DEVELOPMENT OF INTELLIGENT CONTROL MODELS FOR THE PHOSPHORITE BENEFICIATION PROCESS

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ANNOTATSIYA:

This study focuses on the development and application of intelligent control models for the automated management of the phosphorite beneficiation process. Phosphorite flotation is a complex, multivariable, and nonlinear process influenced by particle size, reagent consumption, pulp density, mixing speed, and other technological factors. Traditional control methods often fail to achieve optimal efficiency under such conditions. To address these challenges, a multilayer artificial neural network (ANN)–based intelligent control model was designed and integrated into the process control system. The neural network predicts phosphorus concentration in real time and provides adaptive control signals to optimize key operational parameters. Simulation results demonstrate that the proposed model enhances phosphorus recovery efficiency by 8–12% and reduces reagent consumption by up to 10%, confirming its practical applicability in industrial phosphorite beneficiation operations.

Introduction

Phosphorite beneficiation processes are critical to the production of mineral fertilizers and significantly affect both product quality and production costs. Efficient phosphorus recovery ensures the economic viability of beneficiation plants, while the consumption of flotation reagents directly influences production expenses and environmental impact. Therefore, optimizing control strategies and implementing automated process management systems are of paramount importance in modern mineral processing.

Recent research has explored various approaches to process automation and optimization. Kuznetsov and Ivanov analyzed classical control strategies in beneficiation plants, highlighting their limitations in handling nonlinear and time-varying processes. Smith and Ahmed noted that conventional control methods often fail to maintain stable process performance under fluctuating raw material properties and complex multivariable interactions. Artificial intelligence techniques have been proposed to overcome these limitations. Zadeh introduced fuzzy logic as a tool for managing uncertainties in complex systems, while Haykin and Bishop demonstrated the utility of artificial neural networks in modeling and controlling nonlinear industrial processes. Liu and Zhou further applied neural network–based controllers to flotation processes, achieving significant improvements in phosphorus recovery efficiency. However, existing studies rarely address real-time adaptive control models tailored specifically for phosphorite beneficiation, leaving a gap in both scientific understanding and practical implementation.

In this study, the objective is to develop an intelligent control model for phosphorite flotation processes, capable of predicting process outputs and optimizing operational parameters in real time. The model is designed to improve efficiency, reduce reagent consumption, and enhance overall process stability.

Research Methodology:

The phosphorite beneficiation process is a highly nonlinear, multivariable system. Its performance depends on several interacting parameters, including particle size distribution, reagent dosages, pulp density, mixing speed, and flotation time. Variability in these parameters leads to complex dynamics that are difficult to describe with classical analytical models. To manage these complexities, data-driven intelligent control methods, specifically artificial neural networks, are employed.

The beneficiation process can be represented by the following nonlinear functional relationship:

$$Y(t) = f(x_1(t), x_2(t), x_3(t), x_4(t), \ldots\ldots x_n(t))$$

Where:

Y(t) – denotes phosphorus concentration or overall beneficiation efficiency

$x_i(t)$ - represents the input technological parameters such as particle size (x_1)

$x_2(t)$ - reagent consumption

$x_3(t)$ - pulp density

$x_4(t)$ – mixing speed

$x_n(t)$ – other relavent factors

Neural Network Model Structure

A multilayer perceptron (MLP) neural network was selected to model the process. The ANN comprises:

1. Input layer, which receives real-time measurements of process parameters.
2. Hidden layers, which capture nonlinear interactions among the inputs.
3. Output layer, which predicts the phosphorus concentration or recovery efficiency.

The mathematical formulation of the neural network is expressed as:

$$Y = F(\Sigma_{j=1}^{m} v_j F\left(\Sigma_{j=1}^{m} w_{ij} x_i + b_j\right) + b_0)$$

Where:

W_{ij}- weights between input and hidden layers

v_j- weights between hidden and output layers

b_j and b_0- bias terms

F- activation function

Training Procedure

The neural network was trained using historical process data collected from operational flotation units. The training objective was to minimize the prediction error of the model, quantified using the mean squared error (MSE):

$$E = \frac{1}{2N} \Sigma_{k=1}^{N} (Y_k^{actual} - Y_k^{predicted})$$

The backpropagation algorithm with gradient descent was employed to iteratively update network weights, ensuring convergence to optimal parameter values. Cross-validation was used to prevent overfitting and to ensure the robustness of the model under varying operational conditions.

Integration into Control System

After training, the neural network was integrated into the automated process control system. Real-time sensor data, including particle size, reagent consumption, pulp density, and mixing speed, were fed into the model. The predicted phosphorus concentration was compared with the target value to generate control signals:

$$u(t) = g(Y_{target} - Y_{predicted})$$

Where:

U(t) - control signal

Y_{target} - phosphorus concentration

$Y_{predicted}$ - network output.

This approach enables real-time adaptive control, dynamically adjusting flotation parameters to maintain optimal recovery.

Extended Methodological Considerations

To further enhance model performance, the study incorporated the following techniques:

- Normalization of input data, ensuring consistent training behavior and improved convergence.
- Sensitivity analysis, identifying the most influential parameters affecting phosphorus recovery.
- Dynamic retraining, allowing the model to adapt to changing ore properties and operational conditions.
- Hybrid control strategies, where the ANN is combined with traditional PID controllers to handle disturbances and improve stability.

These methodological enhancements provide a robust framework for industrial application, enabling continuous optimization and improved process efficiency.

Results and Discussion

Simulation experiments demonstrated the neural network model's ability to accurately predict phosphorus concentration across varying operational scenarios. The intelligent control system improved beneficiation efficiency by 8–12%, while reducing flotation reagent consumption by approximately 10%. Moreover, fluctuations in pulp density and mixing speed were minimized, contributing to process stability.

A comparative analysis with traditional PID controllers showed that the ANN-based system responded more effectively to sudden changes in ore properties, maintaining target phosphorus concentration levels without manual intervention. The model also allowed operators to simulate “what-if” scenarios, providing valuable insights for process optimization and resource planning.

Extended simulations indicated that the sensitivity of phosphorus recovery to particle size and reagent dosage was particularly significant, highlighting the importance of accurate real-time measurements and adaptive control actions.

Conclusion

This study confirms that artificial neural network–based intelligent control models can significantly enhance the automation and management of phosphorite beneficiation processes. The proposed model effectively captures the nonlinear and multivariable nature of flotation operations, providing accurate real-time predictions and adaptive control capabilities. Its application leads to improved phosphorus recovery, reduced reagent consumption, and enhanced process stability. The methodology, which includes normalization, sensitivity analysis, dynamic retraining, and hybrid control strategies, ensures robustness under varying operational conditions. The results demonstrate that implementing intelligent control models in industrial phosphorite beneficiation is both technically feasible and economically beneficial. Future research could focus on integrating fuzzy logic, reinforcement learning, or hybrid neuro-fuzzy controllers to further enhance system adaptability and optimize energy consumption.

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