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Production quality performance in manufacturing systems processing deteriorating products

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ABSTRACT

In several manufacturing contexts including food industry, semiconductor manufacturing, and polymers forming, the product quality deteriorates during production by prolonged exposure to the air caused by excessive lead times. Buffers increase the system throughput while also increasing the production lead time, consequently affecting the product quality. This paper proposes a theory and methodology to predict the lead time distribution in multi-stage manufacturing systems with unreliable machines. The method allows to optimally set inventory levels to achieve target production quality performance in these systems. The industrial benefits are demonstrated in a real manufacturing system producing micro-catheters for medical applications.

1. Introduction, motivation and objectives

Production quality has been proposed recently as an emerging paradigm to achieve desired service levels of conforming products in advanced manufacturing systems, by simultaneously considering quality and productivity requirements [1]. With respect to this background, the importance of an integrated analysis of production logistics, product quality and equipment maintenance to achieve balanced manufacturing system solutions has been pointed out. This problem is particularly relevant in manufacturing systems producing deteriorating products.

Product quality and value deterioration due to excessive residence times (or lead times) during production is a significant phenomenon in several technology intensive industries, including automotive, food manufacturing, semiconductor and electronics manufacturing and in polymer forming. For example, in automotive paint shops a car body that is affected by prolonged exposure to the air in the shop floor caused by excessive lead times between operations, is prone to particle contamination, leading to unacceptable quality of the output of the painting process. Moreover, food production is pervaded by strict requirements on hygiene and delivery precision requiring a maximum allowed storage time before packaging. If the production lead time exceeds this limit, the product has to be considered as defective and cannot be delivered to the customer. In these systems, higher inventory increases the system throughput but also increases the production lead times, thus increasing the probability of producing defective items. Therefore, a relevant trade-off is generated between production logistics and quality performance that requires advanced engineering methods to be profitably addressed.

In spite of the relevance of this phenomenon in industry, the analysis of production quality performance under product deterioration has received relatively low attention in the literature. The manufacturing system is considered in a highly aggregate way in advanced Economic Production Quantity (EPQ) models considering quality deterioration [2]. In these works, the quality deterioration due to the parts residence time along the stages of the manufacturing system is neglected. Other works considered supply chain coordination mechanisms in presence of product obsolescence [3]. Furthermore, production control policies based on *WIP* [4] and part release [5,6] regulation could support the achievement of improved production quality performance under product deterioration, although they do not provide mechanisms to directly control production lead times.

The first model considering this interaction is proposed in [7] that analyzed un-buffered systems where the material under processing is scrapped after long machine failures. Moreover, the performance of serial lines with product deterioration is considered under Bernoulli reliability models of production stages in [8], and in small two-machine lines in [9]. While all these works are important to shed light on the problem, they do not provide methods to predict and control production lead time distributions under realistic manufacturing system features. As a matter of fact, a methodology to support the design of manufacturing systems under lead time dependent product deterioration that integrates quality and production logistics implications has never been proposed. Important questions like "What is the impact of buffers on the production rate of conforming products with product quality deterioration?" remain unsolved, resulting in sub-performing system configurations.

To overcome these limitations, in this paper an integrated model of manufacturing systems affected by product deterioration and a new method for the prediction of the production lead time distribution and the throughput of conforming products in these

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systems are developed for the first time. This approach allows setting inventory levels to achieve desired production quality performance in real systems.

2. System description

The considered system is formed by K manufacturing stages and $K-1$ buffers of finite capacity, configured in serial layout (Fig. 1). Stages are denoted as M_k, with $k = 1, \ldots, K$, and buffers are denoted as B_k, with $k = 1, \ldots, K-1$. The capacity of buffer B_k is N_k, that is an integer number. Finite capacity buffers can either model physical conveyors or the implementation of token-based production control rules, such as kanban, regulating the material flow release at each stage [10].

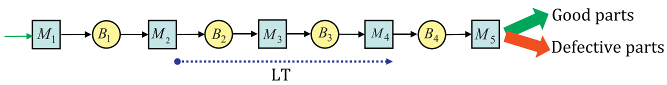

Fig. 1. Representation of the analyzed manufacturing system.

Single stage model. The dynamics of each stage is modeled by a discrete-time and discrete-state Markov chain of general complexity. This setup allows to analyze a wide set of different stage models within a unique framework. For example, stages with unreliable machines characterized by generally distributed up and down times and also stages with non-identical processing times can be considered within the same framework, thus making the proposed approach applicable to a wide set of real manufacturing systems.

In detail, each stage M_k is represented by I_k states, and thus the state indicator α_k assumes values in $\{1, \ldots, I_k\}$. The set containing all the states of M_k is called S_k. The dynamics of each stage in visiting its states is captured by the transition probability matrix λ_k, that is a square matrix of size I_k. Moreover, a quantity reward vector $\mu_{\mathbf{k}}$ is considered, with I_k binary entries. While in the generic state i, M_k produces $\mu_{k,i}$ parts per time unit. Therefore, state i with $\mu_{k,i} = 1$ can be considered as an operational state for stage M_k, while state i with $\mu_{k,i} = 0$ is a down state for stage M_k.

Material flow dynamics. A discrete flow of parts is considered in the system. Stage M_k is blocked if the buffer B_k is full. Stage M_k is starved if the buffer B_{k-1} is empty. Stage M_K is never blocked, i.e., infinite amount of space is available to store finished products. Stage M_1 is never starved, i.e., unlimited supply of raw parts is assumed. Operational Dependent Transitions are considered, i.e., a machine cannot make transitions to other states if it is starved or blocked. State transitions take place at the beginning of the time unit and buffer levels are updated at the end of the time unit.

Part quality deterioration. The quality of parts deteriorates with the time parts spend in a *critical portion of system*, denoted by two integers, e and q with $1 \le e < q \le K$, and composed of those buffers that are between stages M_e and M_q. The lead time of a part is the time spent in buffers $B_e, B_{e+1}, \ldots, B_{q-1}$. For example, for the system in Fig. 1, $e = 2$ and $q = 4$. If $e = 1$ and $q = K$, then the time spent in the whole system is considered. The probability that a part is defective at the end of the line is a non-decreasing function of its lead time. The function $g(h)$ indicates the probability that a part released by the system is defective given that it spent h time units in the critical portion of system. Defective parts are scrapped at the end of the line.

Performance measures. The main performance measures of interest are:

- Average total production rate of the system, denoted by E^{Tot},
- Probability that the lead time, LT, is equal to a given number of time units, h, i.e., $P(LT = h)$,
- Average effective production rate of conforming parts, E^{Eff}, which is given by:

$$E^{Eff} = E^{Tot} \cdot \sum_{h=1}^{\infty} P(LT = h)[1 - g(h)] \tag{1}$$

- System yield, Y^{system}, i.e. fraction of conforming parts: (E^{Eff}/E^{Tot}).
- Total average inventory of the system, WIP.

3. Lead time distribution evaluation

In this section, an efficient and exact analytical method to compute the distribution of the lead time in the critical portion of the system is described. The rationale of the approach is explained in the following. Firstly, the probability that, at the moment when a randomly selected part enters buffer B_e, the system is in a given state is derived. Secondly, the probability that, given that state of the system as initial condition, the last part in buffer B_e crosses the critical portion of the system in h time units is analyzed. By taking the product of these two quantities and summing for all possible states, the distribution of the lead time in the critical portion of the system can be reconstructed. In the following, the steps of this procedure are briefly described.

Starting from the parameters of the stages and according to the modeling assumptions, a discrete time Markov chain, denoted by $\mathfrak{D}_1$, can be determined that characterizes the overall behavior of the system. A state of $\mathfrak{D}_1$ is described by a vector $\mathbf{s_1} = (n_1, n_2, \ldots, n_{K-1}, \alpha_1, \alpha_2, \ldots, \alpha_K)$ where n_k is the number of parts in buffer B_k and α_k is the state of machine M_k. The set of all the system states is denoted by Ω_1 and the transition probability matrix by $\mathbf{P_1}$. The entries of $\mathbf{P_1}$ can be obtained as shown in [11]. The row vector of the steady state probabilities, denoted as $\boldsymbol{\pi_1}$, and the total production rate, E^{Tot}, can be calculated as in [11,12].

The sub-system including only that portion of line that is downstream machine M_e is considered next. This sub-system comprises buffers $B_e, B_{e+1}, \ldots, B_{K-1}$ and machines $M_{e+1}, M_{e+2}, \ldots, M_K$. Machines $\mathrm{M}_1, \ldots, \mathrm{M}_e$ are not considered because, once a part is put in buffer B_e, these machines have no impact on its lead time. For this sub-system, a Markov chain, denoted by $\mathfrak{D}_2$, with initial probability vector $\boldsymbol{\pi_2}$ and transition probability matrix $\mathbf{P_2}$ is determined. $\mathfrak{D}_2$ can be considerably reduced with respect to $\mathfrak{D}_1$. A state of this model is given by a vector $\mathbf{s_2} = (n_e, n_{e+1}, \ldots, n_{K-1}, \alpha_{e+1}, \alpha_{e+2}, \ldots, \alpha_K)$. The set of states of $\mathfrak{D}_2$ will be denoted by Ω_2. Note that, since no machine feeds parts in the first buffer of this model, all parts will eventually leave and the system will get empty. In other words, $\mathfrak{D}_2$ is an absorbing Markov chain [12]. The subset of states in S_2 in which there are no parts in the buffers of the critical portion $B_e, B_{e+1}, \ldots, B_{q-1}$ will be denoted by Ω_0. The lead time in the critical portion of system can be expressed as follows:

$$P(LT \le h) = \sum_{s_2 \in \Omega_2} \boldsymbol{\pi}_{\mathbf{2},\mathbf{s_2}} f(s_2, h) \tag{2}$$

where π_{2,s_2} is the probability that a random part that enters in buffer B_e finds the system in state $\mathbf{s_2}$ and $f(\mathbf{s_2},h)$ is the probability that a part that enters the critical portion in state $\mathbf{s_2}$ leaves machine M_q in at most h time units. The first term in Eq. (2) is obtained by properly mapping the states $\mathbf{s_1}$ in $\mathfrak{D}_1$ into the states $\mathbf{s_2}$ of the sub-system in $\mathfrak{D}_2$. For this reason the matrix $\mathbf{F}$ of binary entries is defined that links the states in $\mathbf{s_1}$ and $\mathbf{s_2}$ if the states of all the stages M_{j+1} and buffers B_j, with $j > e$, are the same. In other words, the initial probability of the state $\mathbf{s_2}$ in $\mathfrak{D}_2$, π_{2,s_2}, has to be equal to the sum of the probabilities that a part is put in the buffer B_e in the connected set of states $\mathbf{s_1}$ in $\mathfrak{D}_1$. Therefore:

$$\boldsymbol{\pi_2} = \frac{\boldsymbol{\pi_1}\mathbf{Q_1}}{E^{Tot}} F \tag{3}$$

where $\mathbf{Q_1}$ is identical to $\mathbf{P_1}$, except that those transitions that do not cause the release of a part in buffer B_e are set to zero.

The second term in (2) can be easily computed as the distribution of the first passage time to Ω_0 in the absorbing Markov chain $\mathfrak{D}_2$ [12]. The probability that the lead time is exactly h is given by $P(LT = h) = P(LT \le n) - P(LT \le n - 1)$. The other performance measures defined in Section 2 can be derived based on the lead time distribution and the total throughput.