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The modeling and prediction of time series based on synergy of high-order fuzzy cognitive map and fuzzy c-means clustering

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ABSTRACT

The time series prediction models based on fuzzy set theory have been widely applied to diverse fields such as enrollments, stocks, weather and etc., as they can handle prediction problem under uncertain circumstances in which data are incomplete or vague. Researchers have presented diverse approaches to support the development of fuzzy time series prediction models. While the existing approaches exhibit two evident shortcomings: one is that they have low efficiency of development, which is hardly applicable in the prediction problem involving large-scale time series, and the other is that fuzzy logical relationships mined in an ad hoc way cannot uncover the global characteristics of time series, which reduces accuracy of the resulting model. In this paper, a novel modeling and prediction approach of time series based on synergy of high-order fuzzy cognitive map (HFCM) and fuzzy c-means clustering is proposed, in which fuzzy c-means clustering algorithm is used to construct information granules, transform original time series into granular time series and generate a structure of HFCM prediction model in an automatic fashion. Subsequently depending on historical data of time series, the HFCM prediction model of time series is completely formed by exploiting PSO algorithm to learn all parameters of one. Finally, the developed HFCM prediction model can realize numeric prediction by performing inference in the granular space. Four benchmark time series data sets with different statistical characteristics coming from different areas are applied to validate the feasibility and effectiveness of the proposed modeling approach. The obtained results clearly show the effectiveness of the approach. The developed HFCM prediction models depend on historical data of time series and is emerged in the form of map, which is simpler, legible and have high-level interpretability. Additionally, the proposed approach also exhibits a clear ability to handle the prediction problem of large-scale time series.

1. Introduction

A sequence of L observed data, say $\mathbf{x} = \{x(t)\}, t = 1, 2, \ldots, L$, ordered in time, is called a time series, where time may be replaced by any other variable of some physical meaning. Time series prediction is a classic issue, in which it plays an essential role how to construct prediction model of time series. As a description of some useful temporal relationship, the prediction model of time series can be developed by observing a past certain variable or a past family of variables and used to extrapolate future values of time series. Several alternatives studied in the past included linear system theory [15], stochastic process theory [24], black-box methodology [14] and dynamical system analysis [16] to develop many classical prediction models of time series such as ARMA, ARIMA, ANN (artificial neural network) model, hybrid ARIMA model [43,20,39,19,45] and alike. These models have widely used in many fields such as predicting stock index, temperature and so on, showing better prediction performance. Whereas these models cannot solve prediction problems under uncertain circumstances in which data are incomplete or vague. In addition, the models are difficult to interpret. Fuzzy set theory can be used to make semantics and represent the data themselves, and facilitate fuzzy reasoning offering a viable alternative to ensure robustness of the prediction models.

In the framework of fuzzy sets theory, the concept of fuzzy time series [35] was first proposed by Song and Chissom to handle prediction problem in which the historical data come in the form of linguistic values. They also proposed a detailed approach to modeling of time series. The development of the model comprises four

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steps as follows: (1) defining and partitioning the universe of discourse; (2) defining fuzzy sets in the universe of discourse and fuzzifying time series; (3) mining fuzzy logical relationships from the fuzzied time series; and (4) performing prediction and defuzzifying of predicted outputs. Based on these four steps, Song and Chissom developed two models of time series — the time-invariant model [34] and the time-variant model [36] to predict the enrollments of the University of Alabama.

In the above-mentioned four steps, step (3) and step (4) exhibit an important impact on the efficiency of development of model and the accuracy of model itself. The time-invariant model [34] applied max–min operations to derive fuzzy logical relationships among adjacent numeric points of time series, while the time-variant model [36] applied min–max operations. Both max–min and min–max operations come with some computing overhead to establish fuzzy relationships so that the efficiency of modeling of time series is reduced, specifically when time series is large-scale. Besides, the defuzzification of prediction outputs in both models also required numerous calculations. In order to reduce the computational overhead and improve the accuracy of these two models, researchers have presented a number improved methods mainly focused on step (3) and step (4). Sullivan and Woodall [39] established a first-order time-invariant time series model based on the Markov model with linguistic labels for probability distributions. Chen [3] proposed a simplified time-invariant model by using simple arithmetic operations to replace the max–min operations in the process of mining fuzzy relationships and performing prediction. Further, Chen applied the simplified model to predict the enrollments of University of Alabama and obtained higher prediction accuracy rate. Huarng and Yu proposed a type-2 fuzzy time series model, in which extra data are used to enrich or to refine the fuzzy relationships obtained from type 1 models (i.e. conventional fuzzy time series models such as Song's model [34], Chen's model [3]) and for improving forecasting performance. Aladag et al. [1] use a feed forward neural network to describe fuzzy logical relationships and realize inference for predicting high-order fuzzy time series. Egrioglu et al. [7] introduced a hybrid time series model to improve prediction accuracy by integrating fuzzy c-means clustering algorithm and artificial neural networks. In their model, fuzzy c-means clustering method and artificial neural networks are employed for fuzzification and defining fuzzy logical relationships, respectively. Singh and Borah [31] presented a model based on hybridization of high-order fuzzy time series model with artificial neural network (ANN) to improve accuracy of prediction. Chen and Kao [4] also proposed a hybrid model based on the use of particle swarm optimization techniques and support vector machines to forecast stock index, in which the particle swarm optimization techniques are used to form optimal intervals in the universe of discourse while the support vector machine is used to convert the forecasting problem into the classification problem. The model is applied to predict stock index and obtain better prediction results.

An evident limitation of all the previously mentioned fuzzy time series models is that they have low efficiency of the development process, i.e. they rely on an ad hoc approach to mine fuzzy logical relationships among adjacent data points of time series and apply rules or intensive computing to perform inference, which is difficult to be applied to handle is large-scale time series. Furthermore, fuzzy logical relationships generated by ad hoc approach can only reveal the local characteristic of time series, but they will not reflect the holistic change trends of time series—a lack of this feature can reduce the prediction accuracy of model to some extent. Thus, it becomes interesting and legitimate develop a new model with higher accuracy to realize prediction of time series in a more efficient manner.

As a soft computing technology, fuzzy cognitive map (FCM) was proposed by Kosko [18], which is treated as an alternative way for knowledge-based representation and inference process for its easy of usage and numeric matrix operation for complex system. In virtue this nature of FCM, it can become an available alternative for modeling and prediction of time series. The literature [23,38,22] showed applications of fuzzy cognitive maps to a range of quite diverse fields. With regard to the processing of long-scale time series, information granulation seems to be more suitable. Just recently, some related researches are reported [6]. Information granulation as an important abstraction mechanism enables us to focus on essential features and ignore irrelevant and sometimes confusing details present in data [28]. The role of information granulation is to structure detailed numerical data (points) into some meaningful, semantically sound entities (information granules). In particular, we granulate information to achieve a high level of interpretability and manage phenomena which are complex and consequently the amount of data become overwhelming. Information granules formed by information granulation can be expressed in the formalism of sets (interval analysis), rough sets, fuzzy sets, shadowed sets or alike. As a representative examples of information granules, fuzzy information granule do use fuzzy sets to express abstract granules in essentially. Zadeh [43] presented a general term capturing the essence of fuzzy sets viewed as examples of information granules:

$$g = (x \text{ is } G) \text{ is } \lambda$$

where x is a variable of a universe of discourse U, G is a convex fuzzy subset of U, and λ is the probability of x belonging to the subset G. Fuzzy information granules can be constructed in many different ways [27] in which fuzzy c-means clustering is the most commonly used method, which provide an ability of constructing fuzzy granules from data with multivariate attribute.

In this study, we assume a global view at temporal data and intend to reveal and describe some meaningful temporal relationships at the level of information granules. Bearing in mind this idea, a new modeling and prediction approach of time series based on synergy of high-order fuzzy cognitive map and fuzzy c-means clustering is proposed. In the approach, fuzzy c-means clustering is used to develop fuzzy information granules from historical data of time series, convert original time series into granular time series (i.e. map time series data into high dimension granular space) and establish the structure of HFCM prediction model of time series, automatically. Subsequently, depending on historical data of time series, the HFCM prediction model of time series is completely formed by exploiting PSO algorithm to estimate all parameters of the model. Finally, the developed HFCM prediction model can realize numeric prediction by performing inference in the granular space. The advantages of the model of time series constructed in this way can be summarized as follows:

- We adopt fuzzy information granules as essential elements to describe fuzzy logical relationships implied in time series, which can help us to observe essential features of time series from a global perspective and make the constructed model have high-level interpretability.
- We express visually the dynamic behavior of time series in the form of map (fuzzy cognitive map), which makes the constructed model relatively simple, legible and transparent.
- Compared with the above-mentioned model-based fuzzy sets theory, the constructed model exhibits higher prediction accuracy.
- The constructed model as a hybrid model can also comparable to some classical hybrid ARIMA.
- Throughout the process of modeling and prediction, our approach is carried out automatically without a great deal of manual intervention, which can overcome the deficiency of low efficiency of development of existing fuzzy time series models and is more adaptable for modeling and prediction of large-scale time series.