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A hybrid intelligent optimization approach to improving quality for serial multistage and multi-response coal preparation production systems

Xianhui Yin[a], Zhen He[a,*], Zhanwen Niu[a], Zhaojun (Steven) Li[b]

[a] College of Management & Economics, Tianjin University, No. 92 Weijin Rd., Nankai District, Tianjin, 300072, China
[b] Department of Industrial Engineering and Engineering Management, Western New England University, 1215 Wilbraham Rd., Springfield, MA, 01119, USA

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ABSTRACT

Modeling and optimization of multiple quality response characteristics (i.e., ash content and calorific value) has been a very important issue that can assure the quality conformance and stability for coal preparation system with multiple operating stages. Although extensive research works have been reported on multistage and multiple responses optimization problem, the traditional physical based model and statistical cause-effect model reaches its limits due to the fast increasing complexity, nonlinearity and high-dimensionality of modern coal preparation system. In addition, these conventional modeling and optimization methods have poor self-adaption and self-learning ability to different operation conditions. Internet-of-things and cyber manufacturing techniques make it convenient to collect larger volumes of sensor data that can provide powerful support for efficient data analytics. The combination of massive industrial data, advanced machine learning models and intelligent optimization algorithms bring new opportunities to deal with these problems. Therefore, this paper attempts to propose a hybrid intelligent technique based multistage and multi-response optimization approach for serial coal preparation system. Firstly, using the support vector regression theory, we construct a mechanism-data hybrid driven and forward-iteration model to reflect the change and propagation mechanism of quality response characteristics along the stage. Secondly, combining with the constructed response models and modified desirability function, the genetic algorithm based backward-iteration optimization search method is presented to determine the globally best processing setting conditions. A real life case study is used to verify the usefulness of proposed approach. Additionally, the performance of surrogate models based on different propagation modeling mode, kernel parameter optimization methods and modeling techniques are comprised and discussed. The results show the effectiveness and superiority of proposed approach.

1. Introduction

Coal preparation is a process that uses mechanical processing technology or chemical treatment methods to remove harmful impurities in raw coal, recycle associated minerals and improve the quality of coal to provide qualified coal products (e.g., clean coal) for different customers. The harmful impurities in raw coal mainly consist of ash, sulfur, moisture, phosphorus and other minerals. Therefore, there exist multiple response characteristics to measure the quality of end product, e.g., ash content and calorific value. In addition, the quality characteristic of coal product is not step-response. They need multiple processing stages to gradually achieve the desired output quality. The primary goal of quality improvement initiative is to determine the global best process operating conditions that simultaneously optimize the multiple desired quality response characteristics.

The traditional quality control methods for coal preparation are quality inspection and empirical adjustment [1]. Firstly, some samples from intermediate and final product are extracted at fixed time and location. Then, these samples are tested and analyzed according to related technical standards. The result of test is used as a reference to assist experienced technicians to adjust corresponding operating settings. These methods are passive ways to optimize quality.

With the advent of modern coal preparation technology, the ability of quality control for coal preparation product has significantly been improved [2]. Especially for some core machines or production stages, the control precision of quality is very high. However, the whole system generally has poor self-adaption and self-learning ability, which causes instability of output quality. In addition, the failure mechanism of production system has become more complex with increasing complexity. Therefore, the related prior knowledge acquisition and corresponding control have become more difficult for technicians. This led to that the coal preparation plants with same technology and equipment

* Corresponding author.
E-mail address: zhhe@tju.edu.cn (Z. He).

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have different quality control ability due to the different efficiency of experience-based knowledge generation and utilization [3]. In order to systemically and efficiently control operation state of production system, many coal preparation plants have installed Manufacturing Execution System (MES). However, the system executes related operation according to stored knowledge and instructions. They cannot actively acquire dynamic knowledge (i.e., process operating conditions) by status assessment and decision-making optimization under different activities, environment and data conditions. Therefore, these control measurements based on MES do not have self-learning and self-adaption ability. Although there is little self-learning and self-adaption ability, the MES has collected and produced large volumes of operational data due to embedded online measure devices. Therefore, there are some studies trying to use data driven Statistical Process Control and pattern recognition technique to effectively monitor abnormal quality characteristics [4,5]. But these approaches can only be used to detect out-of-control signals but do not directly determine the optimum process setting conditions based on desired output quality. Because the output quality at each individual stage may be judged by multiple correlated quality responses, the optimal condition for individual response may not lead to global solution. The simultaneous optimization of correlated multiple responses is generally referred as 'Multiple Response Optimization' (MRO). Although extensive research works have been reported on single stage multi-response optimization problem [6–12], methodologies on Multistage and Multiple Response Optimization (MMRO) problem are quite limited. In the context of MMRO, the interrelation between neighboring stages and conflict among multiple responses optimization at any particular individual stage need to be considered simultaneously to determine the optimal process setting conditions [13,14]. This calls for two important issues in MMRO problem, viz., response function modeling and goal-oriented optimization. For the response function, the dimensionality of the input space of MMRO problem is always considered higher than a single MRO problem. In addition, the response space generated by response function may be highly nonlinear and multimodal. For goal-oriented optimization, the response variables at various stages can be correlated and constrained. Moreover, there are also possibilities of several disjoint feasible operating regions due to the non-convexity of objective function, which results in local optima in response space [15]. There is no guarantee that any single optimization strategy will always reach the global optimal point. Thus, it is always necessary to suggest best possible near-optimal solutions. It is worth mentioning that the near-optimal solutions are not exactly optimal. However, it generally provides better solutions than existing for complex high-dimensionality and high-nonlinearity response optimization problem. It can be seen that traditional quality control and MRO approach reaches its limits due to the fast increasing complexity of modern manufacturing systems (i.e., interrelation between neighboring stages, multiple response optimization, high-dimensionality, high-nonlinearity and non-convexity). There is a need to propose a new approach that is able to cope with this complexity and have self-learning and self-adaption ability. Rapid development of Internet-of-Things (IoT) as well as cyber manufacturing techniques is changing modern manufacturing industry dramatically [16–21]. Massive industrial data are generated from sensors in cyber manufacturing environment. In addition, advances in Artificial Intelligence based big data analytics methodologies are creating new research opportunities for MMRO problem, especially machine learning and heuristic algorithm. The intelligent computing based modeling and optimization methods have been verified having superior performance over conventional methods in dimensional and highly nonlinear modeling, complex constrains programming and non-convexity function optimization.

To address the issues of multistage and multiple response optimization problem for coal preparation system, this paper proposes a support vector regression and genetic algorithm based integrated approach. The hybrid intelligent optimization approach consists of two modules. In the first module, the support vector regression based model is adopted to build the response function between in-process variables and response(s) characteristic(s) at each individual stage. Then, the forward iterative strategy is presented to establish the interrelation between neighboring stages by propagation of response characteristics. In the second module, the objective function combing with surrogate model, composited desirability and adaptive penalty function is formulated. And genetic algorithm based search strategy is selected to determine the global optimal operating conditions with constrains from within stage input variables and relevant response variables form previous stage from final stage to initial stage. The proposed approach could construct model the precise and complex interrelation between inputs and outputs by SVR-based model using learning and training real-time data. And the constructed model can be updated with the collection of real-time data which could reflect the status of manufacturing systems. Additionally, the optimal kernel parameters of the model and operating parameters also could be determined by intelligent search algorithm, which could give timely guidance for production control. Thus, the proposed hybrid approach has self-learning and self-adaption ability to some extent. The overall objective of this paper is to verify a hybrid intelligent optimization approach for multiple quality responses optimization problem in serial multistage coal preparation system. The adoptability and usefulness of proposed approach is verified based on a real life multistage and multi-response coal preparation case.

The remainder of this paper is organized as follows. Section 2 provides related studies on quality management of coal preparation and MMRO problem in a concise manner. Section 3 discusses the characteristics of the modern coal preparation system and corresponding problem formulation. The specific methodology for modeling and optimization is proposed. Section 4 presents a numerical example to verify the effectiveness of proposed approach. This section also discusses the impacts on model accuracy caused by various different modeling idea and optimization methods of the kernel parameter. The conclusion in Section 5 proposes possible avenues of future research directions in this field of study.

2. Literature review

The existing literatures focusing on quality improvement of coal preparation can be classified into two categories, viz. developing coal preparation technology and process quality control. The technology and equipment advancement is a way to improve the quality and efficiency of coal preparation based on physical theory [2,22]. The studies in the literature focused on process quality control are discussed as follows.

Process quality control is a method based on statistical process control technique or data analytics and modeling methods to detect the abnormal quality characteristics or optimize the process operating parameters. Fu et al. [4] proposed a modified Shewhart control chart to monitor the quality deviation. Zhang et al. [5,23] studied the image analysis based pattern recognition and intelligent gray prediction method to recognize the unnatural and they found that the application of intelligent approaches can be more accurate and effective than the traditional monitoring and forecasting methods. The available methods on operation parameter optimization mainly focus on the parameter-oriented design for single production stage or machine based on lower-order regression or mechanism driven models [24–27]. However, the optimal performance on single production stage (local optimum) may not lead to the global optimum of whole system due to the auto-correlation between stages. In addition, the mechanism driven model is still an engineering knowledge "representation", rather than a mathematical model. Thus, there have been no systematic, unified methodologies to reduce the variation or optimize the output quality for serial multistage and multiple response coal preparation process.

A Multistage Manufacturing Process (MMP) is referred to as a process involving multiple stations/stages to produce a qualified product