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Joint design of quality and production control in manufacturing systems

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ABSTRACT

An analytical method for the joint design of quality and production control parameters in unreliable multi-stage lines is proposed in this paper. Specifically, the method optimally sets the sample size, the sampling frequency and the position of the control limits of the quality control charts as well as the number of kanban cards at any production stage, by jointly considering the mutual relations between the controllers. Numerical results compare the solution of this integrated design with the configurations obtained by solving the two problems in isolation with existing techniques. They show that great benefits can be achieved by the proposed integrated design of quality and production control parameters, since it fully captures the interaction between the dynamics of the two controllers.

1. Introduction and problem statement

Quality and production control are vital activities for the profitability of modern manufacturing companies, that are continuously facing product specification and demand changes [1]. Quality control makes it possible to meet high product quality standards, also reducing scraps and reworks. Production control reduces the work in progress (WIP) while meeting the target production rate. Both aspects have been widely analyzed in the literature in the last decades. However, they have been almost always considered in isolation [2]. As a matter of fact, the industrial practice shows that interference between these two control aspects do exist [3] and may lead to globally poor solutions, if neglected. For example, it is known that low WIP improves the ability of identifying quality problems in the system earlier [4]. Thus, the production control parameters have an impact on the performance of the quality control tools. Also, the quality control tools stop the machines when they are detected to work out of control, thus producing defective parts [5]. This reduces the operational time of the machines. Therefore, the quality control action interferes with the production control effectiveness. It is then clear that the mutual relations between quality and production control cannot be neglected while configuring the system as a whole. The dynamics of this phenomenon is represented in Fig. 1. The research question that this paper addresses can be formulated as follows: "What benefits can an integrated design of the quality and production controllers, that fully captures this dynamics, bring to production companies?". For example, consider the 24 stations engine block production line studied in [6]. In this system kanban production control is implemented. Moreover, the inline quality control and inspection is coupled with an extensive 100% quality check at the end of the line. If the demand increases and the line is unsaturated, the number of kanban cards circulating in the system can be increased to achieve higher production rate. However, the question "How much this decision affects the product quality?" is typically neglected. Similarly, if tolerances on a specific product feature tighten, the capability of the process producing that feature and the quality control effort on that feature (inspection frequency and control limits) can be increased. However the question "How much this decision affects the production logistics performance of the system" is typically neglected. To address these relevant industrial issues there is need for an integrated approach that dynamically sets quality and production control parameters to meet changing production targets.

In the literature, the problem of designing production control systems considering logistics performance has been addressed. Problems that have been deeply investigated are the optimal selection of control policy parameters [7] involving basestock, kanban, Hedging Point Policy (HPP) and hybrid solutions, and the comparison of their performance. Also, policies for the real-time control of machine's parameters, i.e. the processing rates, have been proposed [8,9]. In these works, the quality viewpoint is generally neglected. On the other hand, considerable research has been carried out in the design of quality control systems. The most important issues investigated in this area are the optimisation of control chart parameters (sample size, sampling frequency and control limits position), both at a machine [10] and at multistage

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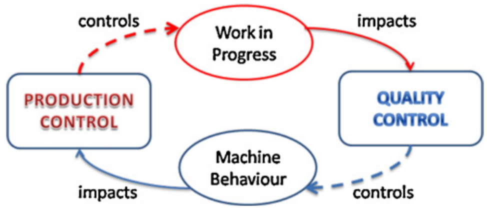

Fig. 1. Interaction between quality and production control.

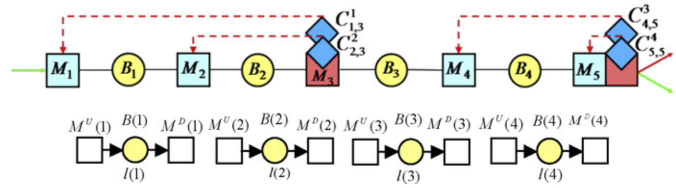

Fig. 3. Representation of the considered system and its Buffer Level Decomposition.

system level [11], the optimal location of inspection points and the definition of optimal inspection policies. In these works the production system configuration is normally considered as given. Recent research carried out both by scientists [12,13] and industrial companies [14] emphasise the importance of jointly considering quality and productivity requirements during the design/redesign phase of production systems. Results showed that decisions taken at a production system level strongly impact the product quality and vice versa. However, the attention has only been focused on integrated performance evaluation methods rather than integrated quality and production control design tools.

This paper proposes a new analytical approach for jointly optimizing quality control and production control parameters. Specifically, the paper considers the presence of kanban production control and statistical quality control charts. An integrated model that jointly includes quality and production control parameters is developed and an approximate analytical method is proposed to evaluate its performance. Moreover, a cost model synthesizes the global performance of the system under a given configuration and a gradient based optimization method searches for the optimal configuration of quality and production control parameters to maximize the profit, also considering demand requirements. Results show that the obtained system configuration outperforms the solutions obtained via independent applications of two existing quality and production control optimization approaches.

2. Integrated manufacturing system model

2.1. Production control policy

Kanban was introduced in the late seventies by Japanese car manufacturer Toyota. Many different formulations of this policy can be found in the literature [15]. The single-stage kanban is a commonly implemented token-based policy, that controls the material flow in the system by regulating the release of raw or in-process parts at the immediate previous production stage. Its behaviour is represented in Fig. 2, where square represent machines, circles represent buffers (dashed line circles are kanban buffers, full line circles are buffers storing parts with kanban cards attached), dashed lines represent information flows and lines represent part flows.

In token-based policies, events are triggered by the movement of tokens that represent demand realizations in the system. A machine cannot start working on a part until the proper authorization token is available. For instance, machine M_2 cannot start working a part until a card is available in the kanban buffer B'_2. Then, the part is processed and stored in B_2 with its kanban. When the part reaches M_3 the kanban is disassembled and sent back to B'_2

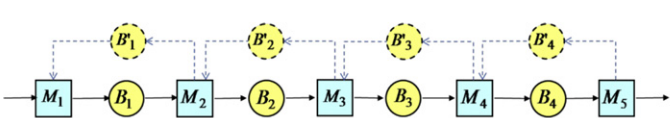

Fig. 2. Kanban controlled manufacturing system.

while the part continues its process in the line. It has been shown that a system operating under kanban is equivalent to a transfer line with finite buffers between each pair of consecutive machines, under the assumption of Blocking Before Service (BBS) [16]. Indeed, the finite buffer limits the maximum amount of material that can be stored between the two consecutive stages exactly as kanbans. The capacity of the buffer is therefore equivalent to the number of kanban cards at stage i. In this paper, this analogy will be used to exploit the availability of techniques for analyzing capacitated multi-stage transfer lines.

2.2. System behaviour

The considered production system (Fig. 3) is organized in serial layout with K machines, M_i, $i = 1, 2, \ldots, K$, separated by $K-1$ finite capacity buffers, B_i, $i = 1, 2, \ldots, K-1$. Finite capacity buffers are used for modelling the kanban control policy. Thus, to modify the capacity of the buffer is equivalent to change the number of kanbans at each production stage. In this paper we consider the presence of three types of stations: machining stations (blue square), inspection stations (red square) and integrated stations.

Machining stations are those realizing machining operations on parts flowing in the system. Inspection stations are those measuring some quality characteristics of the parts produced at one or more upstream machining stations. Integrated stations are those performing both manufacturing and inspection operations. For instance in Fig. 3, machines M_1, M_2 and M_4 are machining stations, machine M_3 is an inspection station which measures quality characteristics of parts already processed by stations M_1 and M_2, and machine M_5 is an integrated station measuring quality features of parts processed by M_4 and by M_5 itself.

Machining stations are unreliable and subject to operational failures. Operational failures are typically random events that instantaneously cause the stop in the production of the machine. They affect the quantity of parts processed by the machine, by reducing the fraction of time it is operational, without directly affecting the quality of the produced parts. In real systems, they are typically fuse damages, tool breakages, wrong part positioning in the working area and mechanical jamming. Moreover, machining stations can produce either being in control or out of control. The in control state is normally characterised by a low fraction of non-conforming parts produced, while the out of control state is normally characterised by a higher fraction of non-conforming parts produced. For instance, the cause for out of control can be the loss of the process settings, the wear of tools or fixtures, the malfunctioning of some machine components, etc. Even if, in general, multiple causes for out of control are possible, the commonly adopted assumption of unique out of control mode is considered for each machine. Moreover, we consider the case in which product features processed at different production stages are independent. In other words, a defective item produced by machining station M_i does not affect the quality of the operations performed at the downstream stages M_j, with $j = i+1, \ldots, K$, i.e., the machines add non-conformities of different types to the processed parts. In order to detect out of control conditions, quality control charts have been developed in the SPC (Statistical Process Control)