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Numerical study on the feasibility of dynamic evolving neural-fuzzy inference system for approximation of compressive strength of dry-cast concrete

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ABSTRACT

This paper assesses effectiveness of dynamic evolving neural-fuzzy inference system (DENFIS) models in predicting the compressive strength of dry-cast concretes, and compares their prediction performances with those of regression, neural network (NN) and ANFIS models. The results of this study emphasized capabilities of online first-order and offline high-order Takagi–Sugeno (TSK) type DENFIS models for prediction purposes, whereas offline first-order TSK-type DENFIS models did not produce reliable results. Comparison between the produced results of an elite high-order DENFIS model with those predicted by the selected NN, regression and ANFIS models showed effectiveness of DENFIS model than the regression model, while its performance was similar to or slightly better than the other artificial prediction tools.

Introduction

Nowadays, the need for robust models which can precisely estimate properties of materials has been increased due to the requirements of design procedures. Sophisticated methods and tools are required to encounter with the complex and dynamic real-world problems in engineering and material sciences. Such methods should be designed in a flexible manner to be able to model and operate in interactive and intelligent environments. This is especially crucial in solving artificial intelligence (AI) problems such as adaptive speech and image recognition, multimodal information processing, adaptive prediction, adaptive online control, intelligent agents on the world-wide web [1,2], and modeling the materials properties [3].

Amongst different AI modeling techniques, artificial neural networks, fuzzy systems and evolutionary algorithms have been the most applicable methods. Recently, novel approaches have been proposed using hybridization of these methods. The main reason has been to take advantage of each individual technique toward improved performance, enhanced reliability, and automated architecture design. Primary hybrid systems were inspired of merging neural networks and fuzzy systems which known as neuro-fuzzy systems [4], and combination of genetic algorithms with fuzzy systems called genetic-fuzzy systems [5]. Systems composed of polynomial fuzzy systems and neural networks were proposed as FPNN [3,6]. FPNNs are the self-organizing meta rule-based systems composed of fuzzy neural networks (FNNs) and polynomial neural networks (PNNs). In these systems, while the FNN demonstrates the premises (If-Part) of the fuzzy model, the PNN is implemented as its consequence (Then-Part).

AnYa [7,8] as fuzzy systems with nonparametric antecedents was proposed as an attempt to revise and simplify the antecedent part of both Mamdani and Takagi-Sugeno fuzzy rule-based systems. In AnYa-based systems, the antecedent part, which plays a key role in learning, is traditionally either predetermined by regular partitioning or clustering or is optimized by supervised learning like error back-propagation or genetic algorithms. AnYa includes a nonparametric antecedent part of a new type which also simplifies the linguistic expression removing the need for logical “AND”, and the ambiguity related to the choice of the t-norm operator. In addition, the neural networks interpretation (which in the case of Takagi-Sugeno (TS) model is of a five-layer network) is simpler and reduces to a four-layer structure [9]. Angelov and Filev

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introduced an online identification approach for the TS model [10]. They used subtractive clustering along with a concept of potential to define the antecedent parts of the rules. In their evolving Takagi–Sugeno (ETS) learning algorithm, the rules may be replaced or increased based on what they called the 'potential' of incoming data. The parameters of consequent parts of rules are updated through recursive optimization. In fact, ETS are characterized by the continuous online learning for rule base learning [11]. Modified and extended versions of ETS approach called as ETS+ were also suggested by Angelov et al. [12,13]. The results of modeling with ETS+ demonstrated its superiority for modeling real data stream in precision, simplicity, interpretability, and computational resources used. A hierarchical on-line self-organizing learning algorithm was also proposed by Angelov to identify a TS fuzzy model [14]. The rules are generated according to the desired accuracy measured by output error and a boundary criterion. The rules may be pruned by observing an error reduction ratio criterion [14,15]. Recently a model called dynamic evolving neural fuzzy inference system (DENFIS) has been proposed in the area of AI modeling which has successfully been applied for simulation and prediction purposes [16]. This model is similar to the evolving fuzzy neural network (EFNN) model in some degree. DENFIS inherits and develops so-called EFNNs dynamic features which make it suitable for online adaptive systems [16,17].

Concrete is known as a composite construction material with very complicated behaviors. It's a truly versatile material, as it consists of a family of ingredients with a large range in color, density, strength and durability characteristics. It is not only versatile depends on its ingredients, mixture proportions, types of production, and other influencing factors, but also its properties are developed during the time. The minimum duration needed to assess concrete properties is 28 days which can be extended to several years; particularly in the case of durability properties. As such, modeling concrete properties as functions of its mixture ingredients and proportions has been recognized as an important topic for research.

Among concrete properties, compressive strength is a major mechanical property which has been used as the foremost property for estimating its quality. Compressive strength is influenced by a number of factors including concrete ingredients, mixture proportions, ratio of water-to-cementitious materials, type of production, age, and curing condition with a high degree of uncertainty. Due to its importance, it has been subjected to prediction tools for several years. Conventional methods of compressive strength prediction were mainly based on the linear and nonlinear regression methods [18–20]. It should be noted that these models were empirical ones and designed, tuned and formulated in the framework of linear or nonlinear functions like polynomials, partial polynomials and exponentials [18,21–23]. Recently, artificial intelligence-based techniques, like artificial neural networks [24–26] and so-called adaptive network-based fuzzy inference systems (ANFIS) [27–29], have successfully been applied in this area.

In light of suitable performance of DENFIS models for prediction purposes and because of the need for predictive models, this paper aims to introduce DENFIS models for approximation of the compressive strength of concrete and compare their efficiencies with those of regression, neural network and ANFIS models. As such, different DENFIS, regression, neural network and ANFIS models are used as prediction tools of the current study. The compressive strength and mixture proportions of dry-cast (no-slump) concrete are used for training and testing the models. No-slump concrete is commonly defined as concrete having slump of 0 to 25 mm [30,31] with wide applications in production of prefabricated concrete products [30] such as concrete masonry units, paving blocks, prefabricated curbs, pipes and the like [32–37].

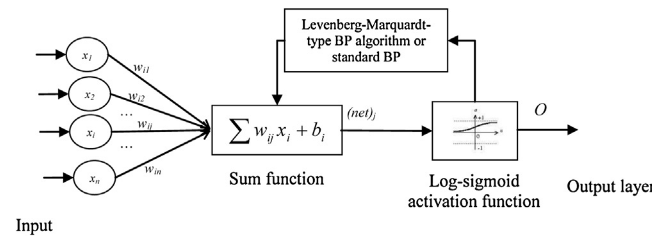

Fig. 1. Architecture of neural network.

Methods of modeling

Regression modeling

As a statistical tool for investigating relationships between independent and dependent variables, regression modeling aims to develop empirical model(s) for system identifications and experimental studies. In such systems, estimation is based on search methods and optimization process which tries to minimize the norm of a residual vector. In this paper, a general parametric regression system proposed in the form of $y = f(\beta_i \times x_i)$ where f is the model's representative function, y is the model's output or dependent variable, β_i are the parameters of the model, and x_i are the independent variables.

Artificial neural network

Artificial neural networks (ANN) are information processing structures that consist of a number of simple processing elements (PEs or "neurons") with densely parallel interconnections. Each PE can receive weighted inputs from many other PEs, and communicate its outputs, if any, to many other PEs. Information is thus represented in a distributed fashion, across the weighted interconnections.

To implement a neural network for modeling purposes, a set of input data are repeatedly presented to the network during a training session and the system learns how to simulate the target output values thought a training algorithm. There are various training algorithms available for such learning process based on back-propagation (BP) approach. Levenberg–Marquardt-type BP (LMBP) algorithm, proposed as a highly accurate algorithm in the literature, was used in this study [18].

Basic architecture of an ANN system, which utilizes the LMBP as training algorithm, is presented in Fig. 1.

Adaptive network-based fuzzy inference system (ANFIS)

ANFIS is the famous hybrid neuro-fuzzy network for modeling the complex systems [27–29]. ANFIS incorporates the human-like reasoning style of fuzzy systems through use of fuzzy sets and a linguistic model consisting of a set of If-Then fuzzy rules. The main strength of ANFIS models is that they are universal approximators [4,38] with the ability to solicit interpretable If-Then rules.

The framework of ANFIS is shown in Fig. 2. For simplicity of illustration, only two inputs (x, y) and one output f_{out} are considered in this figure.

Dynamic evolving neural-fuzzy inference system (DENFIS)

Dynamic evolving neural-fuzzy inference system (DENFIS) is a novel method which has rarely been used in modeling properties of concrete. In this regard, more details of this system are presented in the following subsections: