A Comparison of Production Control Systems in a Flexible Flow Shop

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ABSTRACT

Production control in make-to-order manufacturing environments must address the companies' need for short delivery times and on-time deliveries. Several production control systems may be used to meet these needs. This paper presents a simulation study whose objective is to evaluate the delivery performance of three well-known production control systems, Toyota Kanban System (TKS), Generic Kanban System (GKS) and POLCA, in the context of a make-to-order flexible flow shop. Since TKS has been originally developed for make-to-stock manufacturing an adaptation of it is made to use in make-to-order. Results of a simulation study shows that the adapted TKS outperforms POLCA, but performs worse than GKS. The study is a contribution for the alignment of production control theory to the industrial practice.

Keywords: Production control, make-to-order, simulation

1. Introduction

Production control approaches in make-to-order (MTO) manufacturing environments must address the companies' need for short delivery times and on-time deliveries. Card-based production control systems are simple and yet effective approaches to address these challenges. These systems control both, the release and the flow of jobs throughout the shop floor, towards meeting manufacturing performance objectives. Many card-based control systems, such as the TKS (Toyota Kanban System) [1], have been developed for low product variety and make-to-stock production, requiring therefore a certain amount of inventory at production stages and/ or at finished goods. In high product variety and make-to-order these systems would require a large, most probably unacceptable, amount of inventory. In such environments, different card-based systems are necessary. Examples of card-based systems specifically developed for the make-to-order production are the GKS (Generic Kanban System) [2] and the POLCA (paired-cell overlapping loops of cards with authorization) system [3, 4]. An underlying characteristic of both systems is that they are job-anonymous, i.e., cards are not specific of any job or end item, but can be used by any type of jobs manufactured in the system, contrarily to what happens with the TKS where each card can only be used by a given type of job.

In this paper, we adapt TKS to become job anonymous and compare its performance with that of GKS and POLCA in the context of a make-to-order flexible flow shop. The following research questions are addressed:

- How do card based systems perform in the context of a make-to-order flexible flow shop?
- How does the adapted TKS perform in this context?

The adapted TKS (ATKS) uses the same loop structure of TKS, i.e. one loop of cards per production stage, where the card acquisition process of a job overlaps with the production process. This means that job's required cards at each production stage are attached to the job as it goes through the stages and are not all attached to the job at the release stage, as it happens in the GKS control system. This card acquisition process of ATKS, inherited from TKS, leads to a capacity control process similar to the POLCA system, where the available cards at a production stage signals availability of capacity at downstream stages. Thus, after processing at each production stage, the card is detached from the job only if a new card from a downstream production stage is available to be attached to it. This means that cards loops overlap instantaneously and not during processing at production stages or cells as it happens in the POLCA system. This may avoid the blocking effect of POLCA reported by some authors [5, 6] for the pure job shop.

The remainder of the paper is organized as follows. Section 2 outlines the simulation model that is used to examine the performance of above production control systems and how production is controlled in our production system. Then, Section 4 details the experimental design and the performance measures considered in the study. The results are then presented and discussed in Section 5. Finally, concluding remarks are made in Section 6, where managerial implications and future research directions are also outlined.

2. Shop floor scenario and production control

This section presents the shop floor scenario used in our study and details the production control systems applied to control job release and job flow though the shop floor.

2.1 Simulated Shop

The simulated shop floor consists of a make-to-order flexible flow shop with three production stages. A real-world scheduling study with a similar shop configuration, with two stages and three machines per stage has been reported by Costa *et al* [5]. Each stage has three interchangeable identical machines, as illustrated in Figure 1. At each production stage, each of the interchangeable machines performs the same operation at each product type. Jobs of three product types arrive to the system with equal probability. Each job has three operations - one per production stage. Operation processing times follows the truncated 2-Erlang distribution. The average processing times for each product type is as indicated in Table I. This setting together with the arrival and service rates creates a balanced shop with a steady utilization at all machines of 90%.

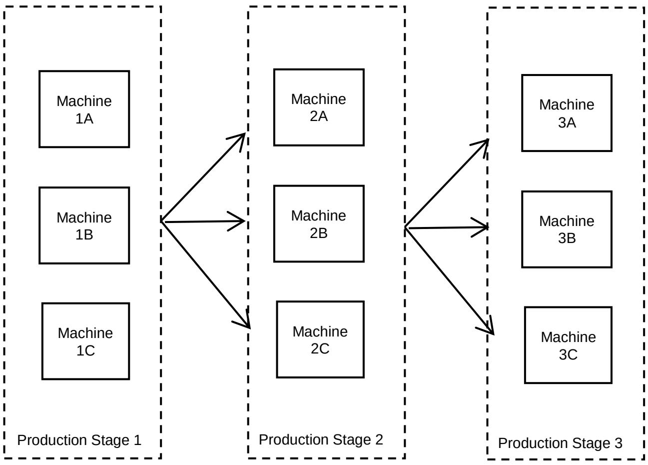

Figure 1. *Shop floor configuration*

The jobs inter-arrival times to the production system follows a stochastic process according to an exponential distribution. As jobs (i.e. orders) arrive to the system, their operation times at the different machines are determined. It is assumed that enough raw materials inventory is always available in the beginning of the first production stage. Jobs are not immediately released to the shop floor but wait in a pre-shop pool for the release decision. This is dependent on the production control system applied. Jobs waiting release in the pool are sequenced by a planned release date. This is determined by backwards scheduling from the job´s due date using the production stages lead times.

Table I. *Average processing times and product mix*

Product Type	Product Mix	Processing time (hrs)
X	1/3	1.5
Y	1/3	1.0
Z	1/3	0.5

Table II summarises the job and shop floor characteristics. The following assumptions are made in the simulation model:

- Machines operate asynchronously, so that jobs can be loaded whenever materials are available.
- Machines' breakdowns are calendar time based and follow the exponential distribution for mean time between failures (MTBF) and for the mean time to repair (MTTR).
- Set-up time is assumed to be sequence-independent and included in the operation processing times.

Table II. *Shop and Job Characteristics*

Shop Configuration	Flexible Flow Shop (FFS)
No. of Production Stages	3
No. of Machines per stage	3
Interchange-ability of Machines	Full Interchange
Machines Capacities	All Equal
No. of Operations per Job	3
Operation Processing Times	Truncated 2–Erlang; (max = 4*mean)
Mean Time Between Failures (MTBF)	Exp. Distribution; mean = 3000 hrs
Mean Time To Repair (MTTR)	Exp. Distribution; mean = 3 hrs
Due Date Determination Procedure	Entry Time + d; d U ~ [10, 30]
Inter-Arrival Times	Exp. Distribution; mean = 0.648 hrs

The simulation model was developed using SIMIO® simulation software. To improve the practical applicability of the findings, the model was kept simple to avoid interactions that might inhibit the full understanding of the effects of the experimental factors.

2.2. Production control

In this paper, production control involves the two following sets of actions: (1) job release and job flow control, and (2) job allocation and dispatching. The former set determines when jobs should be released to the shop floor and controls the flow of jobs through the shop; the latter performs job allocation to alternative machines at each production stage and job dispatching at each machine.
In our study job release and job flow control is based on the three production control systems (ATKS, GKS and POLCA) referred previously. Job allocation to machines at each processing stage and dispatching is performed in two separated steps, i.e. we do first job allocation (as jobs are released to the shop or finished at a previous stage) and then job dispatching (as the machine becomes available). Job allocation to machines is based on two rules: the minimum number of jobs (MNJ) and the least loaded machine (LLM) rules. With the MNJ rule we allocate jobs to the machine that has the minimum number of jobs in queue and in process; with the LLM rule, we measure the workload of the jobs at each machine, in queue and in process, and allocate the next job to the machine least loaded. Since we do not evaluate dispatching strategies in this study, first-come-first-served (FCFS) dispatching is applied at all machine queues.

3. Experimental Design and Performance Measures

The experimental factors and simulated levels of the study are summarised in Table III. Forty-eight simulation cases are tested resulting from three production control systems, two machine selection rules and eight levels of restriction concerning the number of cards that are made available ate each control loop. Each test case runs a minimum of 120 replications – in other to obtain more stable performance curves we have increased the number of replication to 150 for some test cases. The time horizon for a simulation run is 24000 hours and only data of the last 22000 hours are collected, i.e., a warm-up period of 2000 hours is used.

Table III. *Experimental factors and levels*

Factor	Levels	Levels	Mean (mm)
Production control systems	ATKS	GKS	POLCA
Job allocation rule	MNJ	LLM	
Number of cards per loop	Eight levels of restriction		

The numbers of cards made available at each control loop result in different levels of restriction for the workload that is allowed on the shop floor. Since this has an important impact on performance, it was treated as an experimental factor in our study. This factor was tested at eight levels for the ATKS (8, 9, 10, 11, 12, 13, 18 and ∞) and double for the POLCA system, since in this system each job requires two cards, each of which involving two control loops. The infinite value means unrestrictive job release. For the ATKS and the POLCA the same number of cards is used in each control loop, because the manufacturing system is balanced and card loops have identical lead times. The number of cards in the GKS is also tested at eight levels. However, since card loops in the GKS have different lead times, i.e. some cards have longer loops than others, the number of cards made available per control loop is different in the GKS. Thus, the same number, as in the ATKS, is used in the first loop, two times more in the second loop, because this loop includes the first and second stage, and three times more in the third, which includes all three production stages.

The main performance measures considered in the study are the shop throughput time (STT), the total throughput time (TTT) and the percentage of tardy jobs. The STT is the job completion time minus the job release time and the TTT is the STT plus the pool time, i.e. the time the job waits before it is released to the shop.

4. Results and discussion

Figure 1 plots TTT and percentage of tardy jobs against the STT for the production control systems tested. By comparing performance curves, we can determine performance differences among control systems for different values of the shop floor throughput time. A marker on a curve is the result of simulating a production control system for a specific number of cards. Eight levels of cards restriction have been simulated, including infinity. This means unrestrictive release of jobs to shop and is used as a baseline for performance comparisons in the study. The right-hand mark on each curve represents this situation.

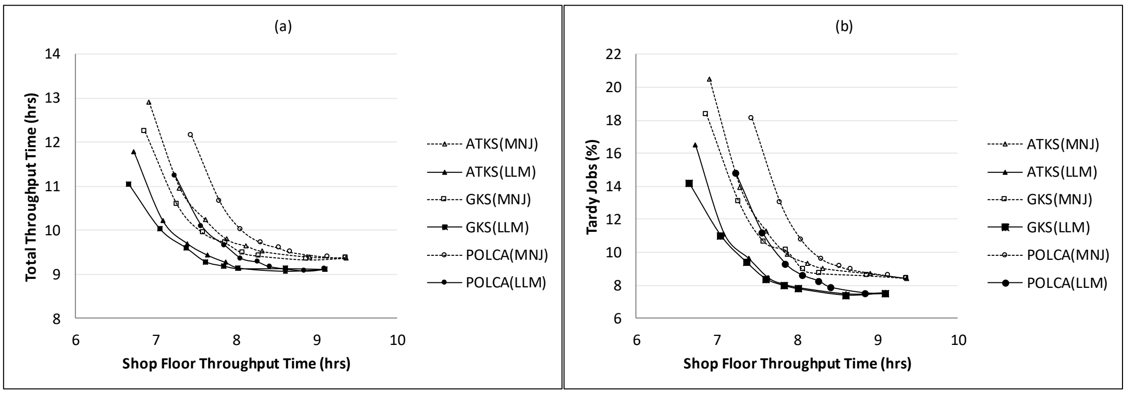

Figure 1. *Performance behaviour of production control system under two job allocation rules.*

Figure 1 shows that decreasing the number of cards per loop which means moving from right to left along the curves, leads to lower STT. This is due to releasing fewer jobs to the shop, i.e., having less working-in-process. This reduction, however, is obtained at the cost of a higher TTT and percentage of tardy jobs, even though for an initial reduction in the number of cards no noticeable deterioration in these performance measures results.

Analysing the performance of the three production control systems, we can see that the ATKS outperforms POLCA, but performs worse, although slightly, than GKS. These results are independent of the job allocation rule used, i.e., the same behaviour is noticed for both job allocation rules. Moreover,

improved system performance is achieved if instead of using the *minimum number of jobs* (MNJ) rule the *least loaded machine* (LLM) rule is used to allocate jobs to machines for processing. This may be explained by the fact that: since this rule more accurately measures work in process at machines decisions for job allocation results in better workload balancing, i.e., avoiding bottlenecks restrictions in the jobs' flow.
The better performance of GKS seems to be due to the fact that in the GKS, once released, jobs are free to flow through production stages without any restriction on job allocation to machines imposed by card acquisition. This restriction exists in both POLCA and ATKS since jobs must wait for available cards to be seized for the jobs to be allocated to machines at a given production stage, and therefore restrained from free flow through the system.

4. Conclusions

This paper compares the performance of three card-based production control systems that use job-anonymous cards, namely GKS, POLCA and adapted TKS (ATKS). The study is performed in the context a flexible flow shop, using discrete event simulation.

Our results show that ATKS outperforms POLCA, but performs worse than GKS. This is worth pointing out, having into account that POLCA was specifically developed for the make-to-order production environment also considered in the study. The relative performance of these control systems seems to be independent of the strategy adopted for job allocation to machines at each production stage. In fact, the two different rules tested exhibit the same performance pattern. These were the *minimum number of jobs* (MNJ) per machine and the *least loaded machine* (LLM) rules. The LLM rule performs better than the MNJ rule, as could be expected due to the finer control of the workload at machines. Our results also indicate that only marginal benefits are likely to be expected from applying the production control systems tested to real shops with configurations similar to the one studied, i.e. balanced flexible flow shops with a balanced mix of products. In fact, only a small reduction on the shop throughput time (STT) was achieved, without occurring performance deterioration of total throughput time (TTT) and percentage of tardy jobs. This performance behaviour of the production control systems seems to be related with the highly-balanced shop configuration considered in the study. In this situation, it seems that production control systems become less useful and uncontrolled release may be a worthy alternative. So more differentiating performance manifestations between the production control systems and unrestrictive release are likely to be observed under less balanced manufacturing situations. To confirm this, future research work should extent the study to evaluate the impact of higher job variety and routing diversity under less balanced and differently configured shop situations on the performance of production control systems, including the adapted TKS here introduced.

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6. Referencies

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