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A hybrid model through the fusion of type-2 fuzzy logic systems and extreme learning machines for modelling permeability prediction

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ABSTRACT

Extreme learning machines (ELM), as a learning tool, have gained popularity due to its unique characteristics and performance. However, the generalisation capability of ELM often depends on the nature of the dataset, particularly on whether uncertainty is present in the dataset or not. In order to reduce the effects of uncertainties in ELM prediction and improve its generalisation ability, this paper proposes a hybrid system through a combination of type-2 fuzzy logic systems (type-2 FLS) and ELM; thereafter the hybrid system was applied to model permeability of carbonate reservoir. Type-2 FLS has been chosen to be a precursor to ELM in order to better handle uncertainties existing in datasets beyond the capability of type-1 fuzzy logic systems. The type-2 FLS is used to first handle uncertainties in reservoir data so that its final output is then passed to the ELM for training and then final prediction is done using the unseen testing dataset. Comparative studies have been carried out to compare the performance of the proposed T2-ELM hybrid system with each of the constituent type-2 FLS and ELM, and also artificial neural network (ANN) and support Vector machines (SVM) using five different industrial reservoir data. Empirical results show that the proposed T2-ELM hybrid system outperformed each of type-2 FLS and ELM, as the two constituent models, in all cases, with the improvement made to the ELM performance far higher against that of type-2 FLS that had a closer performance to the hybrid since it is already noted for being able to model uncertainties. The proposed hybrid also outperformed ANN and SVM models considered.

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1. Introduction

Hybrid computational intelligence is defined as any effective combination of intelligent techniques that performs in a more superior or competitive way than simple standard intelligent techniques. The increased popularity of hybrid intelligent systems in recent times lies in the extensive success of these systems in solving many real-world complex problems [1]. Also, it is an established fact that every approach has its strengths and weaknesses; hence the need for hybrid models that are able to combine the strengths of the individual techniques while complementing the weaknesses of one method with the strength of the other. Therefore, this work seeks to take advantage of the unique capability of type-2 fuzzy logic systems (type-2 FLS) in modelling uncertainties, to improve the performance of the extreme learning machines in order to further boost the generalisation ability of extreme learning machines (ELM) even in the face of uncertainties.

Type-2 fuzzy logic has been generally acknowledged as being better and ideal for uncertainty modeling [2–8]. Recently, type-2 FLS has been proposed as a novel framework for both classification and prediction in order to handle different forms of uncertainties [7,9]. It is able to handle uncertainties that include those in measurements and data used to calibrate the parameters. It has been used in several fields and the results have been promising and very encouraging [10–14]. Therefore, this work seeks to demonstrate that type-2 FLS can handle uncertainties in reservoir well log data [15], and by so doing facilitate an improvement in ELM performance in an hybrid setup, since type-2 fuzzy logic has been specifically invented to deal with different forms of uncertainties [7] that are inherent in our day to day natural encounters and modes of reasoning.

Extreme learning machine is a recently introduced learning algorithm for single-hidden layer feed-forward neural networks (SLFNs) which randomly chooses hidden nodes and analytically determines the output weights of SLFNs. It was developed to address the problems of the classical NN like overfitting problem, local minimal and low speed operation due to its use of slow gradient based learning algorithms for training and the iterative tuning of the parameters of the networks by these learning algorithms. To overcome these problems, a learning algorithm called extreme learning machine (ELM) [16–18] was proposed for single

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hidden layer feed-forward neural networks (SLFNs). It has been established that this algorithm tends to mostly provide better generalization performance at extremely fast learning speed since it is a simple tuning-free algorithm [19]. But we have noticed that ELM suffers from low performance in the area where uncertainties are presumed to be rife as is the case with predicting permeability from well logs. As a result of ELM inability to handle uncertainties adequately, it will be a good contribution to seek to improve its performance through the use of type-2 FLS as a pre-processor for uncertainty handling, in order to take advantage of its unique capabilities. Therefore in this paper, we propose a hybrid approach that will combine the unique attributes of type-2 FLS with those of extreme learning machine by way of improving ELM performance in order to achieve better generalisation ability in all situations including uncertainty-oriented environment.

The problem of permeability prediction is especially complicated in carbonate rocks whose depositional and diagenetic history can be very complex, so that their permeability cannot be causally upscaled from core scale to reservoir scale, or even up to a few feet scale seen by the well logs [20]. Larger than core-sized, vuggy or fractured intervals in carbonates can result in permeability which at the scale of a few feet are significantly higher than the matrix permeability measured in core plugs. Swarms of fractures, if connected, yield very large flow rates, if disconnected, very low flow rates – and this capricious variability is not recorded (or deeply hidden) by the core permeability data [21,22].

Permeability is one of the most important aspects of reservoir properties, and their prediction has been one of the fundamental challenges to petroleum engineers and researchers [23]. Accurate knowledge of permeability property is required to determine the amount of oil or gas present in reservoirs, the amount that can be recovered, the flow rate of oil or gas, the forecast of future production, and the design of production facilities. The overall reservoir management and development requires accurate knowledge of permeability [23,24]. Permeability or flow capacity is the ability of porous rock to transmit fluid [25]. The fact that a rock is very porous does not necessarily translate to it being very permeable. Permeability is the ease with which fluid is transmitted through a rock's pore space. It is a measure of how interconnected the individual pore spaces are in a rock or sediment and it is a key parameter associated with the characterization of any hydrocarbon reservoir [19]. In fact, many petroleum engineering problems cannot be solved accurately without having an accurate permeability value [19]. The problem of permeability estimation is a regression problem that involves predicting permeability from well log parameters that include electrical conductivity, density, sonic travel time, neutron porosity, total porosity, bulk density, resistivity and water saturation. During the past few decades, numerous efforts have been made to forecast permeability using well log data and available core data through laboratory measurements. In some oil fields, representative values for porosity and permeability obtained from different locations are available. Petroleum engineers generally use regression analysis as the main tool to correlate these data [26,27]. In these works, it was generally assumed that a linear or non-linear relationship exists between permeability and other properties of the rock, but unfortunately the method has failed to solve permeability prediction problems [24,28].

The recent successes recorded in the application of artificial neural networks (ANN) to solving various engineering problems has drawn researchers' attentions to its potential viability in the petroleum industry. Thus, in attempt to resolve problems associated with the parametric approach, the standard ANNs have been used to provide better prediction models [29,30]. These works yielded a significant prediction improvement in the oil and gas industries. However, the technique still suffers from several drawbacks. These shortcomings include but not limited to the trial-and-error approach of ANN and most importantly ANN suffers from instability in its predictions and it is unable to model uncertainties that characterize well logs in particular.

Researchers have done their best to address and overcome the problems of ANN. As a result, several variants of ANN and other methods like the support vector machines (SVM) and functional networks (FN) have been proposed and used [28,31], yet each has its limitations that still call for further research of this nature, particularly their inability to handle uncertainties and the need to ensure stability and consistency in permeability predictions.

It is an established fact that geosciences disciplines are not clear-cut and are mostly associated with uncertainties [15], hence the need for fuzzy logic based systems, particularly the newly introduced type-2 fuzzy logic systems (type-2 FLS) that is able to adequately account for different forms of uncertainties [7]. For instance, prediction of core parameters from well log responses is difficult and is usually associated with uncertainties. Earlier methods have not been able to adequately handle these uncertainties [15], but type-2 fuzzy logic derives useful information from the uncertainties and uses it as a good parameter for increasing the accuracy of the predictions while also ensuring stability and consistency.

The choice of type-2 fuzzy logic as being appropriate to this type of problems in relation to the standard fuzzy systems (i.e. type-1 fuzzy systems) has been made due to extensive works that has been earlier carried out and the results demonstrated the superiority of type-2 fuzzy logic over the standard fuzzy systems. More importantly and of recent is the fact that our earlier published work [13] on the same problem clearly compared these two forms of fuzzy systems and the outcome indicated a superior performance output from the type-2 fuzzy logic system. Furthermore, the superiority of type-2 fuzzy systems have been well articulated in previous works [7,9,32,33] that using type-2 fuzzy logic system is the more appropriate choice because even if high level uncertainty is absence then type-2 fuzzy automatically reduces to type-1 fuzzy logic does. But when the degree of fuzziness is high then type-2 fuzzy amply performs its required tasks of higher uncertainty handling capability.

This study mainly aims to investigate the feasibility of using type-2 FLS as a pre-processor to improve the generalization ability of ELM in the face of uncertainty during prediction by way of developing a new hybrid model based on type-2 FLS and ELM for predicting permeability from well logs using real industrial well log data. The well log input parameters to be used include sonic travel time (DT), Micro spherically Focused Log (MSFL), Neutron porosity (NPHI), total porosity (PHIT), bulk density (RHOB), and water saturation (SWT). Comparative studies are also done to investigate how the proposed hybrid model compares with the individual constituent methods and also ANN and SVM as earlier used methods.

The rest of this paper is organized as follows. Section 2 presents a review of related researches and Section 3 presents the proposed model. Section 4 contains the empirical study, implementation process, comparative studies, results and discussions. The conclusion and future work recommendations are provided in Section 5.

2. Related research

Permeability is one of the most important of reservoir properties, and its prediction has been one of the fundamental challenges to petroleum engineers and researchers [23]. In general, permeability determination has been carried out using either empirical, statistical, or the recently introduced "virtual measurement" methods. Respectively, the researchers have utilized the usage of empirically determined models, multiple variable regression, and

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