AN INVESTIGATION ON HYBRID AND NON-HYBRID PRODUCTION CONTROL SYSTEMS UNDER UNBALANCED LINE CONDITIONS: A COMPARATIVE SIMULATION STUDY

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Abstract

Companies have been trying to maximize productivity from their available resources. Only one resource can limit the throughput of the whole system. This resource, the so called "bottleneck" causes inability of a system to respond to sudden changes in demand as a result of capacity restriction. Different production controlling mechanisms have their own way to direct materials through the system in which they can affect the speed of the flow. This study is aimed to at recommending important decision variables for controlling the material flow of both traditional non-hybrid production control systems and hybrid systems under restricted conditions as well as identifying the advantages and disadvantages of each system. Results from the study will give the best alternative for the production system under unbalanced conditions.

Keywords: Hybrid and non-hybrid production control system, bottleneck process, simulation study, genetic algorithm

Introduction

In a highly competitive market, companies cannot survive by just increasing their selling price to cover rising costs. The success of a company will depend very much on its ability to achieve effective operations. Moreover, consumers now require high levels of customer services for a variety of products with a short product life cycle. In such an environment, companies are under pressure with filling their customers' orders, keeping the deliveries of products on time, reducing inventory, as well as knocking down their costs.

A production control system is used to control and manage production systems. It is directed towards planning and controlling the important characteristics of material flows: how much of what materials flow and when. The performance of different production control systems has been studied by many researchers (Huang *et al*., (1998); Krishnamurthy *et al*., (2004); and Takahashi *et al*., (2005); Pettersen and Segerstedt, (2009). A distinction is frequently

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made between push and pull production control systems. Many people believe that pull systems controlled by Kanbans are better at reducing inventories since they try to eliminate queues, while push systems controlled by material requirements plannin (MRP) encourage queues by means of safety stock in order to cushion operations and to increase machine utilization, but with a higher cost.

In the literature, there exist many attempts to define push and pull systems. Bonney *et al.* (1999) showed that the definitions of push and pull are inconsistent between different researchers. Arguments about performance are sometimes circular. If the performance of a pull system is poor, then it may be suggested that this is because the fundamentals of just-in-time (JIT) are not being observed, whereas, if the performance of a push system is poor, then that is a consequence of it being a push system. Spearman *et al.* (1990) said that a pull system does not schedule the start of jobs but instead authorizes production. In reality, both manufacturing and distribution systems contain elements of push or pull to varying degrees, regardless of the identity of the system (Pyke and Cohen, 1990).

The current shift towards the hybrid manufacturing environment is one of the major motivations for this study. Although, there have been numerous MRP/JIT comparisons or integration studies, not much research has addressed the dynamics between these policies, especially under restricted resource capacity. This study examines, by means of simulation, the effect that these systems have on the system performance under unbalanced conditions. The great majority of previous studies of production systems have assumed that real production systems are either perfectly balanced or are nearly so (Powell, 1994); this claim is not based on empirical evidence, but on the assumption that unbalanced lines do not exist because they are less efficient than the balanced lines. However, in reality, there could be some points in the process that hold down the amount of the product the process can produce. This causes inability of the system to respond to sudden changes in the demand as a result of capacity restriction. The question investigated in this study is how the system performance is affected by the flow of each controlling mechanism under this constraint.

Literature Review

A bottleneck is defined as a point in the manufacturing process that holds down the amount of the product that a system can produce (Browne *et al.*, 1998). It causes inability of a system to respond to sudden changes in the demand as a result of the capacity restrictions. Even though it is undesirable, with a limited financial budget, the bottleneck is difficult to avoid. Thus, alleviation of such a problem requires not only explicit understanding of the entire processes, but also a powerful production control system. Powell (1994) provided a study of an unbalanced three3-station serial line. Imbalances in both means and variances were considered. The study concluded that imbalances in means have a stronger effect than imbalances in variances so that when a line is unbalanced in both senses, one can consider that a bottleneck with the unbalance in means is more severe. Chiadamrong and Limpasontipong (2003) studied the relationship of a bottleneck with the size and location of buffer storages. Various experiments were performed to find the best location and optimal size of the buffers under various conditions.

Interest in bottleneck scheduling is a result of the development and aggressive marketing of a proprietary production scheduling system known as Optimized Production Technology (OPT) (Nahmias, 1997). OPT or Drum- Buffer and -Rope (DBR) is based on the Theory of Constraint (TOC) developed by Goldratt (1993). It focuses on identifying bottlenecks in a manufacturing process and intensively schedules the bottleneck resources to improve the system's performance. Under the nine 9 principles of OPT by Jacobs (1984), better use of limited capacity is achieved by finite scheduling of the bottleneck and the use of an increased processing batch size through those bottleneck resources. Riezebos *et al.* (2010) dealt with improving the lead time of a small packaging manufacturer in the Netherlands by using the TOC. They focused on the modifications of its order acceptance and buffer management systems in order to obtain the desired lead-time reduction. Fox (1984) investigated the main bottlenecks on the factory floor and tried to explain them by OPT.

As mentioned earlier, the advantages and disadvantages of push systems such as MRP and pull systems such as Kanban-controlled JIT have been well documented in the literature (see, for example, Lee, (1989); Spearman and Zazanis, (1992)). Krishnamurthy *et al*. (2004) also reported that MRP has an the advantage of a low set-up cost as it operates by a push system. It produces products in batches or a set of products, but it causes a high level inventory as MRP handles uncertainty in the system by keeping high inventory. In a multi-product environment, MRP was also reported by Sun *et al*. (2012) to be more robust than the pull system with Kanbans in terms of inventories and service levels. The Aadaptive pull-Kanban-type pull, proposed by Tardif and Maaseidvaag (2001), was developed as an alternative to the materials flow control in environments with unstable demand. Their simulation results under unstable demand conditions showed a reduction of delays in deliveries as compared to the original Kanban system.

A relatively new research trend associated with the push MRP and pull-Kanban system is to explore the possibility of a hybrid system and to develop a model for the integrated system. The rationale behind these approaches is that both the MRP and Kanban systems have their own unique advantages and disadvantages, and the advantages of both systems can be exploited to achieve better performance (Benton and Shin, 1998). In addition, the MRP and Kanban systems are compatible, and MRP must be considered as a framework that can upgrade the JIT production more efficiently. CONWIP (CONstant Work In Progress) is a pull-oriented production planning strategy but it can also be classified as a push system, as it is a combination strategy between the push and pull systems (Spearman *et al*., 1990). The principle of CONWIP is to release raw materials into the production system according to the final product needed, similar to the pull system, while the material flow inside the system is operated by the push mechanism. A disadvantage of CONWIP is that inventory levels are not controlled at individual stages, which can result in high inventory levels building up in front of the bottleneck operation.

A pull-Kanban system and CONWIP have also been compared by many researchers (for example, Takahashi *et al*. (2005); Jodlbauer and Huber (2008)). Both strategies have an the advantage of a low level of inventory by controlling the amount of work-in-process in the production system. However, this can eventually cause a high set-up cost. Usually CONWIP performs better than a Kanban system with lower set-up and holding costs, as CONWIP can manage its work-in-process level better (Takahashi *et al*. (2005)). Jodlbauer and Huber (2008) compared MRP, Kanban, CONWIP, and DBR in terms of robustness and stability. Their findings suggested that the most robust production control system is CONWIP. Various forms of hybrid systems have also been applied for comparisons. For example, a hybrid production planning of Kanban/CONWIP and hybrid CONWIP/pull combine the concept of a CONWIP with Kanban strategy for controlling the amount of work-in-process in the system (Bonvik *et al*., 2000). By applying the CONWIP constraint in a Kanban system, inventory in the system can be fully controlled. Geraghty and Heavey (2004) also compared a hybrid CONWIP/pull system with a hybrid between a push and a pull system. A hybrid push/pull system operates with the strategy that combines the concept of a push production system into a pull production system, which applies when a product is taken away by customer demand or the next process machine. A signal for refilling that taken product needs to be held until the proper time to reduce the holding cost. Their results showed that the hybrid CONWIP/pull system yields better results under optimal safety and inventory levels.

From the above-mentioned research, there are many operating parameters or decision variables embedded in each production control system. These parameters control the way each system operates. They include batch size, number of Kanbans, offset time, etc. A poor setting on of them results in poor operating conditions and eventually yields poor results. Due to the complexity of these systems, which include a number of if-else conditions, they are considered as non-deterministic polynomial-time hard (NP-hard) problems. A pure mathematical model would be too difficult to formulate and solve. A genetic algorithm (GA) has been widely used in recent years by many researchers to overcome the drawbacks of the mathematical models (Chan and Hu, 2001). The concept of GA is based on natural selection procedures. In order to be in an environment, populations need to adapt themselves to fit the surrounding environment. The one which can develop to fit more is the survivor and lives on. Generally, a GA algorithm has 2 mechanisms, which are mutation and crossover. The algorithm duplicates the concept of natural selection to find various solutions from a set of decision variables, which most fit the problem. A number of researchers have employed GA to find the optimal setting in their systems. For example, Prasertwattana and Chiadamrong (2004) used GA to find the optimal setting for a single manufacturer and multiple retailers' case in a supply chain network. Amirghasemi and Zamani (2015) employed an effective GA for solving the job shop scheduling problem by modifying traditional selection and mutation processes, which could lead to a procedure for obtaining a better solution.

Production Control Systems

In this study, 7 production control systems were introduced for comparison in unbalanced line conditions. They are 5 traditional non-hybrid systems, which are the push system, MRP, Pull-Kanban, CONWIP, and DBR, as well as 2 hybrid systems (CONWIP/MRP and MRP/CONWIP), which are created from a combination between of more than one 1 system from the previous traditional policies. Details of there these policies can be explained as follows:

Push System

A push system operates based on pure customer demand. The total processing time or manufacturing lead time of each order is calculated by adding a safety time to all the process set-up and operation times for planning the starting time to release materials to the production line. Raw materials are then pushed through all processes until they become finished products. Figure 1 shows the mechanism of the push system.

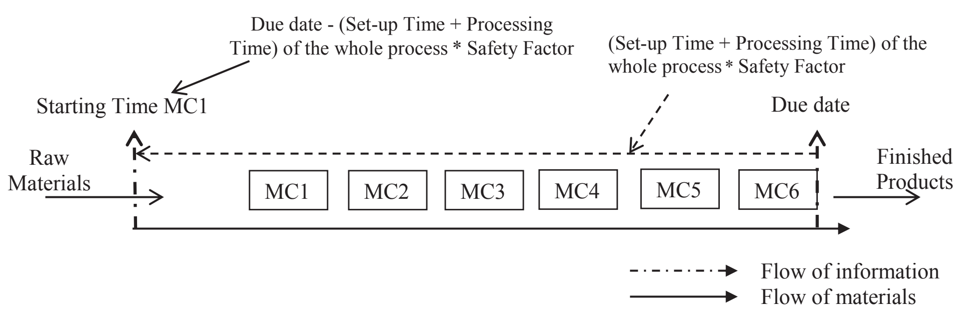

Figure 1. Push system

Material Requirements Planning (MRP)

MRP is also based on a push mechanism. In this model, production scheduling comes from the MRP plan. Each order can operate under the releasing time that is set back by the backward scheduling from MRP. This releasing time is used to prevent an early production, which may create unnecessary finished products and late production, and which can cause the tardiness of the finished products. Figure 2 shows the mechanism of the MRP system.

Pull-Kanban System

In this system, there are a number of parts stored between processes in Kanbans. Each Kanban may contain a certain number of parts and a fractional size of the Kanban cannot be withdrawn. To make it compatible with other systems without Kanbans in terms of a similar number of units produced, a Kanban size of 1 unit is used. As a result, a search has to be made for the an optimal number of Kanbans at each machine. Production starts when there is a customer demand, which takes products from the last downstream process. Then, empty Kanbans are transferred back to the upstream processes, with request for replenishing the required components, which have been taken by the downstream processes. As a result, parts from the upstream processes will be pulled to the downstream processes, according to the actual customer demand.

CONWIP

A CONWIP system is based on the Kanban idea. The difference is that there is no interaction between adjacent processes. The interaction occurs between the finished product and the raw material storing locations. Production starts at the same point as the pull-Kanban system. After finished products have been taken by customer demand from the output CONWIP buffer, a signal is sent to release raw materials into the production system to replenish the ones that have been taken by the customer from the output CONWIP buffer. In order to release raw materials for production, there are certain raw materials releasing conditions, which are the maximum allowed level of work in process (WIPCAP) and the proper releasing time.

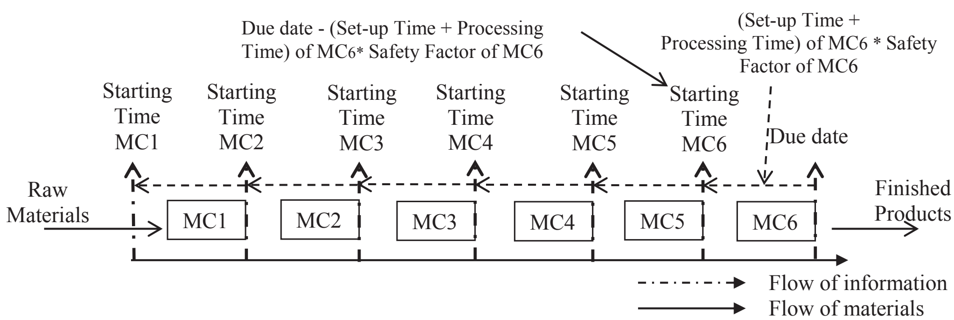

Figure 2. MRP system

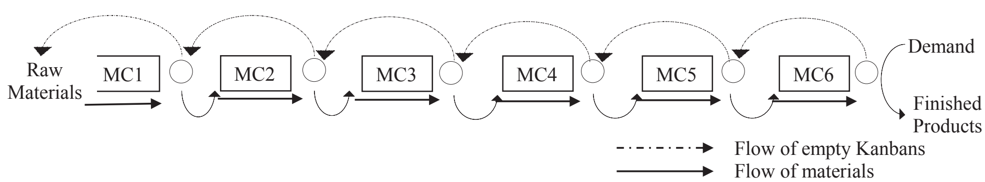

Figure 3. Pull-Kanban system

Production can start when the current level of work-in-process is below the WIPCAP, and it must be started in at a proper releasing time. This proper releasing time can be calculated by adding some amount of offset time called the "work-ahead window" to the manufacturing lead time of each part.

DBR System (MRP/Push)

The procedures of the DBR system are quite similar to an MRP system., but the difference is that this system focuses on the bottleneck operation, called a "drum". All previous processes in front of the bottleneck process should operate at the same pace as the bottleneck process; otherwise, parts will be piled up in front of the bottleneck too early. All processes after the bottleneck process should operate in a push fashion in order to get the finished products out as soon as possible. As a result, there is no holding time by backward scheduling, similar to the MRP system for preventing an early production in this push section. To increase the capacity of the bottleneck resource, a parameter of batch size is added in this system at the bottleneck process (MC3) where parts can be formed in a bigger batch. So, the machine's set-up time can be further reduced, allowing more time for part operation.

Hybrid CONWIP/MRP

This hybrid policy is a combination between the push concept of MRP and the pull concept of CONWIP. Its production control also focuses on the bottleneck process as a breaking point. After the bottleneck process, MRP is applied while CONWIP is applied to the processes prior to the bottleneck operation. There are parts stored in the output CONWIP buffer in front of the bottleneck process. When there is a customer demand, a signal is sent to this buffer and at the same time raw materials are released into the production system to replenish the materials that have been withdrawn from this buffer to the bottleneck process. This process will be done in the CONWIP fashion, as explained before. After the bottleneck process, parts will be controlled by MRP, as explained in the previous section. Similar to DBR, a batch

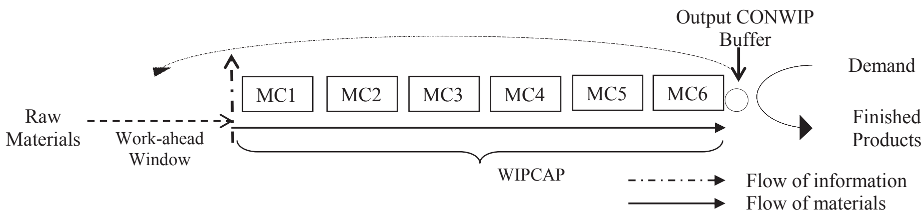

Figure 4. CONWIP system

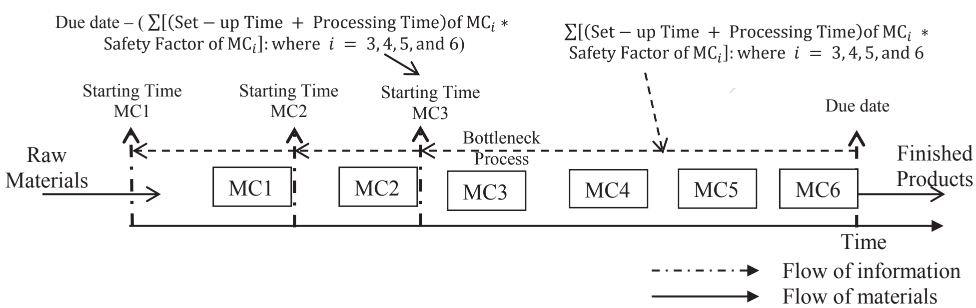

Figure 5. DBR system

size parameter is also added in this system in order to experiment for its optimal size and to increase the capacity of the bottleneck process (MC3).

Hybrid MRP/CONWIP

The only difference between this policy (Hybrid MRP/CONWIP) and Hybrid CONWIP/MRP is that MRP will be applied to the processes in front of the bottleneck process while CONWIP will be applied to the processes after the bottleneck process. Once the customer demand arrives, parts will be taken from the output CONWIP buffer and CONWIP is activated to replenish the parts taken by the demand. At the same time, backward scheduling controlled by MRP will take place, backward from the input CONWIP buffer to the first process.

Product Characteristics

In this study, there are 2 types of products (product F1 and F2), which can be broken down as shown by the bill of materials (BOM) in Figure 8. Both products have 6 processingsteps. Gross demand of products F1 and F2 are generated weekly according to their master production schedules (MPS) at the amount of 15 units on average per each type with the coefficient of variation of 0.1, under a normal distribution.

According to Figure 8, there are 6 machines (operating steps) arranged in the flow line. Each machine operates 1 level of component in BOM, such as machine 6 operates only F1 and F2 while machine 2 operates only B1, B2, B3, B4, and B5. Operating times and set-up times are under negative exponential distribution with the mean in the bottom left and set-up time in the top left. All of these times are in minutes. For example, F2 is operated by machine 6 (MC6) under a mean operating time of 40 min and a mean set-up time of 10 min, negative exponentially distributed. Machine 3 (MC3) is considered to be the bottleneck process since its operation time and set-up time are the longest, which can cause its utilization to be around 80%, whereas other machines' utilizations are only around 50% - 60%. This is about the maximum level of bottleneck severity, which allows the system to reach steady stage conditions and can be considered as a non-terminating type. All components are

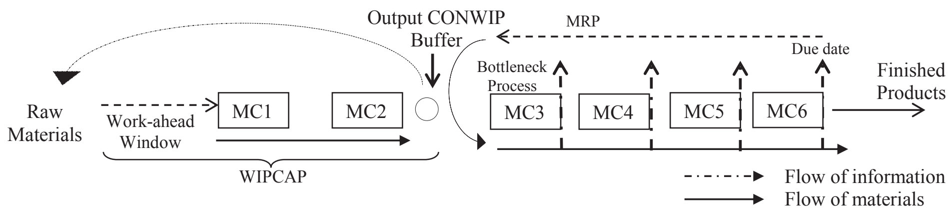

Figure 6. Hybrid CONWIP/MRP system

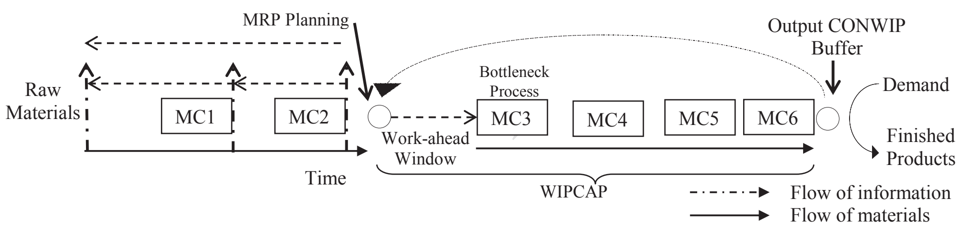

Figure 7. Hybrid MRP/CONWIP system

produced according to lot for lot. Except for components C1 and C2 in DBR and all the hybrid systems, which are operated by the bottleneck process (MC3), parts are produced in batches and the batch size is set to be a decision variable, where its optimal size needs to be decided.

Genetic Algorithm

A GA is a meta-heuristic optimization technique used to find an optimal solution that fits the problem by using natural selection. In order to be in an environment, populations need to adapt themselves to fit the surrounding environment. A GA has 2 mechanisms, which are mutation and crossover.

The crossover mechanism is used to produce a new set of solutions as offspring. are produced from the combination of 2 parents or 2 chromosomes. Each parent chromosome is divided into many sections. An offspring chromosome consists of some sections from 1 parent and some sections from another parent. The other mechanism is mutation. Mutation is random changes in some parts of the parent chromosomesto create another chromosome.

A GA has a set of solutions or chromosomes called a population. Having obtained offspring from both the crossover and mutation processes, all existing populations and offspring are selected from fitness values by using probability to form a new set of a population. The fitness value shows how well that chromosome fits the environment, showing the percentage of survival. Then, after a new set of a population is obtained, the crossover and mutation mechanisms are repeated to create new offspring and a new population is selected until it reaches the terminating condition, as shown in Figure 9.

Genetic Algorithm Parameters

All chromosomes in the GA are created based on each model's decision variables. Each chromosome is constructed based on a binary number. All decision variables need to translate from a decimal number to a binary number. Required bits in each chromosome are calculated by using a range of decision variables, and decimals are required. For instance, there are 6 decision variables in the MRP system. They are the planned queue time or safety time for all machines. Its required bits (denoted with m_i) can be calculated, as following:

$$2^{m_i-1} < (U_i - L_i) \times \left(10^{Decimals}\right) \leq 2^{m_i} - 1$$

where i is a decision variable index for $i = 1, 2, 3, \ldots\ldots, n$

U_i is the upper bound of variable index i

L_i is the lower bound of variable index i

For the planned queue time:

$2^8 < (3 - 0) \times (10^2) \leq 2^9 - 1$, So $m = 9$.

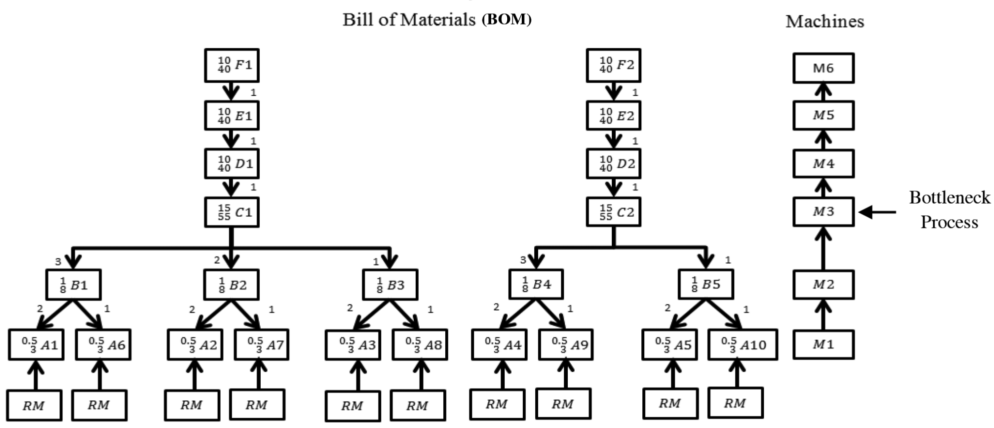

Figure 8. Product F1 & F2's bill of mate rial (BOM) & six 6 operating steps

Therefore the length of each chromosome is equal to the total required bits of all the decision variables. With 6 planned queue time parameters, the length of a chromosome is 9 + 9 + 9 + 9 + 9 + 9 = 54 bits.

Figure 10 shows an example of an experiment on the CONWIP system to obtain the best percentage of crossover and mutation. We have performed a preliminary test to obtain these values. It was found that a crossover rate of 40% and a mutation rate of 20% yielded the best performance as they give the lowest cost (objective function) in our preliminary experiment. A population consists of 20 chromosomes in binary form. Chromosomes in a population are randomly chosen to form 8 offspring from the crossover process or 40% of the population. One of chromosomes is randomly chosen to form 1 mutant from the mutation process. Then, 20% of its total bits need to be mutated to form a new offspring before forming a new population.

Decision Variables

Each policy has different decision variables according to its required operating parameters, as shown in Table 1. For example, the pull-Kanban system has a number of Kanbans at each machine as decision variables while the push mechanism systems have the planned queue time at each machine (material releasing time) as decision variables. In total, the push, MRP, and DBR systems have 1, 6, and 5 decision variables, respectively, and the pull-Kanban and CONWIP have 23, and 4 decision variables, respectively, and the 2 hybrid systems, CONWIP/MRP and MRP/CONWIP, have 10 and 8 decision variables, respectively. All of these decision variables will be searched to find their optimums by the GA.

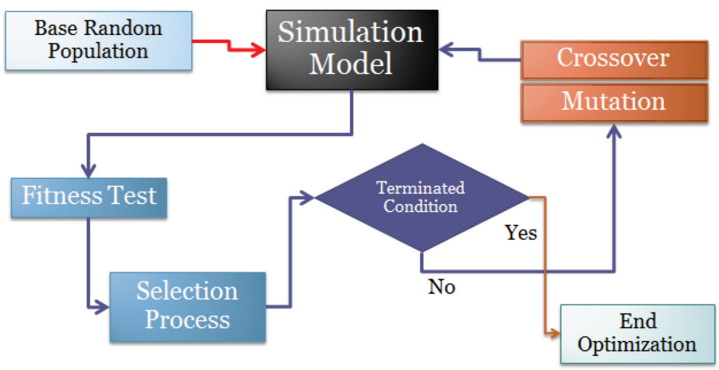

Figure 9. Genetic Aalgorithm's functions

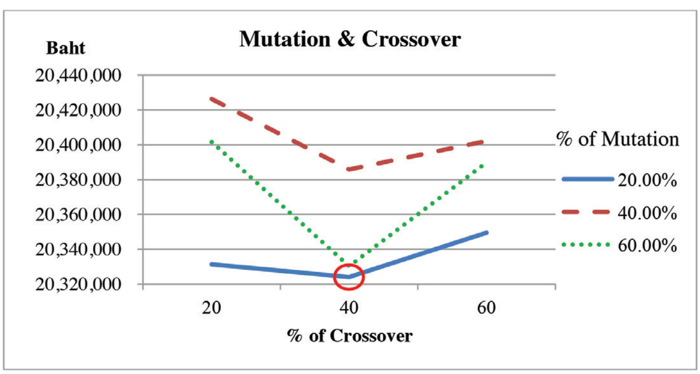

Figure 10. Results of crossover and mutation experiment

Number of Replications and Replication Length

All production control systems are simulated by the ARENA 14.7 software program. Due to the uncertainty in simulation, each production system model requires 15 replications with 5 year periods in each replication where the first 2 years were eliminated as a warm up period. This yields independent observations between replications and brings the confidence intervals (half-width) of the interested observation (total costs of the system) to be within 5% of our

Table 1. Decision variables

Decision variables	Bounds		Traditional systems				Hybrid systems		
	Max	Min	Push	MRP	Pull-Kanban	CONWIP	DBR	CONWIP/MRP	MRP/CONWIP
Planned queue time for all machines (time of)	0	3	✓						
Planned queue time at machine 1 (time of)	0	3		✓			✓		✓
Planned queue time at machine 2 (time of)	0	3		✓			✓		✓
Planned queue time at machine 3 (time of)	0	3		✓				✓	
Planned queue time at machine 4 (time of)	0	3		✓				✓	
Planned queue time at machine 5 (time of)	0	3		✓				✓	
Planned queue time at machine 6 (time of)	0	3		✓				✓	
Planned queue time for machines 3, 4, 5, and machine 6 (time of)	0	3					✓		
C1 batch size	1	20					✓	✓	✓
C2 batch size	1	20					✓	✓	✓
Kanban A1 (units)	1	50			✓				
Kanban A2 (units)	1	50			✓				
Kanban A3 (units)	1	50			✓				
Kanban A4 (units)	1	50			✓				
Kanban A5 (units)	1	50			✓				
Kanban A6 (units)	1	50			✓				
Kanban A7 (units)	1	50			✓				
Kanban A8 (units)	1	50			✓				
Kanban A9 (units)	1	50			✓				
Kanban A10 (units)	1	50			✓				
Kanban B1 (units)	1	50			✓				
Kanban B2 (units)	1	50			✓				
Kanban B3 (units)	1	50			✓				
Kanban B4 (units)	1	50			✓				
Kanban B5 (units)	1	50			✓				
Kanban C1 (units)	1	50			✓				
Kanban C2 (units)	1	50			✓				
Kanban D1 (units)	1	50			✓				
Kanban D2 (units)	1	50			✓				
Kanban E1 (units)	1	50			✓				
Kanban E2 (units)	1	50			✓				
Kanban F1 (units)	1	50			✓				
Kanban F2 (units)	1	50			✓				
Output CONWIP buffer for F1 (units)	1	100				✓			✓
Output CONWIP buffer for F2 (units)	1	100				✓			✓
Output CONWIP buffer for C1 (units)	1	100						✓	
Output CONWIP buffer for C2 (units)	1	100						✓	
WIPCAP (units)	50	1,000				✓		✓	✓
Work ahead window (minutes)	0	2,000				✓		✓	✓
Total number of decision variables			1	6	23	4	5	10	8

point estimate of this value, under 95% of the confidence level.

Cost Model

The performance of each system is measured by using the total costs of the system. So, the objective function is aimed to minimize the costs.

Total costs = $RM + OC + S + LP + HC$ (3)

where:

RM = Raw material cost (Baht)
OC = Operation cost (Baht)
S = Set-up cost (Baht)
LP = Late penalty cost (Baht)
HC = Holding cost (Baht)

Raw material cost

$$RM = RM_C \times N_{RM} \quad (4)$$

where:

RM = Raw material cost (Baht)
RM_C = Raw material cost per unit (Baht)
N_{RM} = Number of units used (units)

Operation cost

$$OC = O_C \times \sum_{i=1}^{6} (OT_i \times N_i) \quad (5)$$

where:

O_C = Operation cost (Baht)
O_C = Machine operation cost per minute (Baht)
N_i = Total number of parts operated by machine i (minutes)
OT_i = Average operating time of machine i (minutes)

Set-up cost

$$S = S_C \times \sum_{i=1}^{6} (ST_i \times n_i) \quad (6)$$

where:

S = Set-up cost of machine i (Baht)
ST_i = Average set-up time of machine i (minutes)
n_i = Total number of set-ups of machine i (minutes)
S_C = Set-up cost per minute (Baht)

Late penalty cost

$$LP = N_L \times LT \times LP_C \quad (7)$$

where:

LP = Late penalty cost (Baht)
N_L = Total number of late parts (unit)
LT = Average late time per unit (minutes)
LP_C = Late penalty cost per minute (Baht)

Holding cost

$$HC = \sum_{i=1}^{6} (HC_j \times N_j \times HT_j) \quad (8)$$

where:

HC = Holding cost (Baht)
N_j = Total number of parts held in stage j (unit)
HT_j = Average hold time per unit at stage j (minutes)
HC_j = Holding cost per unit per minute at stage j (Baht)

Table 2. Unit cost

	Product F1	Product F2
Price	9000 Baht/unit	4500 Baht/unit
Raw material cost	18 pieces × 100 Baht/piece =1,800 Baht/unit	9 Pieces × 100 Baht/piece =900 Baht/unit
Late penalty cost	9000 × 0.2/(8 × 60) 3.75 Baht/min	4500 × 0.2/(8 × 60) 1.875 Baht/min
Raw material cost	100 Baht/piece of raw material type A	
Operating cost	5 Baht/min	
Set-up cost	100 Baht/min	
Late penalty cost	20% of unit price/day	
Holding cost	40% of unit cost at each stage/year	

According to Table 2, the raw material cost is 100 Baht per unit of type A component. For example, product F1 requires 18 pieces of type A components, so the raw material cost of product F1 is 18×100, which equals 1800 Baht. The Ooperating cost and set-up cost are 5 Baht per minute. A late penalty cost is charged at 20% of the unit price per day, which means that 1 day late can cause a penalty cost of 20% of its unit price. The holding cost is also charged by the percentage of unit cost at each stage of the process. As a result, the holding cost of a part towards the end of the line would be more expensive than at the beginning of the line since the unit cost of a more complete unit is more expensive.

Table 3. Solution from the GA

Decision variables	Bounds		Traditional systems					Hybridsystems	
	Max	Min	Push	MRP	Pull-Kanban	CONWIP	DBR	CONWIP/MRP	MRP/CONWIP
Planned queue time for all machines (time of)	0	3	0.74						
Planned queue time at machine 1 (time of)	0	3		0.49			0.76		0.4
Planned queue time at machine 2 (time of)	0	3		1			1.33		0.63
Planned queue time at machine 3 (time of)	0	3		0.6				0.13	
Planned queue time at machine 4 (time of)	0	3		1				1.49	
Planned queue time at machine 5 (time of)	0	3		0.7				0.75	
Planned queue time at machine 6 (time of)	0	3		1.04				1.34	
Planned queue time for machines 3, 4, 5, and machine 6 (time of)	0	3					1.15		
C1 batch size	1	20					3	6	2
C2 batch size	1	20					4	6	5
Kanban A1 (units)	1	50			34				
Kanban A2 (units)	1	50			18				
Kanban A3 (units)	1	50			26				
Kanban A4 (units)	1	50			25				
Kanban A5 (units)	1	50			36				
Kanban A6 (units)	1	50			12				
Kanban A7 (units)	1	50			20				
Kanban A8 (units)	1	50			26				
Kanban A9 (units)	1	50			21				
Kanban A10 (units)	1	50			35				
Kanban B1 (units)	1	50			34				
Kanban B2 (units)	1	50			31				
Kanban B3 (units)	1	50			39				
Kanban B4 (units)	1	50			30				
Kanban B5 (units)	1	50			29				
Kanban C1 (units)	1	50			25				
Kanban C2 (units)	1	50			3				
Kanban D1 (units)	1	50			34				
Kanban D2 (units)	1	50			19				
Kanban E1 (units)	1	50			16				
Kanban E2 (units)	1	50			16				
Kanban F1 (units)	1	50			21				
Kanban F2 (units)	1	50			27				
Output CONWIP buffer for F1 (units)	1	100				29			52
Output CONWIP buffer for F2 (units)	1	100				39			63
Output CONWIP buffer for C1 (units)	1	100						12	
Output CONWIP buffer for C2 (units)	1	100						27	
WIPCAP (units)	50	1,000				340		448	480
Work ahead window (minutes)	0	2,000				992		771	282.31
Total number of decision variables			1	6	23	4	5	10	8

Results and Discussion

Table 3 shows the optimal levels of all parameters in each system, which are obtained from the GA. It also shows the search bounds and guarantees that none of the obtained optimal values hits the searching bounds, which might lead to the local optimum value. All parameters are within the searching range.

The hybrid CONWIP/MRP has the lowest total costs stemming from the lowest set-up costs and relative low holding cost. The lowest set-up cost as compatible to with the DBR is a result of operating with a bigger batch size at the bottleneck process (MC3) to save the machine set-up requirements. Then, introducing CONWIP prior to the bottleneck process, parts would not be launched into the line too early to pile up in front of the bottleneck process, which runs at a slower speed due to control of the amount of WIPCAP and offset time of the work-ahead window as decision variables. After the bottleneck process, parts are produced according to the MRP schedule to match with the due dates. As a result, parts would not be pushed through the line too early and incur a high holding cost.

Regarding the hybrid MRP/CONWIP, it can yield total costs lower than the ones from traditional pull mechanism systems (i.e., Kanban and CONWIP) as a result of lower set-up and holding costs. However, holding parts in a CONWIP buffer further downstream in the line (it should be noted that CONWIP/MRP's buffer is located towards the beginning of the line) causes a high inventory holding cost as the unit cost of more complete parts is more expensive than the unit cost of raw materials. As the holding cost is charged by the percentage of the unit cost at each stage, the holding cost per unit of more complete units becomes more

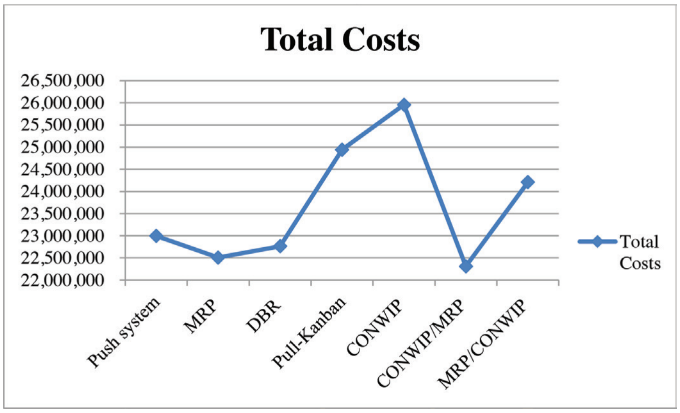

Figure 11. Total costs of all systems

Table 4. Tukey's multiple range test's results

	Ranking from Max to Min						
	Worst						**Best**
Total costs	CONWIP	Pull-Kanban	MRP/CONWIP	Push	DBR	MRP	CONWIP/MRP
Raw Material cost	DBR	CONWIP	Pull-Kanban	Push	MRP/CONWIP	MRP	CONWIP/MRP
Operation cost	CONWIP	DBR	MRP/CONWIP	Push	Pull-Kanban	MRP	CONWIP/MRP
Late penalty	DBR	Push	CONWIP	CONWIP/MRP	MRP	MRP/CONWIP	Pull-Kanban
Set-up cost	CONWIP	MRP/CONWIP	Pull-Kanban	Push	MRP	DBR	CONWIP/MRP
Holding cost	Pull-Kanban	MRP/CONWIP	DBR	CONWIP	CONWIP/MRP	Push	MRP

expensive, and leads to a higher holding cost.

The raw material cost and operation cost of each policy do not show significant differences since all policies operate under the same customer demand with the same MPS. As a result, they are not much different. The late penalty cost also shows not much of a difference among the systems. This is due to the fact that all systems try to avoid this high penalty cost by holding more inventory, as it is cheaper to do so. As a result, significant differences among all systems only come from the cost of holding and set-up (see Figure 12 for the comparison of the holding and set-up costs among the different systems). DBR, which is aimed to improve the efficiency of unbalanced systems, cannot distinguish itself from other push mechanism policies (i.e., push and MRP). Under unbalanced conditions, its set-up cost is the lowest by forming a bigger batch through the bottleneck to reduce the number of set-ups and better utilize the bottleneck process. Its impact is still not enough to decrease the overall costs of this system.

The pull mechanism systems (i.e., CONWIP and pull-Kanban) have the highest set-up cost since 1 part is pulled at a time, so there is a high chance that the consecutive part is from a different type. As a result, a set-up process is required, and the set-up cost would increase accordingly, as compared to the push related mechanism systems (i.e, push and MRP) where products are produced by lot for lot, so that each machine would require less number offewer set-ups.

Regarding the holding cost, it is found that the push mechanism systems (i.e., push system, MRP, and CONWIP/MRP), have a low holding cost since there is no need to hold stock between the processes, while the pull-Kanban system has to pay the highest cost of holding such stock in Kanbans between processes.

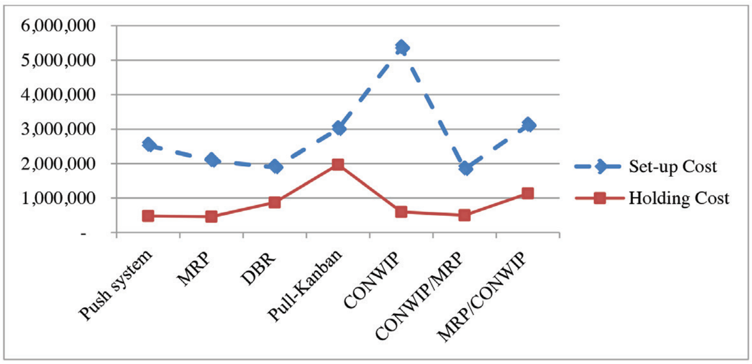

Figure 12. Holding & and set-up costs of all systems

Table 5. Breakdown of total costs and lead time

	Push mechanism systems			Pull mechanism systems		Hybrid systems	
	Push system	MRP	DBR	Pull Kanban	CONWIP	CONWIP/ MRP	MRP/ CONWIP
Total costs (Baht)	22995513	22507162	24941361	25955366	22762964	22310957	24210468
Raw material cost (Baht)	10470300	10470180	10471080	10473120	10470360	10470270	10470240
Machine operation cost (Baht)	9497575	9496887	9497873	9497259	9514232	9496689	9498219
Late penalty cost (Baht)	23353.54	647.64	27266.89	-	15382.75	3491.34	-
Set-up cost (Baht)	2524369	2080031	1891190	3003762	5356659	1838105	3106332
Holding cost (Baht)	479915	459416	875552	1967218	598731	502431	1135676
Manufacturing lead time (mins)	434237	5455.30	6040.57	28519.35	2849.05	9266.33	7669.63

Considering the manufacturing lead time, it was clearly found that the pull-Kanban system has the longest lead time, as a certain number of parts are stored between processes, waiting for a pull signal. As a result, the manufacturing lead time would definitely be longer than other push mechanism systems in which parts do not need to be stored between processes and are produced according to the incoming demand. CONWIP, which takes the benefit of controlling the number of parts being gradually pushed along the line with an optimal number of parts stored in the output CONWIP buffer, has the shortest manufacturing lead time. However, both hybrid systems somehow suffer from keeping a certain number of parts in the output CONWIP buffer. So, their manufacturing lead time would be longer than the push mechanism systems, but far shorter than the pull-Kanban system.

In summary, the hybrid CONWIP/MRP has the lowest set-up cost and a relatively low holding cost, and eventually the lowest total cost since this system benefits both from both the push and pull mechanisms, as well as the bottleneck process which is operated under MRP, with optimal batch size. As a result, a significant set-up time from traditional CONWIP can be saved. However, MRP/ CONWIP would suffer from both the high costs of set-ups and holding as the bottleneck process operates under the CONWIP, so there is a high chance to of have having different consecutive parts launching launched to each machine, which leads to a high set up cost, as well as keeping the finished products in the output CONWIP buffer at the end of the line, bringing a high holding cost as a result.

Conclusions

Push and pull concepts of production control systems were compared using simulation optimization by the genetic algorithm. Each system shows different advantages and disadvantages under unbalanced conditions. The push mechanism systems has have lower set-up and holding costs while the pull mechanism systems has have higher set-up and holding costs due to the fact that parts are needed to be held between processes in Kanbans and produced in a smaller batch size (batch of 1 unit), but their manufacturing lead time is much shorter. By combining the systems, 2 hybrid systems were introduced. Results show that the hybrid CONWIP/MRP performs bestbetter. With CONWIP in front of the bottleneck process, both the holding cost and set-up costs were reduced, where the set-up cost was the shortest lowest and the holding cost was not much different from the push mechanism systems. The lowest total costs obtained from this policy was a result of placing and controlling a proper buffer size in front of the bottleneck process and slowing down parts flowing to the bottleneck process while applying the CONWIP policy in front of the bottleneck process. This helps to reduce holding and set-up costs. In addition, the backward scheduling of MRP after the bottleneck process can prevent an early/tardy production and helps reduce the holding cost and penalty cost as a result.

Further study can also be extended to include a sensitivity analysis of the proposed cost structure as it could affect the way each system performs. Also, more uncertainty in the system can be further studied, such as part defects or machine break-down, to investigate how each system responds under such circumstances.

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