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Modeling sequence scrambling and related phenomena in mixed-model production lines

Gábor Rudolf [a], Nilay Noyan [b,*], Vincent Giard [c]

[a] Department of Industrial Engineering, Koc University, Istanbul, Turkey
[b] Manufacturing Systems/Industrial Engineering Program, Sabancı University, 34956 Istanbul, Turkey
[c] LAMSADE, Paris Dauphine University, France

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ABSTRACT

In this paper we examine the various effects that workstations and rework loops with identical parallel processors and stochastic processing times have on the performance of a mixed-model production line. Of particular interest are issues related to sequence scrambling. In many production systems (especially those operating on *just-in-time* or *in-line vehicle sequencing* principles), the sequence of orders is selected carefully to optimize line efficiency while taking into account various line balancing and product spacing constraints. However, this sequence is often altered due to stochastic factors during production. This leads to significant economic consequences, due to either the degraded performance of the production line, or the added cost of restoring the sequence (via the use of systems such as mix banks or automated storage and retrieval systems). We develop analytical formulas to quantify both the extent of sequence scrambling caused by a station of the production line, and the effects of this scrambling on downstream performance. We also develop a detailed Markov chain model to analyze related issues regarding line stoppages and throughput. We demonstrate the usefulness of our methods on a range of illustrative numerical examples, and discuss the implications from a managerial point of view.

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1. Introduction

There has been significant recent interest in issues related to product sequencing in mixed-product production lines. This interest is in a large part due to the rising prevalence of JIS (Just-In-Sequence) and ILVS (In Line Vehicle Sequencing) systems in the automotive industry, which aim to introduce products to a section of the production line in a specific sequence. In a mass customization environment (Alford, Sackett, & Nelder, 2000) both operators and suppliers can benefit from knowing the sequence in advance, in particular because they can have parts delivered to the line only when needed, which leads to a decrease in inventory and buffering costs. Selecting a suitable product sequence, which takes into account line balancing and product spacing concerns (sometimes in conjunction with other objectives, such as minimizing start-up costs, see, e.g., Giard & Jeunet (2010)), is a well-studied problem; see Boysen, Fliedner, and Scholl (2009) for a general overview. However, factors such as parallel stations, in-line quality control, rework loops, and lot sizing constraints often significantly alter the initial sequence of the products during the manufacturing process, leading to a phenomenon called *sequence scrambling* (also known as *decycling*). This effect can be quantified by taking the difference between the position of a product in the sequence before entering and after exiting a particular section of the production line; the difference is known as the *rank change* or *sequence displacement* of the product. Much of the existing literature on the subject focuses on methods to (partially or completely) restore the altered sequence (Ding & Sun, 2004; Gusikhin, Caprihan, & Stecke, 2008). In particular, problems related to the sizing and usage of automated storage and retrieval systems (ASRS) have been extensively explored; Roodbergen and Vis (2009) provide a thorough survey, while Inman (2003) directly links ASRS sizing to sequence displacement. Another direction of research involves analysis of the effects of sequence scrambling on the downstream performance of the production line, such as the need for safety stocks of alternative components (Camisullis & Giard, 2008).

A common feature of existing studies on decycling is that they take the extent of sequence scrambling as a given, either relying on empirical data or assuming a particular random distribution. In contrast, we aim to directly model the causes of sequence scrambling. In order to do so, we consider a production line section featuring a quality control inspection station, where products

* Corresponding author. Tel.: +90 216 4839618; fax: +90 216 4839550.
E-mail addresses: grudolf@ku.edu.tr (G. Rudolf), nnoyan@sabanciuniv.edu (N. Noyan), Vincent.giard@dauphine.fr (V. Giard).

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which fail inspection are withdrawn to an off-line rework shop to make the necessary rework operations (see Fig. 1). We chose to present our models in this context since, due to modern quality standards and requirements, such stations are widely used in the automotive industry as well as in several other fields (see the survey by Raz (1986), or the more recent overview by Mandroli, Shrivastava, & Ding (2006)). However, our results remain applicable for any workstation with identical parallel processors, and the methodology can be naturally adapted to other types of line segments. In addition, while in the literature it is common to assume that stochastic processing times follow a specific type of distribution (usually exponential), such assumptions are not necessary for our approach.

We develop a detailed Markov chain model of the operation of the production line segment, which allows us to quantify its effects on the overall performance of the line. Markov chains provide a versatile tool for modeling various aspects of production lines (Manitz, 2008; van Bracht, 1995; Xiaobo, Xu, Zhang, & He, 2007). While the focus in this type of analysis is often on the long term characteristics of the system, in many cases it can also be necessary to carefully study the transient behavior (as Narahari & Viswanadham (1994) point out). For instance, automotive production lines are typically re-initialized every day, and the time required to reach steady state can be significant compared to the length of the production day. Accordingly, we first provide a description of the recurrent states of our Markov chain, then proceed to examine its overall structure using decomposition techniques. The model yields analytic expressions of various performance indicators, including the expected line throughput and the probability of operation without a line stoppage.

In addition to our Markov analysis we also improve on and extend some of the developments in Danjou, Giard, and Boctor (2001) to provide computationally tractable formulas describing the probability distribution of the rank change of a product; this is the first time that results of this type appear in the peer-reviewed English literature. The formulas are based on elementary symmetrical polynomials which can be evaluated recursively; we also apply similar techniques to model the effects of sequence scrambling in a mixed-model production line. Specifically, we consider a workstation that installs alternative or optional components that are periodically supplied to the line according to projected demand, and derive tractable recursive formulas for the probability of stock-out, as well as for the distribution of the shortage amount, of these components.

The main novel feature of our approach is that we establish a quantitative connection between parameters of a production line segment (such as the number of parallel processors, and the distribution of processing times), and the effects these parameters have on the performance of other segments of the line via sequence scrambling and line stoppages. This allows managers to evaluate various trade-offs which, to the best of our knowledge, until now have not been discussed in the literature. For instance, our formulas provide a way to quantify the effect that a reduction in the mean or in the variance of stochastic processing times has on sequence scrambling. We can then compare the costs of achieving such reductions to the savings that would result from the decrease in the required size of an ASRS (either to be installed or to be expanded) that restores the sequence.

The rest of this paper is structured as follows: In Section 2 we describe the operation of a production line segment featuring an inspection station, a rework shop, and a buffer. In Section 3 we construct a Markov chain which models the production line segment, and derive structural results which are then applied to obtain formulas for various performance indicators. In Section 4 we derive the probability distribution of the rank change caused by the line segment with the inspection station, then use similar tools to examine the impact of sequence scrambling on a workstation that installs alternative or optional parts. Managerial insights and illustrative numerical results are presented in Section 5.

2. Production line with an inspection station

In this section we consider a production line section that includes an inspection station, a rework shop, and a buffer (see Fig. 1). We note that such configurations are often encountered at body shops in automotive manufacturing. The inspection station can process a single product at a time. There are two possible outcomes of the inspection. If the inspected product passes the test, it is ready to be sent to the next workstation on the downstream line. If the product fails the test, it is withdrawn and sent to the rework shop. The rework shop can typically store and process multiple products at the same time. A product does not leave the rework shop until it is reinspected and passes the inspection. Reinspection is assumed to take place in the rework shop as part of the rework process, not at the inspection station.

We divide the operation of the production line into time cycles, and assume that the same time cycle is shared by the entire line. Each cycle consists of two phases: in the first phase products are processed at the workstations, while in the second phase products are moved between workstations. Below is a detailed description of a single cycle during the operation of the production line section under investigation. The first phase consists of steps 1 and 2, while steps 3–6 constitute the second phase.

1. The products in the rework shop which have not yet passed reinspection are worked on.
2. If there is an uninspected product at the inspection station, it gets inspected.
3. If the pool of products which already passed inspection (consisting of products in the buffer, successfully inspected products in the rework shop, and a product at the inspection station which has passed) is non-empty, a product from this pool is

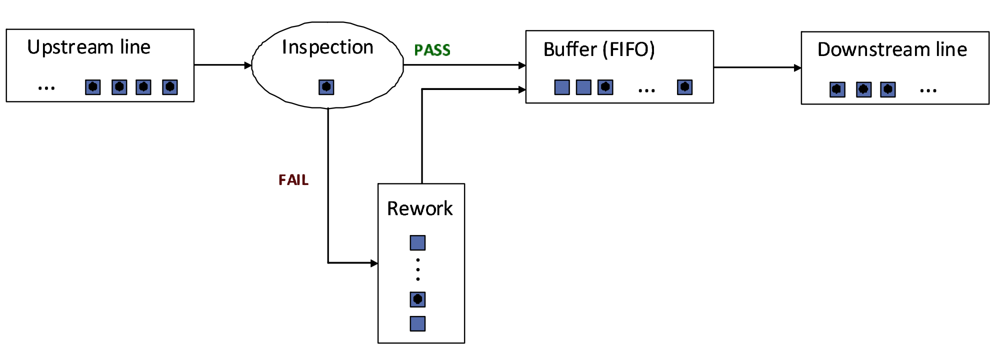

Fig. 1. Production line with an inspection station.

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