European Journal of Operational Research 000 (2015) 1–9

Contents lists available at ScienceDirect

European Journal of Operational Research

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

Production, Manufacturing and Logistics

A multistage and multiple response optimization approach for serial manufacturing system

Sasadhar Bera[a,*], Indrajit Mukherjee[b]

[a] Indian Institute of Management (IIM) Ranchi, Jharkhand 834008, India
[b] Shailesh J. Mehta School of Management, Indian Institute of Technology, Bombay 400076, India

ARTICLE INFO

Article history:
Received 14 September 2014
Accepted 7 July 2015
Available online xxx

Keywords:
Manufacturing
Multistage serial system
Multiple response optimization (MRO)
Desirability function
Ant Colony Optimization

ABSTRACT

A serial manufacturing system generally consists of multiple and different dedicated processing stages that are aligned sequentially to produce a specific end product. In such a system, the intermediate and end product quality generally varies due to setting of in-process variables at a specific stage and also due to interdependency between the stages. In addition, the output quality at each individual stage may be judged by multiple correlated end product characteristics (so-called 'multiple responses'). Thus, achieving the optimal product quality, considering the setting conditions at multiple stages with multiple correlated responses at individual stage is a critical and difficult task for practitioners. The solution to such a problem necessitates building data driven empirical response function(s) at individual stage. These response function(s) may be nonlinear and multimodal in nature. Although extensive research works are reported for single-stage multiple response optimization (MRO) problems, there exist little evidence on work addressing multistage MRO problem with more than two sequential stages. This paper attempts to develop an efficient and simplified solution approach for a typical serial multistage MRO problem. The proposed approach integrates a modified desirability function and an ant colony-based metaheuristic search strategy to determine the best process setting conditions in serial multistage system. Usefulness of the approach is verified by using a real life case on serial multistage rolled aluminum sheet manufacturing process.

1. Introduction

Any product that is delivered to a customer (external or internal) is evaluated by considering multiple quality characteristics or responses. These responses are often referred to as critical-to-quality (CTQ) characteristics, and are measured in different measuring scales. The primary goal of any process improvement initiative is to determine the best process operating conditions that simultaneously optimize the desired multiple responses. The optimal condition for individual response rarely results in an overall best condition for multiple responses. The simultaneous optimization of correlated multiple responses is generally referred to as 'multiple response optimization' (MRO) (Khuri, 1996). The objective of a MRO problem is to determine the best feasible process setting conditions that leads to individual response closer to its target (nominal) value with minimal variability. These responses may have linear or nonlinear interaction(s), which essentially calls for compromise (trade-off) solution(s). Extensive research works are reported on single stage MRO problems. The primary strategy used by various researchers (Awad & Kovach, 2011; Derringer & Suich, 1980; Gomes, Paiva, Costa, Balestrassi, & Paiva, 2013; Khuri & Conlon, 1981; Pignatiello, 1993; Plante, 2001; Tong, Wang, & Chen, 2005) is to solve a MRO problem by reducing the problem dimensionality. These strategies basically convert the MRO problem into a single objective optimization problem by suitable mathematical transformation function(s).

In the context of multistage MRO problems, multiple and different stages required to produce a product are considered simultaneously to determine the best processing condition. A mass manufacturing process generally consist of multiple stages or multistage process (Shi & Zhou, 2009; Yao & Gao, 2009). In a multistage process, each intermediate or final stage may have several response characteristics of interest. Response(s) or response characteristic(s) at the final stage are primarily influenced by stage operating conditions. They are also dependent on various input conditions and response characteristics of previous stage(s). In other words, any intermediate stage input conditions and response characteristic(s) can significantly influence the final stage product quality characteristics (Tagaras & Lee, 1996; Williams & Peters, 1989). Thus, it is assumed that the process

---

[*] Corresponding author. Tel.: +91 651 2280083; fax: +91 651 2280940.
E-mail addresses: sbera@iimranchi.ac.in, sasadhar_bera@rediffmail.com (S. Bera), indrajitmukherjee@iitb.ac.in (I. Mukherjee).

http://dx.doi.org/10.1016/j.ejor.2015.07.018

Please cite this article as: S. Bera, I. Mukherjee, A multistage and multiple response optimization approach for serial manufacturing system, European Journal of Operational Research (2015), http://dx.doi.org/10.1016/j.ejor.2015.07.018

performance at intermediate stage(s) has an influence (direct or indirect) on the final product quality (Zantek, Wright, & Plante, 2002). In addition, any deviation from the specified target value(s) of a response(s) in the intermediate stage may also directly or indirectly influence the response characteristic(s) of the subsequent stages. This results in interdependency between stages in a multistage manufacturing situation. It is to be noted that the response characteristics at the final stage of a multistage manufacturing process defines the end product quality characteristics.

For a multistage MRO problem, sequential or isolated optimization of each stage response characteristics may not lead to final stage optimal solution. This is primarily due to interdependency that exists between various stages and also because of correlated nature of response characteristics. This calls for two major considerations in solving a multistage MRO problem. First, the stage-wise empirical process modeling approach must consider within stage input variables and also the relevant input variable(s) or response(s) from any other previous stage(s). Second, the optimization approach must simultaneously optimize the product quality characteristics and determine the overall best setting conditions for all the stages.

In this paper, optimizing the final stage multiple responses (i.e. product quality characteristics) in a multistage manufacturing system is basically referred to as a multistage multiple response optimization (MMRO) problem. The dimensionality of the input space of a MMRO problem is always considered higher than a single stage MRO problem. The response variables at various stages of a MMRO problem can be correlated and constrained. Thus, the mathematical formulation of a MMRO problem must consider stage constraint(s) with correlated nature of responses. Thus the complexity of a MMRO problem is much higher than a typical single stage MRO problem. The problem complexity also varies depending on a number of constraint conditions and number of independent and dependent variables that exist for a specific problem. In addition, the response space generated by objective function may be highly nonlinear and multimodal by nature. There are also possibilities of several disjoint feasible operating regions, which results in multiple local optima in the response space (Carlyle, Montgomery, & Runger, 2000). There is no guarantee that any single optimization strategy will always reach the global optimal point. In addition, finding the global best solution and implementing that optimal solution may not be also economical or practically feasible. Thus, it is always necessary to suggest best possible near-optimal solution(s) considering both the feasibility and sensitivity from a set of given solutions. It is worth mentioning that the near-optimal solution(s) are not exact optimal. However, it generally provides better solution(s) than existing for complex multidimensional response optimization problem.

A solution approach that considers interrelationship among stages, handles the correlation among the response characteristics, determines the feasibility and sensitivity of a solution seems to be lacking for a MMRO problem. In addition, there is little evidence of research articles dedicated to address a complex MMRO problem from the quality engineering perspective. In view of the given lacunae, a simplified solution approach focusing on mathematical formulation and optimization of MMRO problem is proposed in this paper. The proposed approach mathematically defines an objective function and its associated constraints using modified desirability functions and an adaptive penalty-based maximin desirability index function. The ant colony-based metaheuristic search strategy is selected as an optimization technique to determine the best setting conditions for a constrained MMRO problem. The overall objective of this paper is to verify a comprehensive and simplified solution approach for a MMRO problem in specific manufacturing process configuration. The adoptability of the approach is confirmed based on a real life multistage manufacturing case.

This paper is organized as follows. Section 2 provides related study on MMRO problem in a concise manner. Section 3 discusses various multistage process configurations, proposed problem formulation and optimization search strategy. Section 4 presents a multistage industrial case to verify the effectiveness of the MMRO solution approach. The conclusion follows in Section 5 citing possible avenues of future research directions in this field of study.

2. Related studies

The existing literature on multistage manufacturing process can be classified into two broad categories, viz. controlling and monitoring the multistage process, and quality oriented design optimization (Shi & Zhou, 2009). The literature related to quality oriented design optimization can be further classified into two sub categories. The first sub category is related to quality inspected strategy. The second sub category is related to the process parameter design and optimization. The goal of process parameter design and optimization is to determine the best process operating conditions so as to produce high quality product. The research papers that specifically focus on multistage process parameter design and optimization are discussed below.

From the perspective of control, Niaki and Davoodi (2009) designed a multivariate multistage scheme to monitor and diagnose the possible causes of out-of-control signals. Their approach considers several autocorrelated stages and several correlated quality characteristics within a particular stage. First order Multivariate Autoregressive Model (MAR) is developed from multistage process data to incorporate correlation and autocorrelations within the stage and between the stages, respectively. Artificial neural network model is used to control and classify the magnitude of mean shifts from the MAR generated observations. The proposed approach is a process control scheme for multistage multiple response problem rather than an optimization approach.

From the perspective of optimization, Jin and Shi (1999) develop a stage indexed state space model to incorporate each stage error variance in multistage systems with multiple responses. The state space model has a linear structure and considers variance propagation due to deviations from the targets. The proposed model provides useful insight on sources of variation affecting the product quality. Some other relevant literature in the context of variance propagation for multi stations discrete parts manufacturing processes (e.g. rigid-part assembly and compliant-part assembly) are discussed by Zhou, Huang, and Shi (2003) and Liu, Shi, and Hu (2009). The existing research related to stage indexed state space model mostly focuses on discrete parts manufacturing processes. However, these models do not consider nonlinear relationship(s) between the input and response variables (Shi & Zhou, 2009).

Zantek et al. (2002) propose a systematic approach to measure the impact of previous stage variability on the subsequent stage(s) and also on final stage product quality in a correlated multistage manufacturing scenario. They also determine the amount of investment required for process quality improvement at each stage. The simultaneous equation model and least square estimation method are used to estimate model parameters and variance components. They have studied the deviation from target at each stage and developed a model to study the impact of such variation on the final stage product quality characteristics. Their propose approach identifies the sources of variation in product quality rather than process parameter optimization in different stages.

Bowling, Khasawneh, Kaewkuekool, and Cho (2004) determine an optimal process target levels by employing Markovian properties in order to maximize the expected profit associated with a multi-stage serial production system. The lower and upper specification limits were considered to be given for each stage, and it is assumed that each quality characteristic is governed by a normal distribution. In addition, 100 percent inspection is needed along with expected relevant cost information (e.g. scrap, and rework) to optimize the expected

Please cite this article as: S. Bera, I. Mukherjee, A multistage and multiple response optimization approach for serial manufacturing system, European Journal of Operational Research (2015), http://dx.doi.org/10.1016/j.ejor.2015.07.018