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Performance evaluation of WIP-controlled line production systems with constant processing times

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ABSTRACT

We compared three types of WIP-controlled line production systems with constant processing times such as Kanban, CONWIP (constant work-in-process) and DBR (drum-buffer-rope). Based on the observation that such WIP-controlled line production systems are equivalent to m-node tandem queues with finite buffers under communication blocking policy, we applied a max-plus algebra based solution method for the tandem queue to evaluate their performance. Within our knowledge, this research is the first attempt to apply an exact solution method for comparing all three WIP-controlled line production systems at a time. Six-node numerical examples were also used to demonstrate the proposed analysis. The numerical results can be generalized and also provide some insights in designing production systems under certain limited condition.

1. Introduction

WIP (work-in-process) is an unfinished form inventory that necessarily exists in most of manufacturing processes. It may be either under processing or waiting for next processing. In manufacturing systems with imperfect line balancing, the size and location of the WIP dynamically change due to the unequal pace of workstations and the external supply and demand. We usually allow certain amount of WIP to streamline manufacturing flow and to prevent serious production starving. However, we also observe excessive inventory buildup and difficulties in process management as the WIP increases. Except for the ideal production system with well-balanced workstations, a push system such as MRP (material requirement planning) is likely to incur those production inefficiencies. On the other hand, a pull system such as Kanban, CONWIP (constant work-in-process) and DBR (drum-buffer-rope) controls system throughput by the WIP of the production system and hence is a good candidate for alternative PPCS (production planning and control system).

Kanban system sets a limit on the amount of WIP between every pair of adjacent workstations. Each station triggers the operation of the immediately preceding station by returning an empty Kanban. CONWIP sets a limit on the total WIP in the entire production system. It uses a single global set of cards to control total WIP anywhere in the system. WIP is not controlled at the individual workstation level. Kanban pulls work everywhere (between every pair of workstations), while CONWIP only pulls work at the beginning of the line. When a finished good leaves the production system, the Kanban detached from the finished good returns back to the first workstation and authorize a new production. Once input material enters the system, production continues without permission of the following stations and WIP moves to the next stations. DBR limits the amount of WIP in the preceding stations of the system, up to and including the bottleneck station. Under DBR a drumbeat for the rest of the plant is maintained by sequencing work to be done at the bottleneck operation. The drumbeat is then protected by maintaining a time buffer for parts going to the bottleneck. A rope is tied from the bottleneck to material release points to ensure that material is released only at the rate that is used by the bottleneck thereby preventing excessive increase in inventory.

Various factors other than WIP control policy above also affect the performance of the production system such as type of network, pace of processing times, defective items, buffer size, and feeding of materials. In this study, to develop an analytic model based on the exact solution procedures, we need to simplify the target system to a finite capacitated line production system with constant processing times under work-conserving policy without defective items. We also assume that traffic intensity is high enough to avoid starving at the first workstation, each workstation has a single server, and no rework is needed.

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In this paper, we compare three types of WIP-controlled PPCS such as Kanban, CONWIP and DBR, in a line production system with constant processing times same as Duenyas, Hopp, and Spearman (1993) and Rhee and Perros (1996). Kanban is considered as a tandem queue with a finite buffer for each node. CONWIP is a tandem queue with a common finite buffer shared by all nodes. DBR is a tandem queue with a common finite buffer shared by preceding nodes up to the bottleneck. Pulling a job between nodes in WIP-controlled PPCS can be described as a communication blocking policy, where processing is blocked if the immediately following node is already occupied.

Unlike the infinite buffer case, the steady-state distribution of waiting time in a tandem queue with finite buffers is not simply given as a product form due to the blocking between nodes. Therefore, various approximation procedures by decomposition and simulation have been proposed for such a system. Instead, we use an exact solution procedure based on max-plus algebra to compare the performance of three variations of tandem queue with finite buffers, Kanban, CONWIP and DBR. The max-plus linear system needs only two kinds of operators, 'max' and 'plus' to represent its performance characteristics. It is well known that the max-plus linear system includes various probabilistic system easily found in communication and production such as tandem queue with blocking, fork-and-join type queue and assembly production line.

Previous researches on the performance evaluation of Kanban, CONWIP and DBR are summarized in Section 2. In Section 3, the random vector D_n is derived by translating the WIP-controlled line production system into a tandem queue with finite buffers and then we calculated the actual sojourn time in Section 4. Section 5 formulated an optimization problem to minimize WIP. Some comparison results from numerical examples are shown in Section 6.

2. Previous research

CONWIP has been widely studied due to its superior performance and applicability over the other PPCS such as MRP and Kanban since it was first proposed by Spearman, Woodruff, and Hopp (1990). Spearman et al. (1990), Spearman and Zazanis (1992), and Gstettner and Kuhn (1996) determined the number of cards required to minimize the WIP with a given throughput constraint. CONWIP was found to outperform push system in terms of throughput and WIP, and as compared to Kanban, it was also known to be easier to implement for the dynamic production system with uncertain setup times and large variety of products. Muckstadt and Tayur (1995a, 1995b), Bonvik, Dallery, and Gershwin (2000), and Jodlbauer and Huber (2008) supported the Spearman's result. On the contrary, Gstettner and Kuhn (1996) proposed the simulation result that WIP of Kanban is smaller than that of CONWIP under the same production rate. They figured out that the absolute number of cards and the card distribution over the workstations are important parameters that influence the system performance. Because enumeration of all combinations of operating parameters is not practical, for meaningful comparison between the systems it is essential to operate them under ideal parameter settings with respect to a certain objective such as production rate, quality of service (QoS) and lead time. Roderick, Toland, and Rodriguez (1994) conducted a simulation study to compare CONWIP with MRP in terms of tardiness and cycle time and Chang and Yih (1994) made a comparison between CONWIP and modified MRP. Huang, Wang, and Ip (1998) compared CONWIP, MRP and Kanban in a cold rolling plant and found CONWIP to be superior when focusing on WIP and throughput.

Not much attention has been given to determining the buffer size in DBR. Radovilsky (1998) simply modeled a bottleneck node as an M/M/1/K queue and represented an optimal buffer size with a maximum profit in terms of operating characteristics such as carrying cost, service rate, and arrival rate. Louw and Page (2004) also proposed an open queueing network modeling approach to estimate the size of the time buffers in production systems controlled by the TOC (theory of constraints). Workstations in the production network are modeled as GI/G/m queues and a multi-product open queuing network modeling method is used to estimate the average flow time to the time buffer origin and the standard deviation of flow time. Ye and Han (2008) developed more simplified methods of determining the sizes of the constraint buffer and assembly buffer by using machine view's bill of routing instead of process view's bill of routing.

With a simulation study Cook (1994) compared three systems; MRP, JIT (Just-In-Time) and TOC, and concluded that the TOC outperformed the other two systems. Despite the similarities between DBR and CONWIP, there are little research results to compare these two control systems. Gilland (2002) conducted a simulation study to investigate the performance of the two control systems in Intel wafer fabrication site. It is shown that a given output rate can be achieved with DBR using 15% less WIP inventory, on average, than CONWIP. Additionally, the advantage of DBR over CONWIP increases as the bottleneck moves closer to the beginning of the system. To compare DBR with CONWIP under stochastic processing times, Koh and Bulfin (2004) derived steady state probability for a simple 3-node production line by using continuous time Markov process model, and evaluated the performance measures of the systems. It was found that DBR achieves a higher throughput than CONWIP at comparable WIP levels, and DBR can produce more at most 2.81% products at the same WIP level. From a simulation study, Jodlbauer and Huber (2008) investigated MRP, Kanban, CONWIP, and DBR with respect to service level and WIP. They showed that at the same WIP level CONWIP can perform best followed by MRP, DBR and Kanban. A Kanban achieves lower service levels at comparable WIP levels than other PPCS. For robustness against changing environmental conditions such as machine failure, setup time and demand variation, CONWIP is superior to other PPCS. On the other hand, for stability against system parameter changes such as safety inventory, the sizes of Kanban and buffer, MPR is superior. More recently, Khojasteh-Ghamari (2012) used simulation experiments to compare Kanban and CONWIP in a serial production lines with exponentially distributed processing times and a Poisson arrival process. With respect to the minimum average WIP under the same rate of throughput, his results showed that Kanban is superior to CONWIP in case the average deviation of processing times from the bottleneck rate is less than certain value, say 0.2, while it is not in other cases.

By using max-plus algebraic approach, recently, Seo, Lee, and Ko (2008) and Seo and Lee (2011) investigated the expected waiting times at each node in a Poisson driven finite-buffer deterministic m-node tandem queue with either communication blocking or production blocking. The explicit expressions of waiting time at each workstation were derived and they evaluated the expected waiting times at each workstation. Moreover, they introduced an optimization problem which determines the minimum buffer capacity satisfying the predetermined QoS on waiting time at each node.

In this study we extend the work of Seo and Lee (2011) to three types of PPCS: Kanban, CONWIP and DBR, and compare them in terms of WIP and waiting time. The effect of sequencing processing times is also considered.

3. Translation of WIP-controlled line production systems

We first define the following notation.