A REVIEW AND ANALYSIS OF HORIZONTALLY INTEGRATED HYBRID PRODUCTION CONTROL STRATEGIES

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Abstract:
Traditionally western manufacturing systems have employed production control strategies that push products through the system based on forecasted customer demands. Such strategies aim to maximise the throughput of the system so as to minimise shortage in supply and tend to result in excess inventory in the system that masks flaws in the system. Japanese manufacturing systems, on the other hand employ production control strategies that pull products through the system based on actual customer demands at the end of the line. Such strategies tend to minimise the inventory in the system and unveil flaws in the system at the risk of failure to satisfy demand. A hybrid production system could be characterised as a production system that combines elements of the two philosophies in order to minimise inventory and unmask flaws in the system while maintaining the ability of the system to satisfy demand. One of the earliest examples of such a hybrid manufacturing strategy is Synchro MRP as proposed by Hall, 1983. Synchro MRP proposed utilising push for scheduling but not allowing work to begin unless kanbans are available as well. Such strategies are termed vertically integrated hybrid production control strategies as they involve the integration of push and pull control software for planning and shop floor control. Horizontally integrated hybrid production control strategies (HIHPCSs) involve the integration of push and pull control on the shop floor such that each stage employs either push or pull control but not elements of both. This paper provides a review of the literature of HIHPCSs. In addition, the results of preliminary experimental work on the analysis of the likely benefits to a production system from employing a HIHPCS are presented.

Keywords: *MRP, JIT, Hybrid Production Control Strategies, Markov Decision Process, Simulation.*

1.0 INTRODUCTION

The advantages and disadvantages of push systems such as MRP and pull systems such as kanban controlled Just-In-Time have been well documented in the literature in recent years (Krajewski, King, Ritzman and Wong, 1987; Lee, 1989; Deleersnyder, Hodgson, King, O'Grady and Savva, 1992; Spearman and Zazanis, 1992). A great amount of research effort has been focused on how best to combine JIT and MRP philosophies in order to maximise the benefits of pull control in non-repetitive manufacturing environments. A hybrid production system could be characterised as a production system that combines elements of the two philosophies in order to minimise inventory and unmask flaws in the system while maintaining the ability of the system to satisfy demand.

2.0 LITERATURE REVIEW OF HYBRID STRATEGIES

Several authors have investigated various methods of integrating push and pull control strategies. Kim (1996) classified these attempts into three distinct groups:

1. Approaches that embed JIT into MRP,
2. Vertically Integrated Hybrid Production Control Strategies, and
3. Horizontally Integrated Hybrid Production Control Strategies.

Attempts to embed JIT into MRP can be further sub-classified into two groups:

1. Forecast driven kanban systems, and
2. Requirements driven kanban systems.

Groenevelt and Karamarkar (1988) provide a case study implementation of an embedded JIT-MRP system. Vertically and horizontally integrated hybrid push-pull production control strategies are production control strategies based on the integration, as opposed to the embedding, of push type and pull type production control strategies. Vertically integrated hybrid push-pull production control strategies imply that the strategy consists of two levels. At the first level, push-type production control strategy is implemented to generate the production schedule. At the second level pull-type production control strategy is implemented to ensure that production at a stage is subject to the availability of kanbans. One early attempt to implement such a hybrid production control system is the Yamaha PYMAC system, also known as Synchro MRP (Hall, 1983). Kanban control is used to authorise the production at individual stages and the schedule is released by an MRP system. The main disadvantage of this system is that MRP is linked into every workstation and is therefore very complex to implement. Horizontally integrated hybrid push-pull production control strategies imply that the stages of the production line are not all ordered by one production control strategy but each individual stage will operate under a push or pull control strategy. The bulk of the research on horizontal integration has concerned itself with two issues:

1. Determining the best policy for horizontal integration, i.e. push-pull (where succeeding stages push and proceeding stages pull), pull-push or some other combination of stages pushing and pulling.
2. Comparison of hybrid push-pull production control strategies to traditional MRPII type push production control strategies and JIT pull production control strategies.

2.1 Vertically Integrated Hybrid Production Control Strategies (VIHPCSs)

Grupta and Brennan (1993) developed a model of a real world system controlled by a VIHPCS. The model utilised expert systems in conjunction with simulation. This method was demonstrated to be an effective method of modeling such complex systems. Deleersnyder et al. (1992) felt that the overall complexity of Synchro MRP militated against its application by organizations. They believed that if the number of stages controlled by both production strategies was reduced that integrated hybrid strategies would prove an attractive alternative to JIT and MRP. Figure 1 below depicts the N-stage hybrid production system proposed by Deleersnyder et al. (1992). The manufacturing planner and controller supplies production triggers, $A_j(n)$, to the hybrid workcentres. In a pure Synchro MRP environment the production triggers would be supplied to all workcentres. In the hybrid push/pull scheme proposed by Deleersnyder et al. (1992) only the first stage, MC_1, is controlled by a hybrid push/pull policy. All succeeding stages are controlled by a pull policy. The hybrid push/pull policy, in calculating the production trigger $A_i(n)$, takes into account the demand (via the end item inventory) and the work in progress inventories of the succeeding stages. The new hybrid strategy outperformed pure push, pure pull and Synchro MRP strategies.

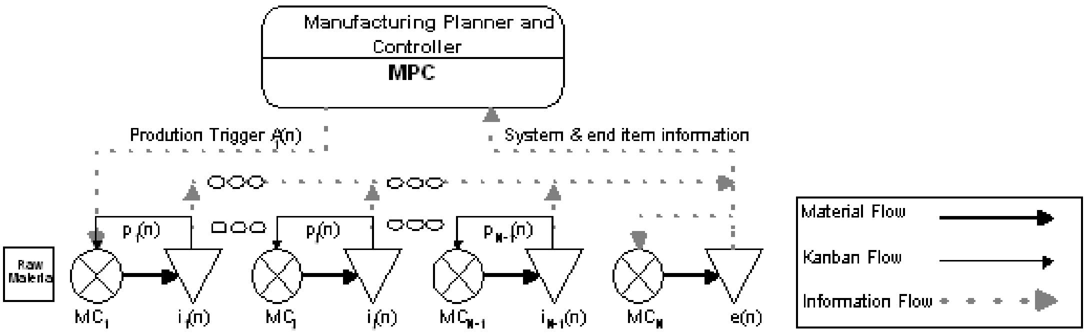


Figure 1: The N-stage hybrid serial production model proposed by Deleersnyder, Hodgson et al., (1992).

2.2 Horizontally Integrated Hybrid Production Control Strategies (HIHPCSs)

Takahashi developed and experimented with a mathematical model for HIHPCSs. The model was developed and presented in three papers published between 1991 and 1996. Takahashi, Hiraki and Soshiroda (1991) compared pure push and pure pull systems with pull-push hybrid systems and found that pull-push hybrid systems would outperform the pure systems. Takahashi, Hiraki and Soshiroda (1994) compared pure push and pure pull systems with push-pull hybrid systems. Once again the hybrid policy outperformed the pure systems. Takahashi and Soshiroda (1996) compared the two hybrid policies with each other. Push-pull integration was demonstrated to yield better results than pull-push integration. However, the model was over simplistic and did not account for capacity constraints and machine reliability (Orth, 1997; Kim 1996).

Hirakawa, Hoshino and Katayama (1992); Hirakawa (1996) developed a mathematical model for a hybrid push/pull system that allows each production stage to switch between push and pull control depending on whether demand can be forecasted reliably or not. The hybrid production rule for stage k with a production lead-time of L_k, requires that $L_k + 1$ periods being divided into two parts. One is F_k periods in which push type control is employed the other part is where the remaining $L_k - F_k + 1$ periods employ pull type control with a replenishment level of $Q(F_k)$. F_k is referred to as the push horizon and is the period in which demand can be reliably forecasted. The main conclusions of this work were that:

1. Pull type systems are effective at minimising the variance inventory when the demand forecast is unreliable and the variance of forecast errors is greater than the variance of demand.

2. Push type systems become more effective when the variance forecast errors is less than the variance of demand.
3. Hybrid systems can be more effective than pure push or pure pull systems if the parameters of the hybrid policy, such as the length of the push horizon, are optimised.

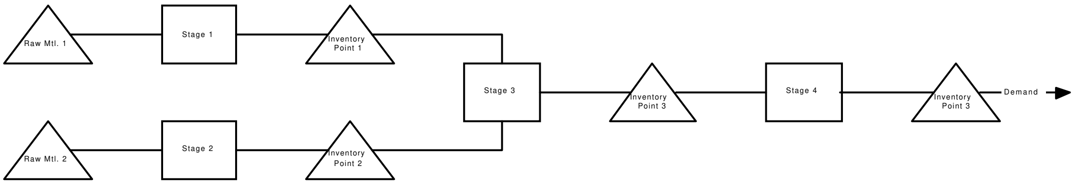
Olhanger and Östlund (1990) recommended rules to assist in the integration of push and pull control philosophies in semi-repetitive manufacturing environments. The focus of the discussion on push-pull integration was in relation to the customer order point, bottleneck resources and the product structure. Olhanger and Östlund (1990) applied their methodology to a packaging facility. The reported results for this case study were that delivery lead-times were reduced, and delivery dependability was increased. In addition, inventory levels were reduced by as much as 75% and the flexibility of the system in responding to changes in market demand had increased significantly. Huang and Kusiak (1998) expanded upon the work of Olhanger and Östlund (1990) using an IDEF 3 model and identified five categories of stages in a manufacturing environment:

1. Critical stages (CS) are stages along the critical path, which is the path with total flow time equal to the flow time of the entire product.
2. Value-adding stages (VAS) are stages that increase the value of the components or products.
3. Bottleneck stages (BS) are stages utilised the most in the system.
4. Batch production stages (BPS) are stages that process parts in batches to decrease job set-up costs.
5. Assembly stages (AS) are stages that perform assembly operations once all the required parts have arrived.

The AS and BPS stages can be readily identified in any manufacturing system. However, the identification of CS, VAS, and BS stages, often, is not an easy task. An IDEF 3 model of a manufacturing system was proposed and a generalised label-correcting (LC) algorithm was developed to determine the label for each stage. After the stages are identified a set of rules are applied to determine the control policies to be employed at the stages. Huang and Kusiak (1998) presented a case study of their technique applied to a manufacturing system producing oval-gear flow meters. After the identification of stages and the application of control strategies to individual stages, a simulation experiment was conducted with eight scenarios. The reported results were that horizontal integration would result in reduced WIP levels and associated costs, decreased mean waiting time in buffers and reduced product lead times.

2.2.1 A Markov Decision Process Model For HIHPCSs

Hodgson and Wang (1991a); Hodgson and Wang (1991b) developed a Markov Decision Process (MDP) model for horizontally integrated hybrid production systems. The model was solved using both dynamic programming and simulation for several production strategies, including pure push and pure pull production strategies and strategies based on the integration of push and pull policies. They initially applied their research to a four-stage iron and steel works, which was a continuous production process. However, in order to simplify the model it was assumed that the production process was a discrete time process, and that demand per period and the amount of inventory were integer multiples of a unit size. The second paper extended the work to a system with five production stages with the first two stages in parallel and the remaining stages as serial production stages. For both experiments, a policy that required stages that input components to the system to push and all other stages to pull was demonstrated to result in the lowest average gain (average system cost).



Hodgson and Wang (1991b) concluded that this policy would be the optimal hybrid integration policy for a K-stage system.

Figure 2: Parallel/Serial four stage production system modelled by Hodgson and Wang (1991a).

What follows is a generalisation of the formulas for the production triggers and objectives, given in Hodgson and Wang (1991a); Hodgson and Wang (1991b) to a K-stage parallel/serial production system. The notation used is based on the work of Pandey and Khokhajaikiat (1996). Let A_k (n) be the production trigger for stage k in period n, D(n) be the forecasted demand and SS be the desired safety stock level of the final product. For a push controlled system the production trigger for a stage, during period n, can be developed from the following equation:

$$A_k(n) = Max\left\{P_k^{\min}, (c+1)D(n) + SS - \left(\sum_{i=k}^{K} I_i(n-1) - C_k(n-1)\right)\right\}, k = 1,2,\ldots,K$$

Equation 1

The number of serial stages succeeding stage k is c. C_k(n-1) is the set of inventories of parallel stages to k but does not include stages with a stage number less than k. When a stage is controlled by a push control policy then the production trigger for the stage can be obtained from Equation 2 for the first K-1 stages and from Equation 3 for the final stage, K.

$$A_k(n) = Max\{P_k^{\min}, I_k^{\max} - I_k(n-1)\}, k = 1,2,\ldots,K-1$$

Equation 2

$$A_k(n) = Max\{P_k^{\min}, SS - I_k(n-1) + D(n)\}, k = K$$

Equation 3

The production objective for a stage, for period n, can then be obtained from Equation 4 for the first K-1 stages. For the final stage, K, the production objective, for period n, can be obtained from Equation 5. The set of inventories of immediate predecessors to stage k in the period n-1 is $\{J_i(n-1)\}_k$.

$$PO_k(n) = Min\left[A_k(n), P_k^{Max}, \{J_i(n-1)\}_k, I_k^{\max} - I_k(n-1)\right], k = 1,2,\ldots,K-1$$

Equation 4

$$PO_k(n) = Min\left[A_k(n), P_k^{Max}, \{J_i(n-1)\}_k, I_k^{\max} - I_k(n-1) + D(n)\right], k = K$$

Equation 5

It is assumed that the raw material stores contain sufficient inventory and consequently the set of inventories of immediate predecessors in Equation 4 for input stages will be ignored.
Pandey and Khokhajaikiat (1996) modified Hodgson and Wang's model to allow for the inclusion of raw material constraints at each stage. The modified model also allows for a stage to require more than one item of inventory and/or more than one item of raw material to produce a part. The model was applied to a four-stage Hair Dryer assembly line. Pandey and Khokhajaikiat (1996) presented results from two sets of experiments. In the first set they modelled a four-stage parallel/serial production line similar to the system modelled by Hodgson and Wang (1991a). The initial stages (stages 1 & 2) operated under raw material availability constraints. Stages 1 and 2 had different order purchasing and delivery distributions. Only stages 1 and 2 had identical production density functions. Sixteen integration policies were considered. In the second experimental set the authors applied the raw material availability constraint to all stages of the production line. The authors concluded that the hybrid policy in which the initial stages operate under push control and remaining stages operate under pull control is the best policy when raw material constraints apply only to the initial stages. When the raw material availability constraint is applied to all stages the push policy becomes optimal control policy. For systems with large variability in demand none of the policies dominated.

Wang and Xu, (1997), proposed that in any manufacturing system, in terms of the flow of material, there are four types of stages:

1. Initial raw material input stage,
2. Serial stage for part processing,
3. Assembly stage, using more than one type of component to produce a product,
4. Final stage, for final assembly, packaging and supply to market demand.

Wang and Xu (1997) proposed that an adjacent matrix of the network graph of a system could be utilised to describe the structure and relations of processing and assembly stages of the system and allow for easy translation into a simulation model.

2.2.2 Determining the Optimal Kanban Distribution and Safety Stock Level in a HIHPCSs

Kim (1996) developed a simulated annealing algorithm that sought to minimise the total cost for a horizontally integrated hybrid production control strategy. The algorithm attempted to determine the optimal kanban distribution at pull stages, the position of the junction point between push and pull controlled stages and the optimal safety stock level to maintain at the junction point. Kim (1996) did not use Hodgson and Wang's model, claiming that it did not model a pull strategy correctly. Instead Kim (1996) applied the simulated annealing algorithm to a simulation model of an existing system. Kim's algorithm only examines the possibility of a single junction point in the system and does not consider multiple junction points.

2.3 Comparison of Hybrid Production Control Strategies

Orth (1997) developed a simulation model that incorporated the original equations to calculate the production for each stage during a time period and repeated the experimental work published by Hodgson and Wang (1991b) in order to validate the simulation model. Orth (1997) claimed that the results produced by the simulation model for the gain were comparable to Hodgson and Wang (1991b) with the exception of the results for the pull approach. Orth (1997) achieved a much higher result of 4.70 for the gain than the reported result of 3.9059 in Hodgson and Wang (1991b). It is probable that this discrepancy can be accounted for by how the production trigger was calculated. In Hodgson and Wang, 1991b, the equation for the calculation of the production trigger, A_k, for a pure pull system is given as:

$$A_k(n) = Min\left[I_k^{Max} - I_k(n-1), I_{k-1}(n-1)\right], \qquad k = 1,2,\ldots,K$$

Equation 6

However, in Hodgson and Wang, 1991a, the equation for the calculation of the production trigger, A_j, for a pure pull system is given as:

$$A_k(n) = Max\left\{P_k^{\min}, KB_k(n)\right\}, \qquad k = 1,2,\ldots,K$$

Equation 7

Where the $KB_k(n)$ term is obtained from the following equations:

$$KB_k(n) = SS - \left(I_k(n-1) - D(n)\right), \qquad k = K$$

Equation 8

$$KB_k(n) = I_k^{Max} - I_k(n-1), \qquad k = 1,2,..,K-1$$

Equation 9

Orth (1997) examined the system from Hodgson and Wang (1991b) further under different probability density functions for demand. In addition, included in the analysis was an additional policy that pulled at the final stage and pushed elsewhere. Labelled policy 9, this policy was the exact opposite of Hodgson and Wang's preferred policy. The results of this experiment demonstrated that for higher average demands policy 4 which pushed at stages 1, 2 and 3 and pulled at stages 4 and 5 outperformed Hodgson and Wang's preferred policy, policy 3 which pushed at stages 1 and 2 and pulled at stages 3, 4 and 5. Policy 3 only outperformed policy 4 for the original Probability Density Function (PDF) for demand. However, as the maximum inventory levels and safety stock level were not optimised for each new demand distribution, Orth's conclusion that under high variability in demand that policy 4 will be optimal cannot be sustained.

Orth (1997) compared pure pull, pure push, Synchro MRP, CONWIP, Hodgson and Wang's policy, the critical policy, Takahashi's model and a CONWIP policy that utilised Hodgson and Wang's policy to calculate production for the stages. The five-stage system described by Hodgson and Wang (1991b) was used as the basis for comparison. Takahashi's model was altered to include a production adjustment value for each stage such that if the stock in a queue fell below a determined safety stock level at the end of a period the production for the next period would be increased by a factor m, where m = SS – I(n-1). CONWIP performed best of all the strategies and the next best was the Hodgson and Wang strategy. Orth (1997) conducted a more detailed analysis of the strategies by constructing a 2^3 factorial experimental design. Three factors were considered, namely demand, production distribution and the structure of the system. Two levels of each factor were considered, the original Hodgson and Wang model and modified distributions for demand and production and a modified system structure (see Orth (1997), pp. 36-37). CONWIP outperformed the other strategies with Hodgson and Wang's policy as the next best. Since the CONWIP cap was continually optimised for each scenario and the parameters for the other strategies were not altered (and may not be optimal) this result may not hold for all conditions. Takahashi's model was the worst performer of all the strategies. Orth (1997) also compared the policies using a simulation model of a PCB fabrication facility. CONWIP outperformed all the other strategies. The next best was the pure pull policy. The good performance of the pull policy was attributed to the fact that the real system operates as a Just-In-Time fabrication facility and the distribution of the Kanbans in the system may have been near optimal.

3.0 EXPERIMENTAL WORK

A series of experiments was conducted to: (i.) validate the work of Hodgson and Wang (1991b) and Orth (1997); (ii.) examine discrepancies between the two results; (iii.) evaluate whether production control strategies other than the pure pull policy are sensitive to changes in the maximum inventory levels; and (iv.) compare the hybrid control strategies to CONWIP. A simulation model was developed to model the 5-stage system described in Hodgson and Wang (1991b).

3.1 Validation of the simulation Model by comparison to published results

The eight policies considered for this experiment were:

1. Pure pull policy;
2. Pure push policy;
3. Push at stages 1 and 2, pull at stages 3, 4 and 5;
4. Push at stages 1, 2 and 3, pull at stages 4 and 5;
5. Push at stages 1, 2 and 4, pull at stages 3 and 5;
6. Push at stages 3 and 4, pull at stages 1, 2 and 5;
7. Push at stage 3, pull at stages 1, 2, 4 and 5;
8. Push at stage 4, pull at stages 1, 2, 3 and 5.

Two scenarios were considered for purposes of the experiment. Scenario 1 was conducted utilising Equations 7-9, above, to calculate the production trigger for the final stage when it is operating under pull control. For reasons detailed earlier it is felt that Hodgson and Wang (1991b) used these equations in their experiment. Scenario 2 used Equation 6, above, to calculate the production trigger for the final stage when it is operating under pull control. As can be readily observed from Table 1, it was found that if Equation 6 is used to calculate the production trigger in the simulation model it would result in an average gain for a pure pull system closer to that reported by Orth (1997). However, if Equations 7 to 9 were utilised in the simulation model an average gain for the pure pull system closer to that reported by Hodgson and Wang (1991b) would be achieved. The reason for this is that the safety stock plus predicted demand (8+4=12) is less than the maximum inventory level of the final workcentre (20). Therefore, Equations 7-9 would result in a smaller production trigger than Equation 6 and, therefore, a smaller average inventory for the final inventory point.

Table 1: Comparison of the results from Hodgson and Wang 1991b, Orth 1997 and the simulation model for the average gain.

Source/Scenario	Policy 1	Policy 2	Policy 3	Policy 4	Policy 5	Policy 6	Policy 7	Policy 8
H&W	3.90588	3.13101	3.10226	3.13086	3.10277	3.36014	3.35101	3.48486
Orth	4.70	3.16	3.15	3.16	3.15	3.38	3.38	3.49
1	3.90971	3.13950	3.11126	3.13947	3.11157	3.36601	3.36703	3.48955
2	4.71061	3.13950	3.11153	3.13968	3.11170	3.36615	3.36727	3.48972

3.2 Sensitivity Analysis of gain achieved by policies to changes in the maximum inventory levels

Orth (1997) noted that the poor performance of the pure Pull strategy may owe more to the maximum inventory levels not being optimal for the problem rather that the mechanisms of the strategy itself. Without providing detailed results, Orth (1997) claimed that if the maximum inventory levels were reduced to 9 for all stages that the pure pull policy would result in an average gain of 2.83. The author also calmed that reducing the maximum inventory levels had no effect on the performance of the other strategies. In order to investigate these conclusions a small experiment was conducted. Table 2 below, provides the details of the parameters that were altered for each scenario. Reducing the maximum inventory levels did improve the performance of the pure pull strategy. However, the magnitude of the improvement was not as great as that reported by Orth (1997). For the pure pull policy, the best improvement in the gain was 3.24210 and this was also achieved when the maximum inventory levels were reduced to 8 for I1 and I2 and 9 for the remaining three stages. In addition and contrary to the conclusion of Orth (1997), altering the maximum inventory levels did affect the performance of the other policies (see Table 3). For policies 2-5 the gain increased, while an improvement in the gain was noted for policies 6-8.

Table 2: Description of the parameters altered for the scenarios.

Scenario	Max of I1	Max of I2	Max of I3	Max of I4	Max of I5
Original	9	9	9	12	20
1	9	9	9	9	9
2	8	8	9	9	9

Table 3: Comparison of the results from the simulation model for the average gain.

Source/Scenario	Policy 1	Policy 2	Policy 3	Policy 4	Policy 5	Policy 6	Policy 7	Policy 8
Original	4.71061	3.13950	3.11153	3.13968	3.11170	3.36615	3.36727	3.48972
1	3.31500	3.14000	3.14300	3.15500	3.14300	3.30400	3.30400	3.31500
2	3.24210	3.15679	3.19719	3.20884	3.19719	3.23697	3.23697	3.24210

3.3 Comparison of the optimal strategy with CONWIP

A final experiment was conducted to compare the performance of the optimal hybrid policy to a CONWIP controlled system. For the purposes of this experiment the parameters of the experiment were as described in Hodgson and Wang (1991b). In order to apply CONWIP control to the system a cap was placed on the amount of work-in-process allowed in the system. This cap was initially set at 15 and the gain achieved by the system was observed. The cap was then increased incrementally and an Operation Characteristic Curve was generated for the gain Vs WIP cap. The optimal WIP cap is the cap that results in the minimum gain for the system. In the CONWIP system, the production of each stage is determined by sampling from the PDF for production in each period given in Hodgson and Wang (1991b). For all stages except the initial stages the production of the stage was subject only to the following two constraints:

1. Component availability from immediate predecessors, and
2. Space availability in the output inventory point.

For initial stages, the production of the stage was constrained by the WIP cap and the space availability in the output inventory point. The CONWIP strategy significantly outperformed the best strategy found in the previous experiments. At a WIP cap[1] of 20, the CONWIP policy resulted in an average gain of 2.89. A similar result was reported by Orth (1997).

3.4 Discussion of the Results

We do not believe that if the final stage in a production line was controlled by a pull strategy that it would consider the predicted demand for the period when calculating the amount to produce in that period, as Equations 7-9 would suggest. But rather it would attempt to replace products removed from the end item inventory point by the demand in the previous period, subject to availability of parts in the inventory points of immediate predecessors, as Equation 6 would suggest. The experimental work has shown that the simulation model we have developed is valid and will produce comparable results to those published in the literature. In addition, the work demonstrated that all policies are sensitive to the maximum inventory levels of the inventory points in the production line. Orth (1997) claimed that only a pure pull policy would be sensitive to changes in the maximum inventory levels. A CONWIP policy was shown to be much more effective at minimising the gain of the system than a hybrid or pure policy. However, if the parameters of the system were optimised a hybrid policy may exist that performs as good if not better than a CONWIP policy.

4.0 CONCLUSSIONS AND PLANS FOR FUTURE WORK

A large amount of research attention has been focused on the topic of how best to integrate push and pull production control philosophies. This work has demonstrated that such systems would result in benefits to a non-repetitive manufacturing environment by minimising the effect of demand forecast errors while maintaining sufficient inventory to protect against shortages in supply. However, we feel that what is missing from this work is a clear set of guidelines for the practitioner implementing a HIHPCS that detail how various parameters of the system could effect the choice of integration strategy. For this purpose, we propose to develop a simulated annealing algorithm that can be used in conjunction with the simulation model and construct an experimental design to examine the various control strategies under optimal conditions in order to determine the effects of parameters such as:

1. Variability in demand,
2. Variability in production quantities due to unreliability of workcentres,
3. Unbalanced workcentres,
4. Multiple product environment with set-ups,
5. Product/component failures due to quality control issues,
6. Product/component failures due to perishability of components.
7. Manufacturing system objective (e.g. minimise costs, maximise throughput, minimise lead times).
8. Manufacturing system topology.

In order to determine the applicability of the results of the experimental process outlined above to a real manufacturing environment, a simulation model of an existing manufacturing system with be developed and experimented with.

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[1] Inventory of raw materials was not included when calculating the WIP level of the CONWIP system for release of parts. A CONWIP cap of 20 would result in total work in process level of approximately 27 when raw material inventory levels are included.

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