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CONFIGURING A PULL PRODUCTION-CONTROL STRATEGY THROUGH A GENERIC MODEL

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Abstract: This paper describes a methodology for the choice of a pull production-control strategy. The methodology is based on the optimization of a generic system that models (i) Kanban, (ii) Conwip, or (iii) Kanban/Conwip hybrid systems. This approach is illustrated through the example of a ten-stage production line. The optimization technique is based on Response Surface Methodology (RSM) and discrete-event simulation.

Keywords: Control systems, JIT manufacturing, Optimization, Simulation.

JEL classification: C0.
1. INTRODUCTION

These last decades, much research has focused on finding ways to improve production control. The Kanban technique has been a kind of revolution. It aims at reducing lead-times and work-in-progress levels in the factory through a pull (instead of a push) strategy. However, the restricted applicability of Kanban has motivated researchers to find alternatives to this control strategy. Therefore, new pull strategies have been developed recently; examples are Conwip (Spearman et al., 1990) and a Kanban/Conwip hybrid (Bonvik et al., 1997). Obviously, the availability of alternatives creates the problem of how to choose a pull control strategy: given a manufacturing system, should its manager decide to implement Kanban, Conwip or Hybrid? The goal of this paper is to propose a novel general approach that incorporates the benefits of Kanban, Conwip, and Hybrid.

This paper is organized as follows. First, this paper introduces Kanban, Conwip, and Hybrid, and reviews studies that compare these strategies. Second, a methodology for selecting one of these systems is derived; this methodology is based on the optimization of a generic model. Third, the approach is illustrated with an application, namely a ten-stage production line model, for which the generic control strategy is optimized; this optimization uses Response Surface Methodology (RSM) and simulation modeling. Finally, advantages of the approach are discussed.

2. PRODUCTION CONTROL STRATEGIES

This paper focuses on pull production-control strategies, applied to production lines. In these production lines, a work station is allowed to produce, only when it receives a request from a downstream station: see figure 1. Thus, only the last machine in the production line has a production schedule (in the usual push systems, a station produces as long as parts are available in its input inventory).

This pull principle has been implemented in several production control strategies: Kanban, Conwip, and Hybrid Kanban/Conwip. The classical pull system is Kanban, where information flows between each pair of stages. Conwip stands for Constant Work In Progress, and is a Push/Pull hybrid. Hybrid Kanban/Conwip combines the characteristics of Kanban and Conwip. These three systems will be further discussed next.

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**Fig. 1 Pull system**
The Kanban strategy has been developed by Dr. Taiichi Ohno, manager at the Toyota Motors company. The principle is to limit the inventory level at each stage of a process, through the use of cards (in Japanese: Kanbans): the number of cards that circulate between two stages determines the level of the Work In Process (WIP) allowed between these two stages (see figure 2).

There are many implementation forms of Kanban: several papers propose adaptations of the original strategy. These adaptations are studied in a number of reviews. Berkley (1992) proposes a classification of the Kanban system models; he uses operational design criteria, such as the blocking mechanism, the withdrawal strategy, and the type of Kanban cards. Huang and Kusiak (1996) gives an overview of various Kanban systems and alternatives, and classifies the previous studies. Chu and Shih (1992) reviews and compares numerous simulation studies on Just-In-Time (JIT) production systems. Price et al. (1994) reviews optimization models of Kanban systems.

2.1 Kanban

As said above, the principle of Kanban control is to impose an upper bound on the inventory size between each pair of stages. Then, each resource works in order to raise the inventory level up to this limit, i.e., to replace the withdrawn parts. The main goal of Kanban is to decrease WIP, whereas throughput is favored by Push (Amin and Altio, 1997). The objective of Conwip is to combine the low inventory levels of Kanban with the high throughput of Push. One way to achieve the Conwip objective is to consider a Push system that at the same time allows only a limited number of parts: raw materials can be released into the system only when the last stage asks for it (Pull principle). This limitation can be implemented through the use of cards, as in Kanban. Within the Conwip system, each stage can pro-
produce as fast as it can (Push principle). Figure 3 shows that the implementation of Conwip is much simpler than the implementation of Kanban: a single set of cards is needed. Actually, a Conwip system can be viewed as a Kanban system with a single card loop that controls the whole production line.

Despite the originality of the Conwip strategy, it has not been studied in much detail. A few studies have focused on discovering relationships for throughput estimation (Duenyas et al., 1993).

2.3 Hybrid Kanban/Conwip

Recently, Bonvik et al. (1997) proposed a new control strategy. The idea is to combine the advantages of Conwip (high throughput with low overall WIP) with those of Kanban (control of inventory levels at each stage). This Hybrid Kanban/Conwip strategy is implemented by adding Kanban loops to Conwip: see figure 4. The last stage does not need a Kanban control, since any part that has progressed to this stage will replace a delivered finished good part: Conwip principle. The resulting strategy behaves most of the time as Conwip, but at a lower overall WIP level in case of a disruption (such as a machine breakdown). Hybrid, however, is much more complicated than Conwip.

The literature on Hybrid is very limited because this strategy appeared only recently. Bonvik et al. (1997) compares Hybrid with Kanban, Conwip, minimal blocking, and Basestock, using simulation experiments. More details on comparison studies will be given in the next section.

2.4 Comparisons among Kanban, Conwip, and Hybrid

Researchers have tried to compare the Kanban method with classical methods such as Materials Re-
quirements Planning (MRP), order point systems, and push-type systems. These studies agree on one fact: a Kanban system is very efficient in an ideal environment (low process and demand variability, few breakdowns, etc.). In a typical Western environment, however, the Kanban method is much less efficient. Some studies even conclude that push systems perform better than pull systems in a Western environment. Gupta and Gupta (1989) and Huang et al. (1983) conclude that high production rates can be realized, only when the number of Kanbans is chosen optimally. Thus, even in unfavorable environments, optimized Kanban systems may perform almost as well as push systems, in terms of output; its WIP level always shows a lower mean and a lower variability.

All comparisons of Conwip with other strategies have used simulation models only; for example, Roderick et al. (1992) simulates Conwip and three order-release strategies. All these studies conclude that Conwip gives the best performance, measured in mean WIP, mean throughput, and proportion of tardy jobs. Thus, Roderick et al. (1992) recommends Conwip as a 'strategy that should be seriously considered by practitioners for implementation in actual shop environments'. Bonvik et al. (1997) performs many simulation studies on a short flow line that makes a single part type. That study concludes that Hybrid outperforms Kanban: Hybrid achieves a high service level target with minimal inventory. However, that study also notices that the results of Conwip and Hybrid are very close.

This short review shows that only a few studies have compared Kanban, Conwip, and Hybrid. Moreover, the choice of a pull strategy seems to depend on the configuration of the production system. Furthermore, it might be argued that comparisons of production control strategies make sense, only when optimal configurations are compared.

3. A GENERIC CONTROL SYSTEM

It is not simple to choose a production control system for a given production system configuration: there are many possible configurations for each control system, as the numbers of card can be set to many integer values. In the previous section it was argued that optimized control systems should be compared. Duri (1997), for example, used this method to compare Kanban, Generalized Kanban, and Base Stock. Hence, in the study of Kanban, Conwip, and Hybrid it would be necessary to optimize three control systems, and then compare them. This paper, however, introduces an alternative: design a generic control system that integrates the characteristics of each pull strategy; that is, this generic control system can model a Kanban, a Conwip or a Hybrid Kanban/Conwip system. Table 1 explains how to set the parameters $C$ and $K_i$ ($i = 1, \ldots, n$) in figure 5, in order to obtain a specific control system.
Fig. 5. Generic control system

Table 1. Generic system for three strategies (Kanban, Conwip, Hybrid)

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Numbers of cards</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>Kanban</td>
<td>∞</td>
</tr>
<tr>
<td>Conwip</td>
<td>c</td>
</tr>
<tr>
<td>Hybrid</td>
<td>c</td>
</tr>
</tbody>
</table>

Using this generic system, a single optimization procedure suffices: the optimal values of the generic control system parameters show which type of control system is best. For example, suppose n = 4 and the optimization procedure leads to C = 64, K_1 = 5, K_2 = 3, K_3 = 4, and K_4 = 4. Then the best control system is a Kanban system, because the Conwip cards are not a binding constraint (hence they do not have an important effect on the production): C > K_1 + K_2 + K_3 + K_4. Sometimes, however, statistical tests may be necessary to determine whether the optimal generic control system is indeed a Hybrid Kanban/Conwip system (not a pure Kanban system or a pure Conwip system). Indeed, the issue is to know when a number of cards may be considered as infinite. If it is not possible to find a known strategy that matches the optimal solution, then a new type of hybrid control strategy has been found!

Various optimization procedures can be used to solve this problem: evolutionary algorithms (Paris et al., 1996), RSM (see next section), analytical techniques (Duri, 1997). Moreover, to model the control systems, different modeling techniques can be used: simulation (Paris et al., 1996), queuing networks (Duri, 1997). This paper uses RSM and simulation.

4. EXAMPLE: A TEN-STAGE LINE

In this section, an example with a ten-stage production line is presented. Simulation and RSM are used to optimize the numbers of cards in the generic production-control model for that system.

4.1 Simulation model for a production system with ten stages

Let the simulation model represent a balanced line with ten machines that produces a single part
type. The process is assumed to be perfectly reliable (no machine breakdowns); the supply of raw materials is continuous and infinite; the probability of a defective product is negligible; and the withdrawal of cards and parts between stages is instantaneous. Processing times at each stage have a lognormal distribution with a mean of one unit of time (minutes) and a coefficient of variation of 0.6. The times between demands follow a uniform distribution. Its coefficient of variation is 0.5. The mean is such that the ratio of demand rate to line capacity is 0.8, which implies that the production line is reasonably loaded. The line capacity is determined by making a pilot simulation of the line, controlled through a Push strategy; this strategy leads to the highest throughput. The line capacity is one part per minute. Thus, the times between demands are uniform on the interval (0.17; 2.33).

Many performance measures have been used in the Kanban literature. Chu and Shih (1992) classifies these measures into three categories: overall, inventory related, and due-date related. Three criteria have been used frequently: facility utilization, output rate, and WIP. But facility utilization may be irrelevant in many cases, because the goal of JIT is not to keep workers and machines busy; see Goldratt and Fox (1986). Thus, as the most important criteria remain WIP and output rate. However, output rate should be measured relative to demand rate: a system should meet demand very fast, but should not overproduce. Hence, a good indicator of system performance is the proportion of demand actually met from stock: service level or fill rate. Thus, the optimization problem is to minimize the WIP level, under the constraint of a prespecified service level. In this paper, the target will be a service level of 99%. This kind of constrained objective is typical of what a manager would ask (see Pierreval and Mahey, 1996).

4.2 Response Surface Methodology (RSM) accounting for constraints

RSM is a heuristic, sequential optimization technique based on regression (meta)modeling, design of experiments (DOE), and steepest ascent; see Kleijnen (1998). An algorithm explaining the RSM steps is shown in table 2.

Table 2. Steps in Response Surface Methodology

| Step 1. | Select a starting area in the search space, either randomly or using prior knowledge about the system to be optimized. |
| Step 2. | Within the selected area, build a first-order regression (meta)model to get an approximation of the system's local input/output transformation. |
| If the (meta)model is valid, then |
| Step 3. | Use the regression model to estimate the gradient vector. This vector indicates the direction of the steepest ascent path. |
| Step 4. | Select a starting point within the area defined in 1. Move from this point, along the steepest ascent path, into the direction that improves the system performance, until no improvement is obtained. |
| Then, select a new area. Go to step 2. |
| Else |
| Step 5. | Build a second-order regression model, within the selected area. |
| Step 6. | Use the model of step 5 to find analytically the input combination(s) that leads to an optimum. |
The steps in this table deserve the following comments.

Step 1: The heuristic nature of RSM is demonstrated by step 1. Repeating the whole procedure with a different starting area may show whether the final solution found by the algorithm is a true global optimum.

Step 2: To estimate the regression (meta)model with minimal variance, DOE (for example, $2^k\cdot p$ designs) is needed.

Step 3: The gradient is completely determined by the estimated regression coefficients (or factor effects; examples of these ‘factors’ are the numbers of cards in Table 1).

Step 4: The optimal step size (to be taken along the steepest ascent path) is not known. Again, heuristics are needed.

Step 5: Second-order regression models involve more effects (quadratic effects and interactions, besides main effects or first-order effects), so the need for DOE is even greater.

Step 6: Straightforward differentiation gives a unique optimum, a saddle point or a ridge.

In the production control example the goal is to minimize WIP, while keeping the service level at 99%. Classic RSM assumes a single response, so RSM must be adapted. A second-order regression model might not be required anymore, as figure 6 illustrates. This figure is a simple case: a single input parameter is considered. The two performance measures may conflict: the decrease of the WIP level to a very low value leads to a major deterioration of the service level; see shaded area. Hence the optimal solution will be a compromise: the optimal generic system will certainly not coincide with the minimal WIP. Thus, there might never be a need to build a second-order regression model, which would be necessary for modeling WIP’s behavior around its minimum.

As the performance measure to be minimized (namely, WIP) conflicts with the constrained performance measure (namely, service level or fill rate), we may not follow the steepest ascent path all the way:

![Fig. 6. RSM with a constraint](image)
this path may endanger the fill rate, whereas another path may decrease the WIP level while keeping the fill rate at an acceptable level. This heuristic adaptation of classic RSM with a constraint is suggested in Kleijnen (1993).

4.3 Simulation experiments

In this paper, simulation is used to model the production system's input/output behavior. SIMAN is selected as the simulation language. The simulation's inputs are the various numbers of cards; the output variables are WIP and service levels. The numbers of cards used in the simulation experiments are selected according to DOE, that is, a $2^{k-p}$ design with $k = 11$ and $p = 7$ is used.

This study focuses on the steady-state behavior of the generic system. Therefore, non-terminating simulation is chosen. A run length of 400,000 time units (416 days of production) is used to get narrow 95% confidence intervals for the estimated performance measures: the length of the intervals should be less than 5% of the midpoint. Moreover, the transient period (of 10,560 time units or 11 days of production) is estimated through plots of the moving average of the performance measures. This start-up period is eliminated. Analysis of all remaining simulation outputs is done through the output processor included in SIMAN. A 'batch' policy is used: the run length is partitioned into days of production; these days are assumed to give independent identically distributed output. So daily performance measures and statistics are computed per simulation run.

4.4 Results of the optimized simulated system

The statistical analysis software SPSS has been used for the computation of all the estimated regression (meta)models. After three stages (i.e., three regression models), RSM led to a configuration of the generic system that could not be further improved. Table 3 gives the various numbers of cards ($K_1, C$) corresponding to the best configuration obtained in this way. The performance of this optimized configuration of the generic system is given by the following 95% confidence intervals: average fill rate is $99.01 \pm 0.34\%$, and average WIP level is $32.8 \pm 0.1$ units.

<table>
<thead>
<tr>
<th>Table 3. Best generic configuration estimated through RSM</th>
</tr>
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<tbody>
<tr>
<td>Number of Kanban cards at each stage</td>
</tr>
<tr>
<td>$K_1$</td>
</tr>
<tr>
<td>3</td>
</tr>
</tbody>
</table>

Models of the other pull strategies were also simulated, in order to answer the following three questions, which were raised in the description of the generic approach.
(i) Is the optimal generic system a Kanban system?

Table 3 shows that in the optimized generic system the sum of the Kanbans (59) is much larger than the number of Conwip cards (34). So practically speaking, the WIP level is controlled by the Conwip constraint. Thus, the optimal generic system is not equivalent to a Kanban system.

(ii) Is the optimal generic system a Conwip system using 34 cards?

The performance of an optimized Conwip control strategy is also simulated. It gives an average service level of 99.34 ± 0.26% and an average WIP of 34 units. We compared the optimal generic system with this Conwip system, using statistical tests (namely, paired t-test with a 95% confidence interval). The result is that there is a significant difference between the WIP levels of the two systems. However, this difference is only about 1.2 (= 34 - 32.8) units of WIP, which is 3.6% of the average WIP level in the generic system. Concerning the fill rate, statistical tests did not show a significant difference between the two systems.

(iii) Is the optimal generic system equivalent to the Hybrid system defined in table 4 (no inventory limit at the last stage)?

Table 4. Hybrid system

<table>
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<tr>
<th>K_i</th>
<th>K_2</th>
<th>K_3</th>
<th>K_4</th>
<th>K_5</th>
<th>K_6</th>
<th>K_7</th>
<th>K_8</th>
<th>K_9</th>
<th>Conwip cards</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>8</td>
<td>34</td>
<td></td>
</tr>
</tbody>
</table>

The performance of the system in table 4 is as follows: the average fill rate is 99.06 ± 0.36% and the average WIP level is 32.9 ± 0.1 units. Statistical tests did not show any significant difference between the performances of this Hybrid system and the generic optimal system.

In summary, for the line configuration under study, the optimal generic system is statistically equivalent to a Hybrid system but not to a Conwip system. However, the WIP difference between Conwip and the generic system is only 3.6%. Thus, an important issue arises: is it practical to implement a more complicated control strategy such as Hybrid Kanban/Conwip if the gain is so small? Actually, it depends on whether this implementation would be a first implementation of a Pull strategy, or whether it would be a replacement of an existing Kanban strategy. In the first case, Conwip might be preferred. In the second case, Hybrid may be chosen because the transformation of Kanban into Hybrid does not require much effort, whereas gains may be significant.
5. CONCLUSION

This paper presented a methodology for the optimal configuration of a pull production-control strategy. The main advantages of this methodology are: it requires a single optimization, and it is very flexible in terms of optimization and modeling techniques. In the example, RSM and simulation were used for the study of a ten-stage production line with highly variable processing times and times between demands. The results showed that, for this production system, Hybrid leads to the best performance. However, as Conwip performs almost as well, Conwip may be preferred to Hybrid in practical cases. Obviously, these conclusions cannot be generalized to all production lines. Fortunately, for a given production system, the methodology proposed in this paper allows the analysts to optimally configure a pull production-control strategy, using a single optimization procedure.

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