



Functional networks as a new data mining predictive paradigm to predict permeability in a carbonate reservoir

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ABSTRACT

Permeability prediction has been a challenge to reservoir engineers due to the lack of tools that measure it directly. The most reliable data of permeability obtained from laboratory measurements on cores do not provide a continuous profile along the depth of the formation. Recently, researchers utilized statistical regression, neural networks, and fuzzy logic to estimate both permeability and porosity from well logs. Unfortunately, due to both uncertainty and imprecision, the developed predictive modelings are less accurate compared to laboratory experimental core data. This paper presents functional networks as a novel approach to forecast permeability using well logs in a carbonate reservoir. The new intelligence paradigm helps to overcome the most common limitations of the existing modeling techniques in statistics, data mining, machine learning, and artificial intelligence communities. To demonstrate the usefulness of the functional networks modeling strategy, we briefly describe its learning algorithm through simple distinct examples. Comparative studies were carried out using real-life industry wireline logs to compare the performance of the new framework with the most popular modeling schemes, such as linear/nonlinear regression, neural networks, and fuzzy logic inference systems. The results show that the performance of functional networks (separable and generalized associativity) architecture with polynomial basis is accurate, reliable, and outperforms most of the existing predictive data mining modeling approaches. Future work can be achieved using different structure of functional networks with different basis, interaction terms, ensemble and hybrid strategies, different clustering, and outlier identification techniques within different oil and gas challenge problems, namely, 3D passive seismic, identification of lithofacies types, history matching, rock mechanics, viscosity, risk assessment, and reservoir characterization.

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1. Introduction

The process of oil exploration has been drastically improved by the availability of information technology, especially artificial intelligence with data mining modeling, as well as advances in seismic technology. Advances have pushed the envelope of what is feasible, both in terms of finding the oil and figuring out how to extract it once an oil and gas company has identified a location. Cutting edge advances in information technology and computational intelligence represent a breakthrough in oil and gas exploration and production. They have helped transform the business of exploration and production, increasing its production efficiency; and generating significant environmental benefits.

Permeability is defined as the ability of porous rock to transmit fluid. It is one of the most crucial reservoir properties and is very difficult to calculate accurately. Generally, permeability is directly measured in a laboratory on rock samples. Last two decades, numerous efforts have been made to forecast permeability using well log data and available core data. The field of permeability prediction is vast, and incorporates many years of effort by expert petrophysicists, geologists and reservoir engineers. The problem with computational methodologies for permeability prediction from logs is the inherent inability of this method to integrate the geological and petrophysical controls on single phase flow. Carbonate reservoirs in particular are characterized by a very wide range of measured permeability for a given porosity, which reflects heterogeneity in pore size, geometry and connectivity.

The relationships for forecasting permeability using wireline logs and core permeability data are based on statistical regression, feed-forward neural networks (FFNs), and fuzzy logic (FL) or adaptive neuro-fuzzy inference systems (ANFISs). Based on these ap-

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proaches, better estimates have been reported compared to that of conventional techniques. Nevertheless, the application of neural networks to reservoir characteristics prediction is quite limited. Attempts were made to apply neural networks and fuzzy logic to permeability prediction, reservoir characteristics, pressure–volume–temperature prediction, and flow regimes and liquid-hold-up (Abdulraheem et al., 2007; Bhatt & Helle, 2002; El-Sebakhy, 2009; El-Sebakhy, Hadi, & Faisal, 2007; Fangming, Zhongyuan, Aming, & Xiaoxia, 2009; Lucia, Ruppel, Jennings, & Laubach, 2001; Nikravesh & Aminzadeh, 2000, 2003). The findings of these works clearly indicate the potential of neural networks, which generally produces better results than those empirical formulae, derived from conventional multiple regression analysis.

The results obtained from neural networks models are reasonably accurate. However, there is a need for further improvement when this method is applied to a complex structure.

The use of combination of neural networks and fuzzy logic has also been reported in literature by Balan, Mohaghegh, and Ameri (1995), Cuddy (1997), Tamhane, Wong, Aminzadeh, and Nikravesh (2000), Lucia et al. (2001), Bhatt and Helle (2002), Nikravesh and Aminzadeh (2000), Nikravesh and Aminzadeh (2003), Kamali and Mirshady (2004), Lim (2005), Sears and Lucia (2006), Kadkhodaie-Ilkhchi, Rezaee, and Moallemi (2006), Chen and Lin (2006), Jeirani and Mohebbi (2006), Lucia (2008), Abdulraheem et al. (2007), El-Sebakhy et al. (2007), Fangming et al. (2009), El-Sebakhy (2009), and Cross et al. (2010). Unfortunately, both neural networks and fuzzy logic inference systems are heuristic modeling approaches and suffer from a number of drawbacks, such as overfitting and local optima. In some cases, these techniques do not perform well, because the parameters in a training algorithm are based on initial guess of random weights, learning rate, and momentum. Therefore, there is a need for predictive modeling framework to estimate permeability and lithofacies from well logs in a carbonate reservoir.

Recently, functional network has been proposed as a new intelligence data mining predictive model in solving numerous of prediction/classification problems, namely, *pattern recognition, bioinformatics, engineering, software engineering, and business applications* (Bruen & Yang, 2005; Castillo, Cobo, Gutierrez, & Hadi, 1999; Castillo, Gutiérrez, Hadi, & Lacruz, 2001, 2008; El-Sebakhy, 2004; El-Sebakhy, 2009; El-Sebakhy, 2010; El-Sebakhy et al., 2007; El-Sebakhy et al., 2010). It has been only utilized in solving two oil and gas industry problems, namely, predicting reservoir fluids PVT properties, Al-Bokhitan (2007) and rock mechanical parameters for hydrocarbon reservoirs, El-Sebakhy et al. (2010). The main motivation of this research is to investigate the strengths and capabilities of functional networks in forecasting the permeability from well logs in a hydrocarbon reservoir and compares its performance with the one of the most common statistics and artificial intelligence modeling techniques.

The workflow of this research is designed as follows: Section 2 of this paper provides a brief literature review. Functional networks intelligent data mining system methodology and examples are described in detail in Section 3. The most common statistical quality measures in predictive modeling are proposed in Section 4. The use of functional networks in identifying the permeability from well logs implementations process and comparative studies are carried out in Section 5. Section 6 contains discussions of results, while Section 7 presents conclusions and recommendations.

2. Literature review

Recently, researchers in both petroleum engineering and computer science have achieved considerable success in forecasting permeability from wireline logs based on statistical regression,

standard neural networks, and fuzzy logic (FL) inference systems, see Lucia et al. (2001), Bhatt and Helle (2002), Nikravesh and Aminzadeh (2000, 2003), Kamali and Mirshady (2004), Lim (2005), Sears and Lucia (2006), Kadkhodaie-Ilkhchi et al. (2006), Chen and Lin (2006), Jeirani and Mohebbi (2006), Lucia (2008), Abdulraheem et al. (2007), El-Sebakhy et al. (2007), Fangming et al. (2009), El-Sebakhy (2009), and Cross et al. (2010) for more details. Most of these empirical and computational correlations are often determined using log-derived parameters, such as, *porosity, density* and *Gamma ray*. Bruce et al. (2000) and Nikravesh and Aminzadeh (2000, 2003) presented state-of-the-art reviews of the use of neural networks for predicting permeability from well logs. They had also developed a *nonlinear regression* tool to obtain transformation between well logs and core permeability. The tool can be used for estimating permeability in un-cored intervals of the well. Though the results that obtained from neural networks and regression models are reasonably accurate, there is room for further improvement in both efficiency and stability, especially in regions with complex geology. In addition, both neural networks and fuzzy logic inference systems are heuristic modeling approaches and suffer from a number of drawbacks, such as overfitting and local optima. Furthermore, in some cases, these techniques do not perform well because the parameters in the training algorithm are based on initial guess of random weights, learning rate, and momentum. Therefore, there is a need for new intelligence predictive modeling frameworks to estimate both permeability and lithofacies from well logs in a carbonate reservoir.

In the last decade, application of fuzzy logic in petroleum engineering field has received considerable attention and it has been successfully applied to address problems on various oil and gas reservoirs such as estimation of lithofacies and permeability using wireline logs, see Cuddy (1997), Tamhane et al. (2000), and Abdulraheem et al. (2007) for more details. For predicting these properties, generally *Gaussian membership* and *fuzzy clustering algorithm* are applied. Based on these approaches, better estimates have been reported compared to that of conventional techniques. The use of a combination of neural networks and fuzzy logic has also been reported in the literature by Nikravesh and Aminzadeh (2000, 2003). This combined approach can be utilized in developing an optimum set of rules for nonlinear mapping between various input parameters. Such rules developed for the training set can be used to predict permeability for a new dataset and are very useful in the case when some of the inputs are missing. Predictive modeling techniques based on fuzzy logic were successful for most of the cases, but were not satisfactory in some cases due to the heuristic approach in dealing with the data.

2.1. Statistical linear/nonlinear regression

Multiple linear regression attempts to model the relationship between two or more explanatory variables and a response variable by fitting a linear equation to observed data. Every value of the independent variable x is associated with a value of the dependent variable y . The regression line for p explanatory variables x_1, x_2, \dots, x_p is defined to be $\mu_y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_p x_p$. This equation describes how the mean response μ_y changes with the explanatory variables. The observed values for y vary about their means μ_y and are assumed to have the same standard deviation, σ . Formally, the model for multiple linear regression given n observations is $y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \dots + \beta_p x_{ip} + \varepsilon_i$, for $i = 1, \dots, n$, where ε_i is the model deviation. One approach to simplifying multiple regression equations is to use the stepwise procedures. These include *forward selection, backwards elimination, and stepwise regression*, which add or remove variables one-at-a-time until some stopping rule is satisfied.

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