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Energy management and optimization modeling based on a novel fuzzy extreme learning machine: Case study of complex petrochemical industries

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ABSTRACT

Energy management and optimization play a key effect in the sustainable development. However, the uncertain data has a direct impact on the production prediction and energy optimization of complex petrochemical industries. Therefore, this paper proposes a novel energy management and optimization model based on the fuzzy extreme learning machine (FELM) method integrated the fuzzy set theory. The minimal, the median and the maximal values of the energy consumption data are obtained by data fuzzification to solve the problem of the fluctuation and uncertainty data. And the cross recombination of triangular fuzzy numbers (TFNs) is applied in the training of the FELM. Moreover, the upper and the lower limits of efficiency values are obtained on the basis of the network generalization to analyze the energy conservation and saving potentials. Furthermore, the FELM has better predictive performance and training speed than fuzzy error back propagation network (FBP) and fuzzy radical basis function network (FRBF) though University of California Irvine (UCI) standard datasets. Finally, the proposed method is applied to manage and optimize the energy status of China ethylene industry in complex petrochemical industries. The experimental results show that the proposed method is effective and applicable in the energy-saving potential, which is indicated up to about 15%.

1. Introduction

The sustainable development strategy has played an important guiding role in building a well-off society in an all-round way. However, China is a country with a large population, the shortage of natural resources and a relatively backward condition in economy and technology. Therefore, the social and economic virtuous circle can be achieved through the resource rational utilization and the environmental protection, especially complex petrochemical industries. The ethylene industry is the most crucial part of the complex petrochemical industries, in which both environmental and economic goals can be achieved by production prediction and energy management. However, in 2015, the ethylene production and the average fuel and power consumption of China Petrochemical Corporation was 11005.2 kt/a and 559.06 kg per ton of ethylene [1], respectively. And the ethylene production and the average fuel and power consumption of China National Petroleum Corporation in 2015 was 5032 kt/a and 594 kg per ton of ethylene [2], respectively. The energy efficiency of the ethylene production in China is far lower than international countries. Moreover, over 50% of operating costs in ethylene plants come from the cost of energy consumption of ethylene plants [3]. Therefore, energy management and optimization of the complex petrochemical industry can bring direct economic and environmental benefit.

In practical efficiency evaluation, there are two commonly used techniques named the mean method and the optimal index method [4]. However, these approaches can barely provide the energy efficiency benchmark of improvement factors, thus brings obstacles to the optimization decision. Meanwhile, some other drawbacks also reduce the usefulness of methods, such as the lack of predictive ability and the biased analysis caused by imprecise data.

In order to address these above issues, this paper proposes a novel fuzzy extreme learning machine (FELM) method integrated the fuzzy set theory to build the energy management and optimization model. The minimal, the median and the maximal values of the energy consumption data are obtained by data fuzzification to process the imprecise data. And then the triangular fuzzy numbers (TFNs) are integrated together with the FELM method to get the predictive production capacity and the efficiency evaluation. Though the University of California Irvine (UCI) standard datasets, the proposed method has advantages of higher forecasting accuracy, faster training speed than fuzzy error back propagation network (FBP) and fuzzy radical basis function network (FRBF), and can avoid from falling into the

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local optimum. Meanwhile, with the input and output data fuzzified in triangular form, the robustness of evaluation method can be enhanced to overcome the noise and fluctuation in the crisp data. Moreover, the experimental results in managing and optimizing the energy status of China ethylene industries show that the proposed method is effective and applicable in the energy-saving potential, which is indicated up to about 15%.

The remainder of this paper has been arranged as follows. The development of energy prediction and management based on the fuzzy-based and ANN-based methods are introduced in Section 2. Section 3 describes the FELM analysis framework in detail. The validation test of the FELM based on the UCI standard dataset is laid out in Section 4. In Section 5, we present a case study about energy prediction and optimization of the ethylene production system based on the FELM. Finally, Section 6 gives the discussion about the experiment and Section 7 provides the conclusion.

2. Related work

Energy prediction and efficiency evaluation plays an important role in energy-saving and emission reduction. In the previous studies, different indexes and methods was proposed to analyze the energy efficiency and optimize the energy configuration of complex chemistry industries. The index decomposition analysis (IDA) is a typical method to manage the energy performance. Geng et al. obtained the activity, the structure and the intensity of three energy performance indicators (EPIs) that affect the energy consumption based on the IDA method [5]. Zhou et al. discussed and analyzed the macro energy efficiency evolution method based on the IDA [6]. However, the inherent shortcoming of not taking the energy-saving knowledge into account makes it difficult for decision-makers to optimize the energy usage.

Meanwhile, the stochastic frontier analysis (SFA) is a widely used method for estimating the efficiency by using stochastic frontier production functions. Jones et al. focused on the efficiency of electricity consumption in the Portuguese productive sector using the SFA [7]. Lin et al. adopt the SFA to study the average energy efficiency and energy-saving potentials of the Chinese chemical industry based on the assumption of the trans-log production function [8]. However, because the effects of stochastic factors are taken into consideration, the parametric frontier approach of the SFA may cause the disagreement among distributional assumptions and objective circumstances.

Compared with the SFA, data envelopment analysis (DEA) is a nonparametric frontier efficiency analysis method for multi-input and multi-output systems. The DEA was applied widely in the areas of energy and environmental analyses. Sueyoshi et al. proposed an improved DEA to assess the performance of energy industries [9]. Han et al. proposed an energy efficiency evaluation method based on the Malmquist production indexes integrated the improved DEA cross model [10]. However, the efficiency discrimination of DEA will be poor when more than a third of efficiency values are set to 1 [11]. Meanwhile, the uncertain and noisy characteristic of the statistical data may result in the erroneous evaluation [12]. Therefore, with the imprecise energy consumption data, the DEA is quite sensitive to outliers and just can handle crisp input and output data.

For solving problems exposed by the above methods, this paper proposes a novel fuzzy ANN method based on the fuzzy set theory. Zadeh proposed the fuzzy set theory and described fuzziness in precise mathematical languages [13]. Coppi et al. compared two kinds of clustering models for the left and right fuzzy data by using the empirical information affected by imprecision or vagueness [14]. Xiong et al. explored the application of the fuzzy set in association rules mining [15]. Chen et al. extended previous fuzzy mining approaches to handle the time-series data and the additional experiment showed favorable results [16]. In the energy efficiency evaluation of industry sectors, Kao et al. analyzed the fuzzy input and the output to the involved independent processes for parallel production systems [17]. Han et al. proposed an efficiency analysis method based on fuzzy DEA cross model with the fuzzy data for ethylene production systems in complex chemical industries [18]. Therefore, the fuzzy set theory is effective in predicting and optimizing the energy status of complex petrochemical industries.

The ANN is an important branch of artificial intelligence, with self-adaptive, self-organizing and self-learning characteristics. Meanwhile, the ANN is a dominant data-driven model in the machine learning area and has been widely applied in modeling and predicting. The BP neural network proposed by Rumelhart and McClelland is one of the most widely used methods currently [19]. Han et al. proposed an improved DEA integrating the BP neural network method for analyze the energy efficiency of complex petrochemical industries and get satisfactory results [20]. Other applications of the ANN covered a wide range of fields including the petrochemical industries [21,22], renewable energy field [23] and pharmaceutical industries [24]. The ELM is a single-hidden layer feedforward neural network proposed by Huang et al. [25]. With respect to the classical BP neural network, the ELM is more popular for enhancing capabilities in terms of generalization and training speed. At the same time, it can avoid the local minimization problem in traditional models. Geng et al. proposed an energy optimization and analysis modeling based on the ELM focusing on complex chemical processes [26]. Naji et al. used the ELM to estimate building energy consumption [27]. In addition, the ELM was also found a wide utilization in some comprehensive problems like classification in food industry [28], modeling for the batch process [29] and wind speed forecast [30], engine control [31] and nonlinear process optimization [32]. Extensive experiments on a standard UCI dataset show that the ELM is a simple neural network learning algorithm with high training speed and generalization accuracy. However, the inevitable error and the noise bring fluctuations to complex industrial data. The direct use of the ELM to predict the products and analyze the energy status of the petrochemical industry may lead to the poor modeling performance and the low forecast accuracy. Based on the above analysis, the advantages and disadvantages among various methods are shown in Table 1. Therefore, this paper introduces the FELM by using the TFNs to improve the fault tolerance of this method. Meanwhile, the FELM method is applied to manage and optimize the energy status of China ethylene industries.

Table 1
Advantages and disadvantages among various methods.

Method	Advantages	Disadvantages
IDA	A typical and simple method	Deep factors of energy intensity change are not taken into account
SFA	The effects of stochastic factors on outputs are considered	The disagreement among distributional assumptions and objective circumstances
DEA	A nonparametric frontier efficiency analysis method for multi-input and multi-output systems	Quite sensitive to outliers, and just can handle crisp input and output data
BP	A dominant data-driven method and fast modeling	May lead to the local minimization problem
ELM	Enhancing capabilities in terms of generalization and training speed, and can avoid the local minimization problem better	May lead to the poor modeling performance and the low forecast accuracy