% and 5%, respectively. The smaller the percentage, the busier a system becomes and the higher the demand rate. Table 12 shows the results obtained for the performance measures for these mean demand inter arrival times. The assembly problems are balanced using MA-GA approach since it is more efficient.

From Table 12 and Fig. 13 the following observations are noted:

- Generally, decreasing mean demand inter arrival times decreases the service level regardless of PCS used to control a system. B-CONWIP achieves better results in terms of service levels than BK-CONWIP as shown in Fig. 13a. In BK-CONWIP, number of Kanban cards for each workstations limits the service level and also limits the level of WIP among workstations. When mean demand arrival rate is increased it pushes the WIP levels to the limit. At a certain point this limit leads to increasing backorders. This leads to decreasing the service level. On the other hand, In B-CONWIP, there are no Kanban cards. Only CONWIP cards are assigned to the whole system to control the system WIP level, and balancing algorithms are used to control the level of the WIP among workstations instead of Kanban cards. Removing the limit on WIP between workstations set by Kanban cards; improves the service level with less backorders. Thus the service levels achieved by B-CONWIP are better than those achieved by BK-CONWIP for the same mean demand inter arrival times.
- As shown in Fig. 13b decreasing mean inter arrival times leads to increasing average system WIP levels in a system controlled by B-CONWIP while the average system WIP levels almost remains the same in a system controlled by BK-CONWIP. As an illustration, in B-CONWIP, when mean demand inter arrival time decreases, more parts are allowed to

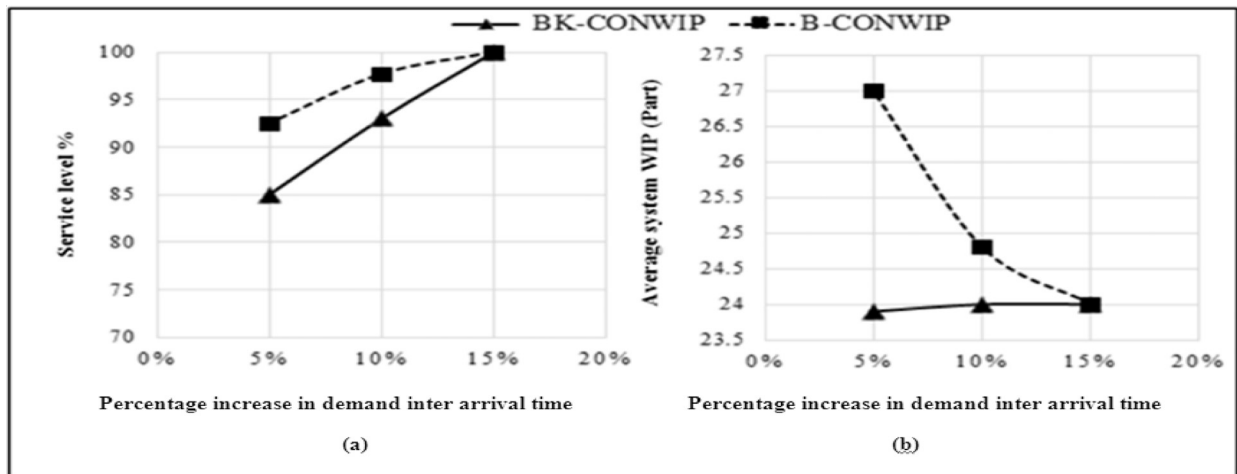


Fig. 13. Impact of change of demand arrival rates on average WIP and Service level (Heskia problem).

Table 13

Results obtained from balancing algorithms at Cycle time = 1.8 min.

Balancing algorithm	Number of WS	E (%)	W_v
PriGA	7	94.75	0.012
MA-GA	7	96.8	0.008

enter the queues of workstations since there are no Kanban cards to limit the number of parts. As a result, average system WIP also increases. On the other hand, in BK-CONWIP, extra demands are not allowed to enter the system when the Kanban limit is reached, and these demands are backordered. So the average system WIP remains almost constant which is an advantage in this case.

- WIP variation depends only on the balancing approach used. It is not affected by which PCS is used. As shown in Table 12, WIP variations resulting from applying both PCS are almost the same.
- A two-sample *t*-test with a 95% confidence level is conducted on the difference in mean service levels and mean system WIPs of BK-CONWIP and B-CONWIP. The *p*-value reported in Table 12 shows that all differences are statistically significant.

4.2. Mixed product assembly system results

4.2.1. Balancing of mixed assembly system

The steps of Thomopoulos [29] approach formerly explained are applied to perform the balancing and task assignments in the mixed-product assembly system. PriGA and MA-GA are used to perform the balancing and task assignments. Table 13 shows the results obtained from both balancing algorithms.

In a mixed product assembly system, the sequencing in which products are launched into a system to start processing has to be taken into account. The sequencing is essential for systems operated under push disciplines since there is an identified production schedule of how many and in what order products must be produced in a specific period. Thus, the best sequence of launching products into a system must be determined by a sequencing algorithm to optimize assembly system utilization and reduce the idleness in a system. In this research, since a pull production system is used, sequences are determined based on real-time demand arrivals which are not known in advance and are not forecasted. In order to take the effect of sequencing into account, instead of a sequencing algorithm, randomly generated sequences are used to launch demands for two products into a system. In order to obtain randomly generated sequences, different random number streams were used to sample from demand inter arrival time distributions for both products. Each random number stream generates a different sequence. The effects of these random sequences on the performance of an assembly system, operated under pull disciplines, are monitored. Figs. 14 and 15 show the histogram of service levels and average system WIP, respectively, for a mixed product assembly system controlled by B-CONWIP and balanced by MA-GA. These histograms are constructed using 1500 random sequences. As shown in Fig. 14, service levels range between 98.4% and 99.9%. Also, as shown in Fig. 15, the average system WIP levels obtained from 1500 sequences range between 20 and 21 parts. It can be concluded that the change of a sequence do not have a major effect on the performance measures. Similar results were achieved in the other models

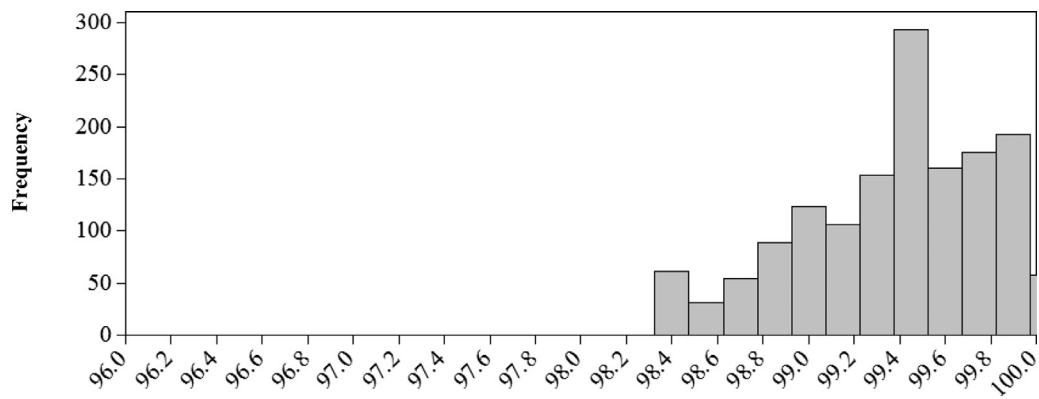


Fig. 14. Service level in the mixed product assembly system with 1500 random sequences.

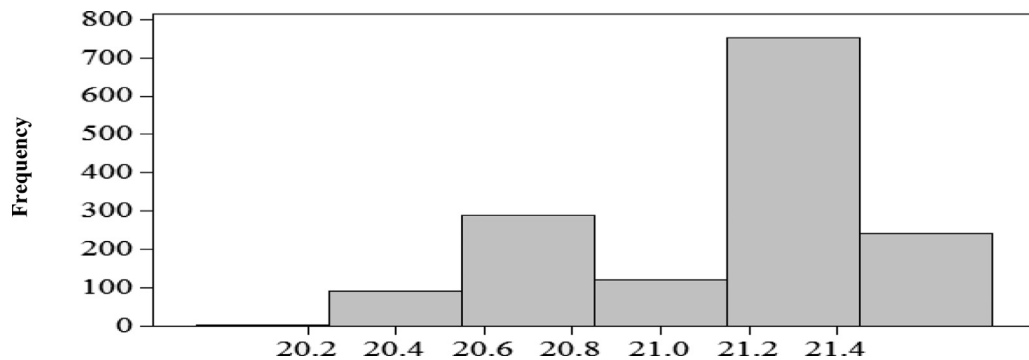


Fig. 15. Average system WIP in the mixed product assembly system with 1500 random sequences.

Table 14

Optimal values of control parameters at 100% service level for the mixed product assembly system.

Optimal values of control parameters obtained by OptQuest				CONWIP	Kanban						Basestock
Workstation number					1	2	3	4	5	6	----
Balancing approach	KDP Type	PCS	Product	-----							
PriGA	Shared	BK-CONWIP	1	14	8	7	8	6	7	6	13
			2								13
		B-CONWIP	1	14	Without Kanban						13
			2								12
	Dedicated	BK-CONWIP	1	9	5	4	4	5	3	4	17
			2	9	4	5	3	4	4	4	15
		B-CONWIP	1	9	Without Kanban						17
			2	8							15
MA-GA	Shared	BK-CONWIP	1	14	7	7	8	7	6	7	12
			2								10
		B-CONWIP	1	13	Without Kanban						12
			2								10
	Dedicated	BK-CONWIP	1	11	5	4	4	3	4	5	15
			2	10	4	5	5	4	3	5	13
		B-CONWIP	1	10	Without Kanban						15
			2	10							13

4.2.2. Control parameter settings

The number of workstations and task assignments from the balancing algorithms are used as inputs for simulations models. Another important input is mean demand arrival rate. According to the data collected from the garment facility, received demands for trousers and jackets are Poisson distributed with a mean of 240 units per day for trousers and 230 units per day for jackets.

Models are optimized by OptQuest for Arena to set the control parameters at their best values which minimize the average system WIP and maximize the service level. Table 14 summarizes the best values of the control parameters that achieve minimum average system WIP and 100% service level.

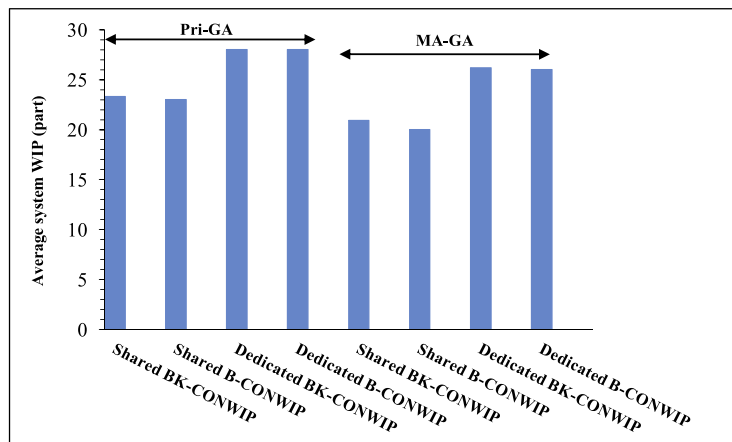


Fig. 16. Average system WIP of the mixed product assembly system.

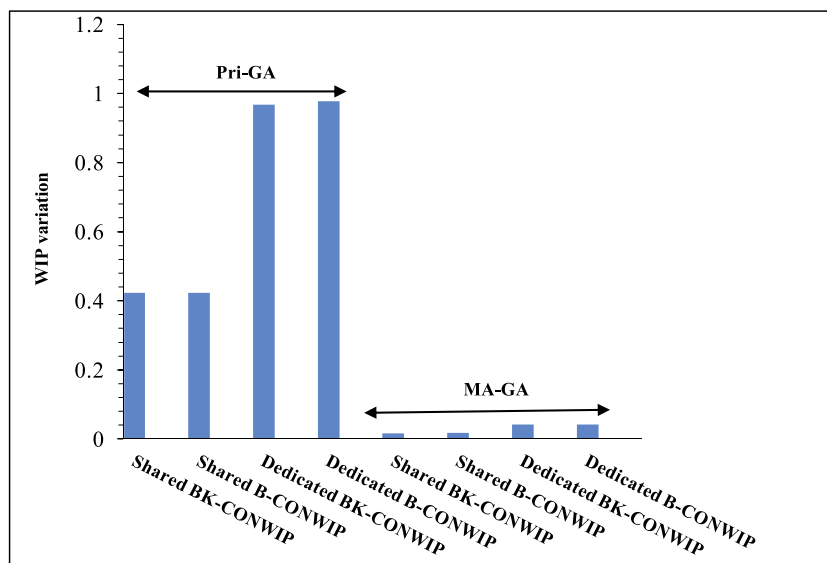


Fig. 17. WIP Variation of the mixed product assembly system.

From Table 14 and Figs. 16 and 17, the following points are noted:

- The basestock levels required with PCS that use S-KDP are less than those that use D-KDP, which reduces the average system WIP.
- As shown in Fig. 16, in terms of average system WIP, the PCS using S-KDP achieve lower results than those using D-KDP.
- Figs. 16 and 17 show that both B-CONWIP and BK-CONWIP achieve mainly similar performance in terms of average system WIP and WIP variation, when the same KDP and balancing algorithm are used. This similarity in performance makes B-CONWIP superior to BK-CONWIP since B-CONWIP is easier to implement. Especially, when the system assembles more than one product and has a large number of workstations.
- A system that uses B-CONWIP with S-KDP is easiest to control and optimize than the other alternatives. Because B-CONWIP with S-KDP has only two control parameters which are the CONWIP cards and basestock levels.
- The more efficient the balancing approach, the more control on WIP among workstations, which leads to reduced WIP variation. This is shown clearly in Fig. 17.

4.2.3. Effect demand rate change

The mean demand arrival rates are varied, while other control parameters are fixed. The mean demand arrival rates are increased by 10%, 20% and 50% of the original mean demand rate for both products. The assembly system is balanced by MA-GA approach since it is more efficient.

From Table 15 and Figs. 18 and 19, the following points are noted:

Table 15

Impact of change of demand arrival rates on performance measures of the mixed assembly system.

Demand	KDP	PCS	Service level (%)	p-value	Average system WIP(parts)	p-value
Original demand	Shared	BK-CONWIP	100	–	20.1	–
	Dedicated	B-CONWIP	100		20	
Original demand increased by 10%	Shared	BK-CONWIP	100	0.01	26.2	–
		B-CONWIP	100		26.2	
	Dedicated	BK-CONWIP	94		20.7	
		B-CONWIP	98		27	
Original demand increased by 20%	Shared	BK-CONWIP	91	0.01	26.4	0.01
		B-CONWIP	96		34	
	Dedicated	BK-CONWIP	85		20.7	
		B-CONWIP	93		37	
Original demand increased by 50%	Shared	BK-CONWIP	83	0.0025	26.5	0.0025
		B-CONWIP	91		41	
	Dedicated	BK-CONWIP	56		20.8	
		B-CONWIP	62		50	
	Dedicated	BK-CONWIP	51	0.0025	26.5	0.005
		B-CONWIP	59		53.5	

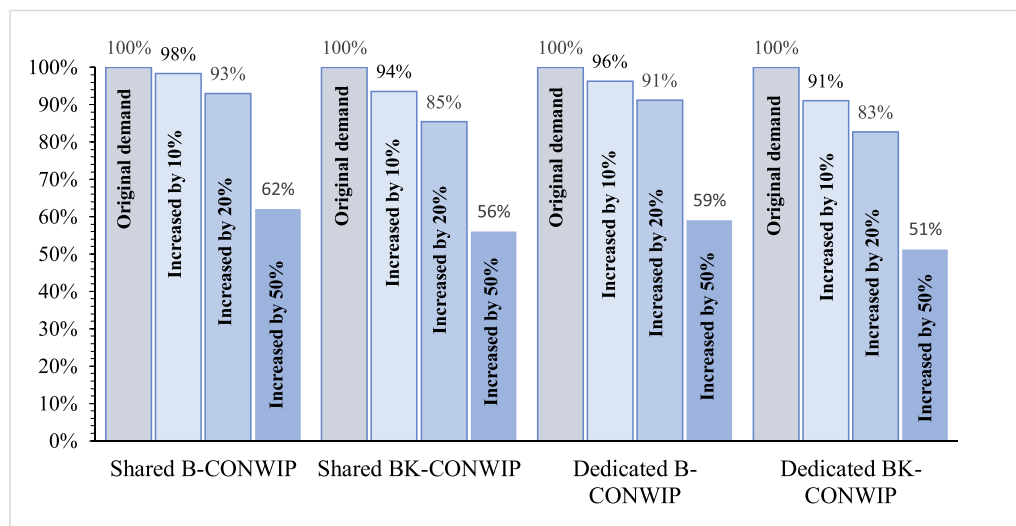
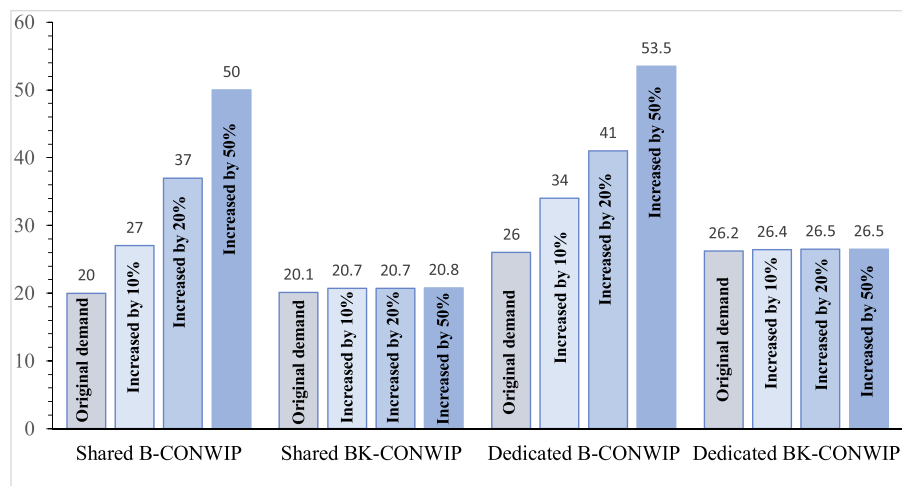
**Fig. 18.** Impact of change of mean demand arrival rates on Service level in mixed product assembly system.**Fig. 19.** Impact of change of mean demand arrivals rates on the average system WIP in Mixed product assembly system.

Table 16

Performance of PCS in single model assembly system with lost demand.

Percentage increase in mean inter arrival times	Problem	PCS	Service level (%) with lost demand	Service level (%) with backordered demand	Average system WIP(parts) with lost demand	Average system WIP(parts) with backordered demand
15%	Heskia	BK-CONWIP	100	100	24	24
		B-CONWIP	100	100	24	24
	Tonge	BK-CONWIP	100	100	27.3	27.3
		B-CONWIP	100	100	27.4	27.3
	Arcus2	BK-CONWIP	100	100	22	22
		B-CONWIP	100	100	22.1	22
10%	Heskia	BK-CONWIP	93.1	93	21.4	24
		B-CONWIP	97.6	97.7	23.6	24.8
	Tonge	BK-CONWIP	94.6	94.6	25.7	27
		B-CONWIP	99.3	99.4	28	29.3
	Arcus2	BK-CONWIP	93.2	93.2	20.4	21.8
		B-CONWIP	99.4	99.4	22.6	24.6
5%	Heskia	BK-CONWIP	85	85	20	23.9
		B-CONWIP	92.7	92.7	25	27
	Tonge	BK-CONWIP	88.1	88	23.6	27.2
		B-CONWIP	98.05	98.1	28.8	31
	Arcus2	BK-CONWIP	86.7	86.7	19.3	21
		B-CONWIP	98.5	98.5	22.3	26.3

- In general, increasing mean demand arrival rates decreases the service level regardless of PCS used. But B-CONWIP performs better than BK-CONWIP based on service levels as shown in Fig. 18.
- As shown in Fig. 19, increasing mean demand arrival rates leads to increasing the average system WIP in a system controlled by B-CONWIP while remaining the same in a system controlled by BK-CONWIP.
- The PCS using S-KDP perform better than those using D-KDP based on performance measures since S-KDP has a faster response to demand occurrence.
- When service levels are more important in the mixed-product assembly systems, B-CONWIP with S-KDP is superior to other PCS.
- When WIP levels are more important in the mixed-product assembly systems, BK-CONWIP is superior to B-CONWIP.
- WIP variation depends only on the balancing approach used. It is not affected by which PCS is used.
- Fig. 18 shows a significant change in service levels when demand rates increase in both PCSs. On the other hand, Fig. 19 shows that only B-CONWIP average WIP levels significantly change while BK-CONWIP being not affected. This confirms the superiority of BK-CONWIP when WIP levels are more important.
- Table 15 shows the results of a two-sample *t*-test with a 95% confidence level conducted on the difference in mean service levels and mean system WIPs of BK-CONWIP and B-CONWIP. The *p*-value reported shows that all differences are statistically significant.

4.2.4. Effect of demand loss on PCS performance

To study the effect of demand loss on the performance of both strategies in both single and mixed product assembly systems, the same experiments conducted to study the effect of demand rate changes are used with the same control parameters and conditions except that unsatisfied demand is not backordered but rather lost. Tables 16 and 17 show the results obtained for performance measures for both strategies in both systems. From Tables 16 and 17 the following observations are noted:

- When unsatisfied demands are treated as lost demands, the service levels obtained are largely similar to those obtained when unsatisfied demands are treated as backorders since the service levels are calculated based on demands that are immediately satisfied without any additional delay. Therefore, in both cases the number of unsatisfied demand is the same whether it is backordered or lost. In this case the service levels only depend on PCS and KDP used.
- The tables show a decrease in average system WIP in both PCSs when unsatisfied demand is treated as lost. This decrease increases with increasing demand rates in both systems. This decrease can be explained due to the fact that, lost demand does not affect the WIP level of the system and demand signals are not sent back to workstations. On the other hand, backordered demand increases WIP levels and has to be dealt with through demand signals sent back to workstations.
- B-CONWIP outperforms BK-CONWIP in single and mixed product assembly systems with respect to service levels and is slightly behind with respect to average system WIP.

4.2.5. Effect of product mix

The product mix in the mixed product assembly system is varied and performance measures are monitored. Originally the product mix was 51% for product 1(trousers) and 49% for product 2 (jackets) which correspond to 240 units/day and 230 units/day from each product, respectively. Two other product mixes are tested one with (70% product 1/30% product 2) and another with (90% product 1/10% product 2) while keeping all original control parameters fixed.

Table 17

Performance of PCS in mixed product assembly system with lost demand.

Demand	KDP	PCS	Service level (%) with lost demand	Service level (%) with backordered demand	Average system WIP(parts) with lost demand	Average system WIP(parts) with backordered demand
Original demand	Shared	BK-CONWIP	100	100	20.2	20.1
		B-CONWIP	100	100	20	20
	Dedicated	BK-CONWIP	100	100	26.3	26.2
		B-CONWIP	100	100	26	26
Original demand increased by 10%	Shared	BK-CONWIP	94	94	18.7	20.7
		B-CONWIP	98	98	22	27
	Dedicated	BK-CONWIP	91	91	25.7	26.4
		B-CONWIP	96	96	30	34
Original demand increased by 20%	Shared	BK-CONWIP	85	85	15.4	20.7
		B-CONWIP	93	93	25	37
	Dedicated	BK-CONWIP	83	83	23.3	26.5
		B-CONWIP	91	91	29	41
Original demand increased by 50%	Shared	BK-CONWIP	56	56	11.8	20.8
		B-CONWIP	62	62	30.8	50
	Dedicated	BK-CONWIP	51	51	16.9	26.5
		B-CONWIP	59	59	32	53.5

Table 18

Performance of PCS under product mix variation.

Product mix variation	KDP	PCS	Service level (%)	P-value	Average system WIP(parts)	p-value
Original demand	Shared	BK-CONWIP	100	–	20.1	–
		B-CONWIP	100		20	
	Dedicated	BK-CONWIP	100	–	26.2	–
		B-CONWIP	100		26.2	
70% product 1 30% product 2	Shared	BK-CONWIP	94.7	–	20.1	–
		B-CONWIP	94.7		20	
	Dedicated	BK-CONWIP	86.3	0.005	21.1	0.01
		B-CONWIP	90.6		23.6	
90% product 1 10% product 2	Shared	BK-CONWIP	72.2	–	20.1	–
		B-CONWIP	72.2		20.1	
	Dedicated	BK-CONWIP	62.7	0.01	18.5	0.025
		B-CONWIP	69.3		20.8	

The results are shown in Table 18. The results show the superiority of B-CONWIP over BK-CONWIP with respect to service levels when the D-KDP is used while being similar when S-KDP is used in the two additional product mixes. Moreover, the performances of both PCSs are similar with respect to average system WIP with BK-CONWIP having a slight advantage when D-KDP is used.

It is also shown in the table that as the product mix difference increases the service level decreases significantly and more so when using D-KDP. On the other hand, average system WIP is not affected by product mix when using S-KDP and decreases with increasing product mix difference when D-KDP is used in both PCSs.

These results are expected because the original control parameters were based on a balanced system using a specific product mix. Changing the product mix unbalances the system and requires re-balancing according to the Thomopoulos concept and re-calculating the control parameters. It is clearly shown that S-KDP is more flexible in dealing with situations of variable product mixes than D-KDP because control parameters can be used by either product type which minimizes the effect of the unbalanced systems. In D-KDP the product with the higher mix will face a shortage of Kanban and CONWIP cards while the other product will face an abundance of these cards. The p-values of a two-sample *t*-test show that the differences are significant at a 95% confidence level.

4.2.6. Production managerial insight

A production manager in charge of systems similar to the ones covered in this work should realize the complexities associated with such systems. The manager should understand the analysis procedure followed in detail. It is imperative that this procedure be implemented as presented to fully reap the benefits of either strategy. In summary, MA-GA should be adopted as a balancing algorithm in all situations as it is more efficient. Results from balancing algorithms such as number of work stations and task assignments to workstations are used to setup and layout the production floor. These results are fed into simulation models which are then optimized with respect to service levels and average system WIP to determine

control parameters used on the production floor such as number of Kanbans and CONWIP cards as well as Basestock levels in every station.

These parameters can be used consistently as long as the production environment is stable and demand rates are within 20% of the original demand rate. As demand rates increase to 50%, a considerable drop in service levels and increase in average system WIP is expected. Overall, when service levels are more important to the manager, B-CONWIP should be adopted which improves customer satisfaction. On the other hand, if average system WIP is more important due to limited space between work stations, BK-CONWIP should be adopted. Managers dealing with variable product mixes and not wanting to re-run the balancing process of the assembly system for each mix should resort to using S-KDP over D-KDP as it is more flexible and less affected by such variations.

5. Conclusions

In this study, a new pull PCS, B-CONWIP, has been suggested and examined. This PCS was used to control the flow of materials and information in balanced assembly systems. Many conclusions were summarized from this work as follows:

- In general, when an assembly system is balanced by an efficient balancing approach, the system can be operated under pull disciplines without Kanban cards where the system balancing can be used instead of Kanban cards to limit WIP among workstations. This makes the system easier to control and optimize, especially, when the number of workstations is large or the system assembles more than one product. It has been proven that the performance of B-CONWIP that does not have Kanban cards is largely similar to the performance of BK-CONWIP.
- In both single and mixed product assembly systems, when demand arrivals are increased B-CONWIP is preferable if the service level is more important while BK-CONWIP is preferable if WIP level is more important.
- When mean demand arrival rates increase, Kanban cards become a barrier, so extra demands cannot be transferred to workstations to allow parts to be processed.
- Generally, PCS with Shared authorization cards perform better than PCS with Dedicated authorization cards.
- WIP variation mainly depends on the efficiency of the balancing approach. The more efficient the balancing approach, the less WIP variation.
- Treating demand as lost instead of backordered results in decreased average system WIP and does not affect service levels in both PCSs
- It is shown that S-KDP is more flexible in dealing with situations of variable product mixes than D-KDP because control parameters can be used by either product type which minimizes the effect of the unbalanced systems.

As future work, there are several opportunities for extensions. The proposed PCS, along with BK-CONWIP, can be applied and compared in other types of assembly systems such as U-shape assembly systems and multi-product assembly systems with significant set up times and unreliable processes. Another extension is to evaluate both strategies when assembly task times are stochastic. Also, these PCS can be applied in assembly systems that have parallel workstations. Other priority rules such as earliest due date which handle extremely urgent demand first can be considered instead of FIFO rules used here. Also, production systems with more than two products and product mixes can be considered.

Appendix A. Data sets of experimental work

Table A.1

Task times and precedence relations for the mixed product assembly system.

Task (k)	Task time on jackets (Sec)	Time task on trousers (Sec)	Predecessor
1	20	0	–
2	17	24	–
3	0	6	–
4	17	0	–
5	16	6	–
6	16	0	4,5
7	19.5	15	6
8	0	15	7
9	17	9	8
10	26.5	0	9
11	19	9	1,4
12	13	9	10
13	20.5	0	11,12
14	16	6	13
15	23.5	30	14
16	0	3	15
17	25	15	16
18	9	15	17
19	12	9	18
20	15	15	3
21	5	19	20
22	0	8	21
23	12	10	22
24	17	22	2, 23
25	9	11	24
26	3	5	25
27	3	0	25
28	6	9	27
29	16	19	28
30	19	24.5	27
31	9.5	7.5	19
32	18	15	30
33	0	25	32
34	17.5	19.5	–
35	16.5	13.5	–
36	0	22	34
37	19.5	0	36
38	20	21.5	32, 35, 37
39	22.5	20.5	38
40	25.5	27.5	39
41	0	6.5	33, 40
42	8	6	41
43	12	10.5	42
44	0	8.5	29, 30, 31, 43
45	8.5	11.5	44
46	13	10	45
47	19.5	17.5	46
48	11.5	13	47
49	13.5	11	48
50	9	9	49
51	14.5	0	50
52	16	18	50
53	15	28	51,52
54	0	8	53
55	9.5	26.5	54
56	13	14.5	55
57	10.5	17.5	53
58	0	11	57
59	25.5	15.5	56, 58
60	19	17	59
Total	759	745	---

References

- [1] T. Al-Hawari, M. Ali, O. Al-Araidah, A. Mumani, Development of a genetic algorithm for multi-objective assembly line balancing using multiple assignment approach, *Int. J. Adv. Manufact. Technol.* 77 (5–8) (2015) 1419–1432.
- [2] B. Baynat, J.A. Buzacott, Y. Dallery, Multiproduct Kanban-like control systems, *Int. J. Product. Res.* 40 (16) (2002) 4225–4255.
- [3] A.M. Bonvik, C.E. Couch, S.B. Gershwin, A Comparison of production-line control mechanisms, *Int. J. Product. Res.* 35 (3) (1997) 789–804.
- [4] J.A. Buzacott, Queueing models of Kanban and MRP controlled production systems, *Eng. Costs Product. Econ.* 17 (1) (1989) 3–20.
- [5] Y. Dallery, G. Liberopoulos, Extended Kanban control system: combining Kanban and base stock, *IEE Trans.* 32 (4) (2000) 369–386.
- [6] M. Faccio, M. Gamberi, A. Persona, Kanban number optimization in a supermarket warehouse feeding a mixed-model assembly system, *Int. J. Product. Res.* 51 (10) (2013) 2997–3017.
- [7] J. Geraghty, C. Heavey, A review and Comparison of hybrid and pull-type production control strategies, *OR Spectrum* 27 (2–3) (2005) 435–457.
- [8] A. Grosfeld-Nir, M. Magazine, A. Vanberkel, Push and pull strategies for controlling multistage production systems, *Int. J. Product. Res.* 38 (11) (2000) 2361–2375.
- [9] W.J. Hopp, M.L. Spearman, *Factory Physics*, Mc Graw–Hill, New York, 2001.
- [10] R.K. Hwang, H. Katayama, M. Gen, U-Shaped Assembly line balancing problem with genetic algorithm, *Int. J. Product. Res.* 46 (16) (2008) 4637–4649.
- [11] W.D. Kelton, R. Sadowski, N.B. Swets, *Simulation With Arena*, fifth ed., McGraw. Hill, Singapore, 2010.
- [12] Y. Khojasteh-Ghamari, A Performance Comparison between Kanban and CONWIP controlled assembly systems, *J. Intell. Manufact.* 20 (6) (2009) 751.
- [13] G.E. Kimball, General principles of inventory control, *J. Manufact. Oper. Manag.* 1 (1) (1988) 119–130.
- [14] J.P.C. Kleijnen, E. Gaury, Short-term robustness of production management systems: a case study, *Euro. J. Oper. Res.* 148 (2) (2003) 452–465.
- [15] A. Krishnamurthy, R. Suri, Performance Analysis of single stage Kanban controlled production systems using parametric decomposition, *Queueing Syst.* 54 (2) (2006) 141–162.
- [16] F. Lolli, R. Gamberini, C. Giberti, B. Rimini, F. Bondi, A simulative approach for evaluating alternative feeding scenarios in a Kanban system, *Int. J. Product. Res.* 54 (14) (2016) 4228–4239.
- [17] R.P. Marek, D.A. Elkins, D.R. Smith, Manufacturing controls: understanding the fundamentals of Kanban and CONWIP pull systems using simulation, in: *Proceedings of the 33rd Conference on Winter Simulation*, IEEE Computer Society, 2001, pp. 921–929.
- [18] O.A. Olaitan, J. Geraghty, Evaluation of production control strategies for negligible-setup, multi-product, serial lines with consideration for robustness, *J. Manufact. Technol. Manag.* 24 (3) (2013) 331–357.
- [19] C.E. Onyeocha, J. Geraghty, A modification of the hybrid Kanban-CONWIP production control strategy for multi-product manufacturing systems, *International Manufacturing Conference (IMC29) proceedings*, 2012.
- [20] C.E. Onyeocha, An Investigation of pull control strategies and production authorization cards in a multi-product plant in the presence of environmental variability, *Comput. Sci. Appl.* 1 (2) (2014) 67–84.
- [21] C.E. Onyeocha, Effect of product mix on multi-product pull control, *Simul. Modell. Practice Theory* 56 (2015) 16–35.
- [22] R. Piplani, A.W.H. Ang, Performance comparison of multiple product kanban control systems, *Int. J. Product. Res.* 0 (2017) 1–14.
- [23] A. Scholl, R. Klein, *Assembly line balancing*, (Uploaded November 2007), 2007 (Accessed April 29, 2017). <http://assembly-line-balancing.mansci.de/>.
- [24] S. Sharma, N. Agrawal, Selection of a pull production control policy under different demand situations for a manufacturing system by AHP-Algorithm, *Comput. Oper. Res.* 36 (5) (2009) 1622–1632.
- [25] M.L. Spearman, D.L. Woodruff, W.J. Hopp, CONWIP: a pull alternative to Kanban, *Int. J. Product. Res.* 28 (5) (1990) 879–894.
- [26] Y. Sugimori, K. Kusunoki, F. Cho, S. Uchikawa, Toyota production system and Kanban system materialization of just-in-time and respect-for-human system, *Int. J. Product. Res.* 15 (6) (1977) 553–564.
- [27] S.K. Goyal, S.G. Deshmukh, A critique of the literature on just-in-time manufacturing, *Int. J. Oper. Product. Manag.* 12 (1) (1992) 18–28.
- [28] R. Suri, *Quick Response Manufacturing: A Companywide Approach to Reducing Lead Times*, Productivity Press, New York, 1998.
- [29] N.T. Thomopoulos, Mixed model line balancing with smoothed station assignments, *Manag. Sci.* 16 (9) (1970) 593–603.