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Decision support systems for effective maintenance operations

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ABSTRACT

To compete successfully in the market place, leading manufacturing companies are pursuing effective maintenance operations. Existing computerized maintenance management systems (CMMS) can no longer meet the needs of dynamic maintenance operations. This paper describes newly developed decision support tools for effective maintenance operations: (1) data-driven short-term throughput bottleneck identification, (2) estimation of maintenance windows of opportunity, (3) prioritization of maintenance tasks, (4) joint production and maintenance scheduling systems, and (5) maintenance staff management. Mathematical algorithms and simulation tools are utilized to illustrate the concepts of these decision support systems. Results from real implementations in automotive manufacturing are presented to demonstrate the effectiveness of these tools.

1. Introduction

In response to the challenges of fluctuating markets and the need for production of high volume of mixed products in a flexible manufacturing system (FMS), industry experts were surveyed for enabling technologies to improve the performance of flexible manufacturing. A survey was conducted by a CIRP Working Group on “Flexible Automation-Assessment and Future” in collaboration with the ERC for reconfigurable manufacturing systems during fall 2001 through summer 2002. The survey findings provide significant insights into the reasons for success and failure of FMS in the manufacturing industry. System capital cost was found to be the most critical factor in the success of large FMS. The cost of maintenance was the number two factor. The survey reveals that industry is dissatisfied with the high cost of maintenance of FMS and the actual system productive uptime is 25% lower than expected when installing the systems [1].

Generally, a large FMS contains many production machines, material handling and other pieces of equipment – all of which may break down during normal operation. These systems require (i) regularly scheduled maintenance or preventive maintenance (PM), (ii) repairs of machines reactive to the machine failures, and (iii) incidental maintenance tasks that require relatively small effort such as adding coolant or replacing tools. Appropriately coordinated maintenance-scheduling decisions can increase the system productivity if they are done based on information that is transferred comprehensively across hierarchical levels of control and management. Proper maintenance scheduling must consider both productivity and product quality. However, the mere use of maintenance scheduling is usually insufficient to obtain feasible solutions based on traditional combinatorial optimization methods because of the complexity of production processes [2]. Model-based maintenance decision support systems are needed to achieve high productivity and cost effectiveness of the overall system [3,4].

Decision making for effective maintenance of large systems is complex because it depends on several independent sources of information: (a) The Current health condition of each machine including: down; running; idling; being maintained; or just about to breakdown, (b) the scheduled daily, weekly and monthly maintenance plan, (c) machine health degradation profile, (d) throughput target and production rate, (e) costs of maintenance resource, i.e., labor, spare parts, tools, etc., and (f) the system configuration and decision alternatives [5].

Given the information from the machine and cell levels as inputs, the system-level controller is the best one for making effective maintenance decisions. These inputs then are compared to the overall production requirements that are sent down from the enterprise level. Design, control and management of such maintenance activities in large systems boost their productivities and increase their reliability and responsiveness to changing operations [1].

To this end, several important issues need to be addressed for the effective maintenance of large systems. They include (1) how to assess the impact of a machine breakdown on the factory throughput and determine what to do first, (2) if an unscheduled machine failure occurs, or if several events occur simultaneously, which reactive maintenance job has the highest priority (3) which machine failure is most seriously endangering the production schedule, (4) where are the opportunities for maintenance without affecting production throughput, and (5) how to efficiently utilize the factory resources (e.g., maintenance crews) on the critical sections of the systems.

This paper addresses some of the questions raised above. We present several newly developed maintenance decision support tools for machining systems. We introduce throughput bottleneck

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detection and prediction techniques for guiding maintenance planning based on throughput-critical machines (Section 2) and a related method for estimating maintenance opportunities in a production line with machines and buffers (Section 3). From a joint production and maintenance perspective, we discuss maintenance tasks prioritization problem and an option-based model for maintenance scheduling (Sections 4 and 5, resp.). Section 6 presents a new decision support tool for effective maintenance personnel staffing management.

2. Throughput bottleneck detection

In [6], Koren et al. demonstrated that system configuration affect throughput. Specifically, they show that machine downtime has a different effect on expected throughput depending on system configuration. A single machine failure in a serial line configuration without buffers leads to the stoppage of the entire system because other machines are blocked or starved. However, in a parallel configuration, if a machine fails, the system only loses a portion of its productivity because alternative paths exist for parts to be processed [7]. Therefore, given different system configuration it is important to understand how machine level reliability affects the overall system productivity and how increasing machine level reliability by maintenance improves optimal performance.

2.1. Bottleneck detection for serial lines

Throughput bottlenecks impede and constrain the productivity of every production line. Effective and efficient identification and prediction of bottleneck machines in a production line can help to better understand the fundamental laws that govern the production system behavior and provide implication for production and preventive maintenance planning including optimum preventive maintenance schedules, opportunity window of performing preventive maintenance tasks, maintenance resource allocation policy, etc.

A bottleneck machine is defined as a machine that impedes the system performance in the strongest possible manner. Generally, the performance improvement on bottleneck machines results in a significantly higher overall system throughput improvement than that on non-bottleneck machines. Below we introduce the definition of bottleneck applicable to serial production lines and suggest methods of bottleneck detection. A bottleneck is defined as the machine that has the maximum ratio of overall system throughput increment $\Delta TP_{sys,i}$ to its own standalone throughput increment ΔTP_i during a certain period [8,9]. Mathematically, the definition can be formulated as: if $\Delta TP_{sys,k}/\Delta TP_k = \max\{\Delta TP_{sys,i}/\Delta TP_i$, for all $i\}$, then machine k is the throughput bottleneck in a serial line with n machines and $n-1$ buffers. The overall system throughput is a function of individual machine throughput and buffer size: $TP_{sys}(t) = f(TP_1(t), \ldots, TP_n(t), B_1(t), \ldots, B_{n-1}(t))$.

Conventional methods for bottleneck identification in existing literature can be categorized into two classes: analytical based [10–12] and simulation based [13–15]. Simulation-based methods are very useful to identify the short-term bottlenecks [15]. However, high cost, long development time and possible misinterpretation of simulation results greatly impede their wide application. For the analytical method, the system performance measures are described by probability distributions which prohibit a short-term analysis with changes in throughput target.

Data-driven throughput bottleneck detection was proposed to provide short-term analysis based on real time data such as machine up- and down-time, buffer count, and throughput [16]. For a modern factory, more detailed online data such as blockage time and starvation time that reflect the overall system dynamics and inner work of machines is available [17].

The heuristic methods assume that a bottleneck machine will often cause the upstream machines to be blocked and the downstream machines to be starved. A bottleneck machine will also have a lower total blockage plus starvation time than that of its adjacent machines. A "turning point" is defined as the critical machine where the trend of blockage and starvation changes from blockage being higher than starvation to starvation being higher than blockage. Fig. 1 shows the blockage and starvation times from a real serial production line.

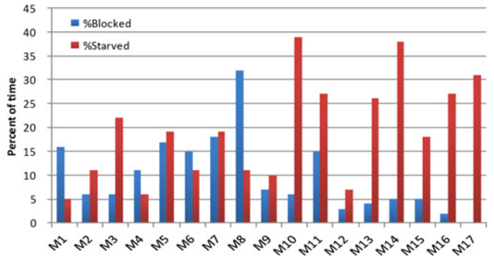

Fig. 1. Blockage and starvation time percentage in a serial line.

2.2. Bottleneck prediction for complex systems

Based on the data driven method, the latest performance of the system is measured and corrective action will be applied. It is true that the bottleneck of a previous time period may not be the bottleneck for the next time period. However, the impact of the previous bottleneck will last until the system dynamics stabilize and the balancing situation has changed so that the bottlenecks switch to other locations. In fact, in a designed balanced system with finite buffers, one will always observe some "bottleneck inertia phenomenon" [18]. A test was conducted for an extreme case using a simple five-machine-four-buffer serial transfer line. For the first shift (8 h), machine M3 is the significant bottleneck as shown in Fig. 2. System behaviors for the next shift are further observed. If the performance of M3 is significantly improved, the bottleneck continues to be M3 for first couple of hours then gradually moves to other machines as illustrated in Fig. 2. This simple test demonstrates that when a given machine changes its behavior drastically, and the impact of that machine on the overall system performance will lasts for some time period.

Therefore, developing a bottleneck prediction method to monitor the system performance and track the bottleneck location becomes an important task. In [9], a method for throughput bottleneck prediction based on the time series model (i.e., ARMA) through transforming the blockage time and starvation time of each station into time series. The results show that downtime increment on bottleneck machine will result in lower ARMA model orders than that for non-bottleneck machines.

3. Estimation of maintenance opportunity

For production lines consisting of multi-unit systems with an interrelated system structure and material flow, modeling and understanding of the complex interactions provides maintenance decision makers with good opportunities to perform maintenance which will minimally affect production. The name "opportunistic" comes from the available opportunities from shutting down caused by a machine failure to perform preventive maintenance (PM) task on other non-failed machines [19,20]. The philosophy of opportunistic maintenance comprises of utilizing observed or predicted situations in a manufacturing system to conduct maintenance operations while minimally affecting the normal

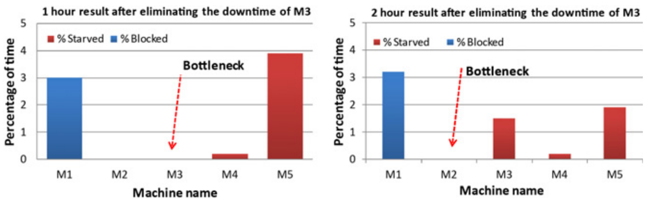

Fig. 2. Illustration of bottleneck inertia phenomena [8].