Throughput Analysis in Automotive Paint Shops: A Case Study

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***Abstract*—In this paper, an overlapping decomposition method is used to estimate the throughput of a production system with multiple rework loops. The idea of the method is to decompose the system into a couple of serial lines and modify the parameters of overlapping machines to accommodate the effects of other lines. Using this method, the throughput of an automotive paint shop is analyzed and continuous improvement procedures are described.**

***Note to Practitioners*—Painting is an important element of vehicle production. A paint shop has been a system bottleneck in many automotive assembly plants due to its complexity. Fast and accurate analysis of its system throughput is important for design and continuous improvements. This paper introduces an iterative method to analyze the performance of paint shop type production systems, i.e., systems with multiple rework loops. The method has obtained good results in both theoretical study and applications on the factory floor. In addition, a case study at an automotive paint shop is introduced and continuous improvements process to identify and eliminate system bottlenecks is described. The presented method can also be applied to other production systems with similar structures.**

***Index Terms*—Overlapping decomposition, paint shop, rework loop, throughput analysis.**

I. Introduction

Painting is an important element of vehicle production. A paint shop is a system bottleneck in many automotive assembly plants due to complexity inherent in the process, production control policies and rigorous quality requirements [1]. In automotive paint shops, rework loops are often required when a job needs multiple passes or is defective. Jobs can enter the painting booths multiple times, either for repaint or for "tutone" operation (i.e., to have different colors painted). The use of rework loops in paint shops can significantly increase the system throughput and reduce scrap, cost, etc. To design, operate, and improve the performance of paint shops, accurate throughput analysis, which is a critical enabler for continuous improvement is necessary and important.

Throughput analysis of production systems has attracted intensive attention (see reviews [2], [3] and books [4]–[6]). For two-machine systems, there exist exact analytical solutions. For longer lines and assembly systems, different aggregation and decomposition techniques have been used to approximate system performance. However, in spite of all these efforts, the results on production systems with rework loops, i.e., paint-shop-type systems, is quite limited.

Although some analytical methods have been developed to analyze closed-loop queueing networks (see reviews [7] and [8]), most of them do not address the unreliable nature of a production system and do not study the rework type system directly. There are a limited number of studies on throughput analysis in closed-loop production systems or paint shops. Closed-loop serial production lines with a fixed number of carriers, where parts are loaded on recirculating pallets at the first machine and unloaded at the last after the part has undergone all the required operations, have been studied in [9]–[12]. Specifically, paper [9] analyzes an asymptotically reliable two-machine two-buffer closed-loop line and describes a case study in a paint shop. Paper [10] presents a decomposition approach for longer homogeneous production lines and investigates the optimal number of carriers which maximizes system throughput. Paper [11] introduces thresholds for blocking and starving probabilities to take into account the correlation between number of parts in the buffer and uses loop transformations to decompose the system into two-machine building blocks to estimate the performance of systems with both small and large loops. In addition, by using Taylor series expansions, an approximation method is described in [12] for highly reliable closed-loop systems.

However, for production systems with unequal machine speeds and multiple rework loops (which are common in paint shops), to our best knowledge, there are no analytical methods available in the literature to analyze their performance. The main contribution of this paper is an iterative approach to estimate the throughput of such systems and illustrate its applicability through a continuous improvement project at an automotive paint shop.

To this end, the remainder of the paper is structured as follows: Sections II formulates the problem. The approach of throughput analysis is presented in Section III. Using this approach, Section IV introduces a case study at an automotive paint shop. The conclusions are formulated in Section V. All proofs are given in the Appendix.

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II. Problem Formulation

A typical structure of an automotive paint shop is shown in Fig. 1, where the circles represent machines and the rectangles are buffers. The system consists of a main line and three rework loops, including repair, tutone and polishing (denoted as subscripts r, t, and p, respectively). A description of notations of machines and buffers is introduced as follows:

Main line:	$m_1, \ldots, m_M, \quad B_1, \ldots, B_{M-1}$
Repair loop:	$m_{r1}, \ldots, m_{rR}, \quad B_{r1}, \ldots, B_{rR+1}$
Tutone loop:	$m_{t1}, \ldots, m_{tT}, \quad B_{t1}, \ldots, B_{tT+1}$
Polishing loop:	$m_{p1}, \ldots, m_{pP}, \quad B_{p1}, \ldots, B_{pP+1}$
Merge machine:	m_{j_r} (repair/tutone merge)
	m_{j_p} (polishing merge)
Split machine:	m_{k_r} (rework split), $\quad m_{k_t}$ (tutone split)
	m_{rk_p} (polishing split).

A defective part is sent to the repair loop at machine m_{k_r}. Then, at machine m_{rk_p}, the parts needing minor repairs are corrected in the polishing loop and merged with the main line at machine m_{j_p}, whereas the severe defective parts are stayed in the repair loop and back to the main line at machine m_{j_r} for repaint. In addition, some parts may need different colors, they are routed to the tutone loop at machine m_{k_t}. The tutone parts are joined with the main line at machine m_{j_r} for another paint.

The following model is considered throughout this paper.

i) Each machine m_i has two states: up and down. When up, the machine is capable of producing with the rate S_i parts per unit of time; when the machine is down, no production takes place.

ii) The up and downtimes of each machine m_i, are exponentially distributed with parameters p_i and r_i, respectively. In other words, p_i and r_i are the failure and repair rates, respectively.

Remark 1: Assumption ii) implies that $T_{\rm up}(i)$ and $T_{\rm down}(i)$, the average up and downtimes of m_i, equal to $(1/p_i)$ and $(1/r_i)$, respectively. The exponential distribution is used to simplify the analysis. This