Robotics and Computer-Integrated Manufacturing 26 (2010) 145–155

Contents lists available at ScienceDirect

Robotics and Computer-Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Tool maintenance optimization for multi-station machining systems with economic consideration of quality loss and obsolescence

Sun Ji-wen *, Xi Li-feng, Du Shi-chang, Pan Er-shun

School of Mechanical Engineering, Shanghai Jiaotong University, Shanghai 200240, China

ARTICLE INFO

Article history:
Received 22 August 2007
Received in revised form
20 May 2009
Accepted 8 July 2009

Keywords:
Preventive maintenance
Multi-component maintenance
Quality loss
Obsolescence cost
Multi-station machining system

ABSTRACT

Tools used in a machining process are vulnerable to frequent wear-outs and failures during their useful life. Maintenance is thus considered essential under such conditions. Additionally, it is widely recognized that the maintenance of manufacturing equipments and the quality of manufactured product are highly interrelated. However, few detailed study has been found in the literature dealing with the effects of maintenance policies on the operational performance of such a system, especially the long-term average cost. The need for a method to determine the optimal tool maintenance policy has become increasingly important. Since the multiple tools in a multi-station machining system generally have significant interactive impacts on the product quality loss, the optimal multi-component maintenance models for several policies are investigated to address the interdependence among these tools. Three distinctive multi-component maintenance policies, i.e., age replacement, block replacement, and block replacement with minimal repair, are identified and analyzed. The proposed approach focuses on these maintenance policies with consideration of both component catastrophic failures, and the interdependence of component degradations on the product quality loss as well as the obsolescence cost. The effects of various maintenance policies on the system performance are simulated, and they are used to determine the best policy for a given system. An illustrative example is used to demonstrate effectiveness and applicability of the proposed approach. The results presented a comparative analysis of specified maintenance policies with respect to the total maintenance cost with consideration of the product quality loss and the obsolescence cost.

1. Introduction

In most industrial processes, the machine tool reliability plays a major role in manufacturing product with a high quality. Tool related costs contribute to a significant portion of the expense of producing parts. Furthermore, increased worldwide competitions, continuous advancement in the manufacturing technologies have all amplified the importance of tool management. Typically, a plenty of tool components are involved in the manufacturing process. Therefore, a proper tool management policy is highly demanded to improve the product quality and reduce overall production costs. One imperative aspect of the tool management is the tool maintenance or tool replacement policy.

Multi-component maintenance is intensively studied in recent literature, various maintenance policies and related models have been investigated [1–4]. The use of mathematical modeling for the purpose of maintenance planning and optimization has also received growing attention. Many of these models have considered the economic dependency among the components, and have further pointed out that an opportunity existed for group replacement on several components, provided that a joint replacement cost of several components is less than that of the separate replacements of individual ones. Group maintenance policies based on the number of failed components were rigorously studied [5–7]. Lam and Yeh [8] investigated the optimal maintenance policies for a deteriorating system. However, few of these models have captured cost related to the joint tool degradation and the quality loss. The degradation costs of the tools are either ignored, or separately assigned to each component. This makes the tool maintenance policy intricate and hard to be implemented in industry.

The research on preventive maintenance (PM) and minimal repair for machines or tools to maintain system reliability has also been prevalent [9,10]. Often used to improve the system condition before it fails, conventional PM policy assumes that the system after each intervention is restored to be ‘as-good-as-new’. The best policy has to be selected for a given system with respect to its failure, repair, and maintenance characteristics. Mathematical sophistication of maintenance models has increased with the growth in the system complexity. Extensive research has been published in the areas of maintenance modeling, optimization, and management, while less can be found on maintenance related issues of multi-station machining systems. Alternatively, a minimal repair restores the function of the system in such a way that

* Corresponding author. Tel.: +86 21 5474 8442.
E-mail addresses: jwsun@sjtu.edu.cn, stewensun@yahoo.com.cn (S. Ji-wen).

0736-5845/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rcim.2009.07.005

its failure rate remains as it was just before the failure occurrence, as is often called 'as-bad-as-old'. This seems plausible for the failure behavior of the system when one of its many non-dominating tools is replaced by a new one.

The tool maintenance studies should be coupled with economic analysis aiming at reducing the associated costs of downtime, replacement and repair. This entails evaluating and trading off conflicting objectives of operational performance and cost. In this way, a new methodology is developed with consideration of the following characteristics:

(1) two different types of failures, namely the degradation due to drifts, and the catastrophic failures due to random shocks;
(2) joint and interactive effects of multiple tools on the product quality loss;
(3) easy-to-implement maintenance/replacement polices; and
(4) obsolescence cost due to technologic innovation.

To the best of the authors' knowledge, no existing maintenance model concurrently captures these characteristics, which has not yet been sufficiently explored and exploited. In this research, a systematical methodology is proposed for the multi-station discrete manufacturing process to minimize the overall production costs, including the maintenance costs, the product quality loss, and the obsolescence cost. The remainder of the paper is organized as follows: the related cost due to the product quality loss and the obsolescence are presented in Section 2. Various multi-component maintenance policies incorporating the relevant cost issues are investigated in Section 3. An example is provided in Section 4 and is used to demonstrate the developed methodology. Finally in Section 5, some concluding remarks and future directions are offered.

2. Related costs for tool maintenance

Despite the corrective maintenance (CM) and PM costs, some other related costs should also be included, such as the cost due to the dimensional deviation of the workpiece as the product quality loss, and the cost of obsolescence due to the technologic innovation. In this section, the costs of CM and PM are omitted, hereafter mainly the cost of quality loss and obsolescence will be discussed. These issues are formalized in a quantifiable manner, which aim to examine how these cost constraints play fundamental roles in the selection of maintenance policies, and the optimality determination of a specific maintenance policy.

2.1. Quality loss

It has been suggested that a close interdependence exists between tool maintenance and product quality. Despite this obvious interdependence, a formal relationship between maintenance and quality has neither been proposed nor investigated. Therefore, the quality loss due to poor quality product manufactured by associated tools will be discussed. Firstly, a concept of manufacturing system component (MSC) is introduced in terms of multi-component maintenance, and it is defined as a specific physical part in the manufacturing process. The MSC is generally used to conduct specific operation, such as to cut, drill, shape, form, locate, or hold the workpiece. Examples for the MSCs are the cutting or drilling tools in a machining process and the locating pins in an assembly process. The functionality of each MSC is described by the MSC state, and the MSC state is continuously altering with the time and working conditions, which is different in comparison to the binary states notation in the traditional reliability theory [11]. In order to simplify the modeling process, hereafter the tool components which have relatively critical impacts on the system reliability are represented by the MSC and both can be interchangeably used.

Most traditional maintenance policies are focused on the direct downtime or the performance loss of each tool. The impact of the MSC state on the product quality in a manufacturing process is not well addressed in existing maintenance models. The degradation of a certain MSC from its designed nominal value may significantly deteriorate the product quality, which incurred a product quality loss later. The degraded states of MSCs can be set back to their predetermined nominal values during the manufacturing process through calibration and readjustment, repairing, or simply through the replacement of the corresponding ones. Properly maintaining the states associated with MSCs is crucial in the product quality assurance and the system productivity. Product quality in a machining process is usually measured by the dimensional deviations of its critical features, i.e., key product characteristic (KPC). Therefore, the related cost of quality loss can be expressed by the Taguchi quality loss function [12] or quadratic loss function (QLF) as follows,

$$L(Y) = K(Y - Y_0)^2 \tag{1}$$

where $L(Y)$ represents the quadratic loss function of the KPC Y, the constant Y_0 denotes the target value for Y, and the positive constant K is determined by the financial consideration of the manufacturing process. By taking expectation of Eq. (1), the quality loss can be expressed as

$$E[L(Y)] = K[Var[Y] + (E(Y) - Y_0)^2] \tag{2}$$

where $E[\cdot]$ and $Var[\cdot]$ are the expectation and variance, respectively.

Let n be the total number of the MSC in a manufacturing process, the ith degraded MSC is measured by the MSC state X_i, $i = 1, 2, \ldots, n$. Let μ and $w(\tau)$ denote the mean and variance of the degradation rate of MSCs, $\mu = [\mu_1 \mu_2 \ldots \mu_n]^T$. As lots of degradation processes exhibit changes with linear trends, the degradation of the ith MSC over time, or the MSC state is given by

$$X_i(\tau_i) = X_i(0) + \mu_i \tau_i + w_i(\tau_i) \tag{3}$$

where τ_i is the age of the ith MSC or the time elapsed since its last replacement, μ_i and $w_i(\tau_i)$ are known constant and uncertainty of the degradation rate of the related MSC, which capture the uncertainty of the mean shift parameter, and the random change of the working environment. $w_i(\tau_i)$ is assumed to follow a zero-mean normal distribution, that is $w_i(\tau_i) \sim N(0, \sigma_i^2 \tau_i)$, where σ_i^2 is the variance of $w_i(\tau_i)$. Hence,

$$E[X_i(\tau_i)] = E[X_i(0)] + \mu_i \tau_i \tag{4a}$$

$$Var[X_i(\tau_i)] = Var[X_i(0)] + \sigma_i^2 \tau_i \tag{4b}$$

In order to quantify the impacts of the MSCs on the product quality, an interaction model is formulated as:

$$Y(\tau) = \alpha^T X(\tau) + \beta^T z + X(\tau)^T \Gamma z + \eta + \varepsilon \tag{5}$$

where $Y(\tau)$ is the KPC's deviation dependant upon the age of a certain MSC, and τ is the age of the MSC or the time elapsed since its replacement; $X(\tau)$ denotes the set for the states of all the MSCs, i.e., $X(\tau) = [X_1(\tau) X_2(\tau) \ldots X_n(\tau)]^T$; z is the noise with zero mean and a covariance of $Cov(z)$; $\alpha \in \Re^n$, $\beta \in \Re^m$, and $\Gamma \in \Re^{n \times m}$ are known coefficients; η is a constant and $\varepsilon \sim N(0, \sigma_\varepsilon^2)$ is the unmodeled noise. Therefore, given the MSC state $X(\tau)$, the expectation and variance of $Y(\tau)$ can be obtained from Eq. (5) as

$$E(Y(\tau)|X(\tau)) = \alpha^T X(\tau) + \eta \tag{6a}$$