ADVANCED MANUFACTURING CONTROL SYSTEMS: A SIMULATION COMPARATIVE ANALYSIS

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Abstract

This paper presents a comparative analysis of advanced manufacturing control systems using simulation. In particular, three PULL production philosophies have been analysed: a Just In Time (JIT), a CONstant Work In Process (CONWIP) and a hybrid system environments.

These different production control philosophies have been applied to flow shop systems with four, six and eight machines, evaluating the manufacturing system performance (i.e. Service Rate, WIP, finished Goods, Time in System, Maximum Queue Size). The performances have been analysed both in an ideal case (machines efficiency equal to 100%) and in a real case (machines efficiency lower than 100%), so as to consider machine breakdowns. To overcome the limit of low performance in presence of a machine failure, two further solutions have been proposed, taking into account the introduction of kanban-break cards together with a re-allocation of workers during a machine downtime towards the upstream work centres.

Keywords: Just In Time (JIT); CONstant Work In Process (CONWIP); hybrid system; kanban; simulation;
Introduction

A modern manufacturing planning and control system should plan the production of the right parts, at the right time, with low global costs. In its simple form, the “manufacturing process” is a composition of material and information flow: to improve the overall performance of manufacturing operations and to obtain time and cost saving, work in process limiting control strategies has become essential. To this purpose, during the past years, many researches focused their attention on finding ways to improve production planning and control systems. New or revised methodologies to manage the flow of material, components, tools and associated information were introduced and these can be split into push, pull and hybrid systems (Hoop and Sperman, 2000). The entire manufacturing systems, from purchasing to shop floor management, can be controlled on either push (i.e. MRP) or pull (i.e. kanban) systems.

The main push system is the Material Requirements Planning (MRP) and its evolutions, such as MRP-II and Enterprise Resource Planning (ERP) (Kusiak, 2000). In a push system, production is controlled by a central planning system, which takes load forecast as future demands. In a push environment the work order is a schedule of what should be started (or pushed) into production based on demand, otherwise the goods can not be delivered on time.

On the other hand, in a pull system the authorisation of the release of work order is based on the system status. So the production is controlled by a decentralised control system. Ever since the introduction of the kanban pull system (or Toyota Production system or Just In Time (JIT)) (Monden, 1993), many other pull control policies have appeared in literature such as CONstant Work-In-Process (CONWIP) (Hoop et al., 2000), syncro MRP (Hall, 1986) and other hybrid policies (Bonvik et al., 1997).
Many papers have investigated the performance of push and pull systems. Kanban and CONWIP systems performances were comparatively analysed (Takahashi and Nakamura, 1998) showing that both systems have advantages and disadvantages. Spearman and Zazanis (1992) compared a CONWIP system with a pure kanban one, and found that a CONWIP system particularly provided a greater throughput. Also Elkins et al. (2001), by using simulations, illustrated the performance of kanban and CONWIP systems during the control of job shop manufacturing environments composed of four workstations, producing two different types of goods. More recently, traditional kanban and CONWIP systems were compared with an ordering system called synchronised CONWIP system (Takahashi et al., 2005). The authors, through a formulation of inventory level and performance measures, by comparing those systems, developed a mathematical model that described the three alternative control methods. Based on their numerical studies, the authors argued that their synchronised CONWIP system presented a better performance in respect to the other two systems, especially when used for managing complex supply chains.

CONWIP performances were estimated by Duenyas and Hopp (1990b), who developed an approximation method to assess variance of production output, which processing times were assumed to be exponential. Always Duenyas and Hopp (1990a) proposed an approximation method to obtain a throughput and average number of jobs for assembly lines. Performance and design implications for CONWIP systems were investigated by Dar-el (Dar-el et al., 1999) when production lines were characterised by multiple bottlenecks.

All these previous studies assumed that no machine breakdowns and supply chain failures occurred during a normal exercise of the manufacturing system. To fill in this gap, in this paper a comparative analysis of kanban, CONWIP and a hybrid system has been developed, considering both the ideal case (machines efficiency equal to 100%) and the real case (machines efficiency...
lower than 100%). In particular, the different production control philosophies are applied to flow shop systems evaluating the manufacturing system performance so as to consider machine breakdowns and supply chain failures. Keeping into account the introduction of kanban-break cards together with a re-allocation of workers during a machine downtime towards the upstream work centres, two solution are proposed to overcome the limit of low performance in case of machine breakdowns.

**Overview of kanban, CONWIP and hybrid system**

*Kanban control*

JIT is a management philosophy that strives to eliminate sources of manufacturing waste by producing the right part, in the right place, at the right time. The general idea is to establish flow processes (even when the facility uses a job or a batch process layout) by linking work centres so that there is an even, balanced flow of materials throughout the entire production process, similar to that found in an assembly line.

The production authorisation in JIT management philosophy is based on a kanban production control system. A kanban is a card attached to the carrier or container of a lot used to match what needs to be produced in a work station and what needs to be delivered to the next station: what is required to be produced in a specific station depends on what the next station needs. Finally the production is consequently modulated by end customer orders. The kanban card contains information about lots and quantities involved in the production process. The logic of a kanban production control system is reported in figure 1.
Figure 1: kanban information flow process control.

Generally, there are two types of kanban assigned to every lot, namely, a production-kanban that denotes the need to produce more parts and a conveyance-kanban that denotes the need to deliver more parts to the next station. No parts can be produced unless authorized by a production-kanban and no parts can be moved unless authorised by a conveyance-kanban.

The essence of the kanban concept is that a work centre should only deliver components when they are needed, so that there is no storage of excess inventory in the production area. In addition, kanban limits the amount of inventory in the process by acting as an authorization to produce more parts or components. Since kanban is a chain process where orders flow from one process to another, the production or delivery of components is “pulled” to the production line.

**CONWIP control**

An alternative to a kanban production control system is represented by the CONWIP technique. In CONWIP systems, cards are assigned to the whole production line (Hopp et al., 1990): the idea behind CONWIP is that a new job is introduced to the line whenever a job departs. When beginning the production, all available cards are located at the beginning of the line (on a bulletin board). When orders arrive, and there are enough available cards in the system, the necessary cards are attached to the order, and together they proceed through the production line. When the order is completely processed in the line, and leaves the final station, the card is dropped off and released back to the beginning of the line, as reported in figure 2.
CONWIP controls the WIP by controlling order releases to the shop floor. No order can enter the line without its corresponding card. The detailed flow control mechanism of CONWIP is extensively discussed in Hopp and Spearman (2000).

**Hybrid system control**

A hybrid system control policy is a combination between kanban and CONWIP techniques. It is also known as the “two-boundary hybrid” (Bonvik et al., 1997). Figure 3 shows a hybrid kanban/CONWIP production control system: as it can be observed, it consists of a CONWIP system with capacity restrictions in the intermediate buffers by means of a kanban system.

Note how similar this is to a kanban control: cards circulate between the machines and buffers. The sizes of the buffers are determined by the number of cards in circulation. The only difference is that cards detached from finished goods are passed to the first machine instead of the last. From there, they follow the parts back to the finished goods buffer. The decision variables concerning this system are the number of cards related to each station, with the exception of the
last station, and the number of cards from the last station to the first one (equal to the total WIP in the system).

**Simulations models of kanban, CONWIP and hybrid system**

The different flow shop simulations have been conducted in Simul8 9.0, developing three different flow shop configurations producing only one type of product. For each configuration, machine breakdowns and/or supply chain failures are considered.

The first system is characterised by four serial workstations with identical processing time; in the second and third simulations, systems with six and eight work centres are considered. In these two simulations, the processing time for each workstation clearly identifies a bottleneck station and the loss of productive efficiency may regard only one station that is prior to such bottleneck. This assumption was made in order to understand the consequences involved by a lack in feeding the bottleneck station. Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) are increased with respect to the first simulation.

The variance reduction technique of Common Random Number (CRN) (Law and Kelton, 2000) is employed to synchronise usage of random numbers in the three different simulations so that the systems are compared under similar conditions and the differences between systems are only due to the different production control policies adopted. In particular each simulation uses the same sequence of work order arrival and considers the same processing times for each job.

**First simulations**

In Table 1, simulation data concerning the flow shop system with four stations is reported.
Table 1: simulation data for the four workstations case.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value type</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job inter arrival time</td>
<td>54 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 1</td>
<td>20 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 2</td>
<td>30 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 3</td>
<td>51 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 4</td>
<td>43 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Failure rate (all WSs)</td>
<td>2000 min</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Repair rate (all WSs)</td>
<td>60 min</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Product shelf life</td>
<td>480 min</td>
<td>exact</td>
<td>-</td>
</tr>
<tr>
<td>Simulation horizon</td>
<td>96000 min</td>
<td>exact</td>
<td>-</td>
</tr>
<tr>
<td>Simulation warm up</td>
<td>64000 min</td>
<td>exact</td>
<td>-</td>
</tr>
</tbody>
</table>

In particular, the possibility of breakdowns is considered for all the workstations, with the same failure and repair rates. The simulation warm up period was esteemed according to Law and Kelton (2000), taking into account the standard deviation of the average time in system as reported in figure 4.

![Figure 4: warm up period for simulation based on average time in system.](image)

The number of cards used to control WIP in the three different control policies was evaluated using the heuristic approach proposed by Elkins (Elkins *et al.*, 2001). With the aim to obtain a
service level higher than 95%, the number of cards for each workstation and for each control policies is:

i ) for the kanban system, through Monden’s formula (Monden, 1993), the sequence of cards is 2-6-6-8 (i.e. 2 cards from workstation 1 to workstation 2 and so on), so that the maximum level of WIP is equal to 22 units;

ii ) for the CONWIP system, with the Hoop and Spearman (1990) formula, the number of cards is equal to 11 units;

iii ) finally, for the hybrid system environments the sequence of cards is 1-7-9/11 (i.e. 1 cards from workstation 2 to workstation 3 and 11 CONWIP cards).

In order to overcome the inevitable overall performance reduction due to machines breakdowns (or supply chain failures), two solutions are proposed and analysed.

The first one considers the emission of a special card named kanban-break that enters the flow shop before the workstation out-of-order. Such kanban-break is emitted during the repair time of the out-of-order workstation when the rack is empty. This permits the production flow on the station upstream of that out-of-order, while allowing WIP to go downstream. When the broken station will go back online, it will start to work the emitted kanban-break revoking them from the line.

The second solution, applicable only in a few cases, consists in the emission of a kanban-break with a re-allocation of workers during a machine downtime in the workstations located upstream. The revocation of the kanban-break after machine repairs arrests the information flow for the first workstation. Therefore it is possible to shift the worker of the first workstation on a work-centre interested by the failure, assuming double production time of such station. This re-allocation of worker is kept for the time necessary to remove the kanban-break.
The simulation results of manufacturing system performance, service rate, average WIP, average time in system and total buffer size for the kanban system policies in an ideal case, in a real case (considering workstation breakdown), in a real case with kanban-break and in a real case with kanban-break plus worker shift are reported in figure 5.

Figure 5: performance of kanban production control system simulation.

For the CONWIP production control policy, the simulation is conducted as per the above described kanban system. So, the simulation results of CONWIP system in an ideal case, in a real case (considering workstation breakdowns), in a real case with a kanban-break and in a real case with a kanban-break plus worker shift are reported in figure 6.
Figure 6: performance of CONWIP production control system simulation.

Finally, figure 7 shows the performance obtained by an hybrid production control system in an ideal case, in a real case (considering workstation breakdowns), in a real case with a kanban-break and in a real case with a kanban-break plus worker shift.
Figure 7: performance of hybrid production control system simulation.

**Second and third simulations**

The second and third simulations were conducted by considering flow shop systems with six and eight stations respectively. In Tables 2 the simulation input parameters for the second case is reported.

**Table 2: simulation data for the six workstations case.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value type</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job inter arrival time</td>
<td>90 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 1</td>
<td>20 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 2</td>
<td>30 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 3</td>
<td>40 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 4</td>
<td>80 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 5</td>
<td>50 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 6</td>
<td>30 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Failure rate (all WSs)</td>
<td>500 min</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Repair rate (all WSs)</td>
<td>120 min</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Product shelf life</td>
<td>480 min</td>
<td>exact</td>
<td>-</td>
</tr>
<tr>
<td>Simulation horizon</td>
<td>96000 min</td>
<td>exact</td>
<td>-</td>
</tr>
<tr>
<td>Simulation warm up</td>
<td>10500 min</td>
<td>exact</td>
<td>-</td>
</tr>
</tbody>
</table>
In the second simulation campaign, a flow shop system with six workstations is considered. Processing times were chosen in such a way as to clearly identify a bottleneck station, specifically, number 4. Moreover, the possibility of breakdowns was considered for all the workstations, with the same failure and repair rates. For each of the three different control policies, the number of kanban was computed as above describe.

The simulation results of manufacturing system performance, service rate, average WIP, average time in system and total buffer size for the kanban system policies in an ideal case, in a real case (considering workstation breakdown), in a real case with a kanban-break and in a real case with a kanban-break plus worker shift are reported in figure 8.

Figure 8: performance of kanban system in second simulation.
The simulation results of CONWIP system in an ideal case, in a real case (considering workstation breakdown), in a real case with a kanban-break and in a real case with a kanban-break plus worker shift are reported in figure 9.

![Graphs showing performance metrics of CONWIP system](image)

Figure 9: performance of CONWIP system in second simulation.

Finally, figure 10 shows the performance obtained by a hybrid production control system in an ideal case, in a real case (considering workstation breakdown), in a real case with a kanban-break and in a real case with a kanban-break plus worker shift.
Figure 10: performance of hybrid system in second simulation.

Finally, tables 3 report simulation input parameters for the third case.

Table 3: simulation data for the eight workstations case.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value type</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job inter arrival time</td>
<td>90 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 1</td>
<td>20 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 2</td>
<td>30 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 3</td>
<td>40 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 4</td>
<td>30 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 5</td>
<td>20 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 6</td>
<td>80 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 7</td>
<td>50 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Processing time WS 8</td>
<td>30 min/job</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Failure rate (WS 3)</td>
<td>500 min</td>
<td>mean</td>
<td>exponential</td>
</tr>
<tr>
<td>Repair rate (WS 3)</td>
<td>120 min</td>
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<td>exponential</td>
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<tr>
<td>Product shelf life</td>
<td>480 min</td>
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<tr>
<td>Simulation horizon</td>
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</tr>
<tr>
<td>Simulation warm up</td>
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<td>exact</td>
<td></td>
</tr>
</tbody>
</table>
In the third simulation campaign, a flow shop system with eight workstations is considered. Also in this case, the processing time of one particular station, number 6, was chosen to clearly identify a bottleneck station. Differently from the previous case, breakdowns were only allowed in station 3, considering a repair time sufficient enough to transform this station in a bottleneck when breakdown occurs. In this way, the line presents a natural bottleneck located near the end side, which switches near the beginning of the line in case of breakdowns. For each of the three different control policies, the number of kanban was computed as in first simulation above describe.

The simulation results for the kanban, the CONWIP and the hybrid system policies are reported in figure 11, 12 and 13 respectively.

Figure 11: performance of kanban system in third simulation.
Figure 12: performance of CONWIP system in third simulation.
Discussion of results

From a global point of view, the three different production control policies (kanban, CONWIP, hybrid system) show the same behaviour in the three simulation campaigns. In particular, the hybrid system generally obtains a better performance than the other two policies.

Considering the “service rate” performance index in the first simulations, the kanban production control policy and hybrid system sound to be more sensible with respect to the production system failures. In fact, for those production control policies the reduction of “service rate” for the ideal case were equal to 2.31% and 2.43%, respectively, in case of machine breakdowns. On the contrary, the CONWIP policy showed a high steadiness with respect to machines failures.
In the second simulation, in which six stations and increased MTTR were considered, the
aforementioned performance differences are kept for hybrid and kanban systems, while a worsenng in CONWIP performance is highlighted. Those remarks can be formulated for the third simulation, too, where eight workstations and failures in only one machine were considered. The introduction of kanban-break made it possible to obtain a small improvement in “service rate” performance index, but it involved a worsening in the other performance indexes, particularly for the “average WIP”. On the contrary, the use of kanban-break cards together with a re-allocation of workers during a machine downtime towards the upstream work centres made it possible to achieve an improvement of the “service rate” performance index, even if a worsening in the “average WIP”, as reported in the previous case, was emphasized. The “average time in system” performance index showed the same trend as the “average WIP” in all the production system configurations.

Finally, kanban and CONWIP systems reported a substantial worsening for the “total buffer size” performance index when kanban-break cards and kanban-break plus worker shift were adopted. For the hybrid system, such a performance decrease of the “total buffer size” index was not as consistent as in the other two policies.

In conclusion, the introduction of kanban-break cards and kanban-break plus worker shift to overcome the limit of low performance in presence of a machine failure are interesting only for the hybrid system environment.

**Conclusion**

Generally, it is noted that better performances are obtained by a simulation conducted on hybrid system control policies in respect to the traditional kanban and CONWIP systems. In particular
for the same value of service rate, hybrid systems present lesser values of average WIP, average time in system and total buffer size.

The proposed solutions, keeping into account the introduction of kanban-break cards together with a re-allocation of workers during a machine downtime towards the upstream work centres allow to obtain a significant increase of service rate accompanied by a modest increment of average WIP and average time in system.

Simulation results show that CONWIP control policies are stable enough and insensitive to inefficiencies, so even in real conditions (machines efficiency lower than 100%) the solutions proposed are not interesting. The introduction of a kanban-break and a kanban-break plus worker shift gets better performance but presents an unacceptable increase of total buffer size.

Finally, for traditional kanban control policies the proposed solutions involve improper augment of average WIP and total buffer size and only a little improvement of other performances.
References


