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ASSESSING THE RELIABILITY OF ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM (ANFIS) MODELS FOR FORECASTING AZERBAIJAN'S ECONOMIC GROWTH

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SUMMARY

The purpose of this research – This research evaluates four ANFIS models for forecasting Azerbaijan's GDP per capita growth rate, aiming to identify optimal architectures for strategic planning. The study balanced model complexity with predictive accuracy by analyzing training and forecasting errors across various configurations.
The methodology of the research – The methodology involved testing ANFIS models in MATLAB using two FIS generation methods (grid partitioning and subtractive clustering) and eight membership function types. Each configuration was trained on historical data, with performance measured by Training Error (RMSE) to diagnose overfitting and Forecasting Error (RMSE) on unseen data to assess reliability.
The practical importance of the research – The practical importance of the research is that its findings offer insights for policymakers in emerging economies. By pinpointing effective model architectures, it provides a framework for more informed economic planning and policy formulation.
The results of the research – The results revealed significant performance variations, with subtractive clustering proving superior to grid partitioning, which often caused severe overfitting. The most reliable configuration was Model 4, using subtractive clustering and a triangular membership function ("sub-trimf"), which achieved the lowest forecasting error of 6.9907.
The scientific novelty of the research – the novelty is its systematic evaluation of ANFIS models for Azerbaijan's economy, providing empirical evidence that subtractive clustering is a more robust forecasting approach for this type of economic data.

Keywords: ANFIS, economic growth, Azerbaijan, forecasting, neuro-fuzzy systems

Introduction

Accurate forecasting of GDP per capita growth is crucial for effective policymaking and economic planning, particularly in dynamic emerging economies like Azerbaijan. Traditional linear econometric models often struggle with the inherent non-linearities and complex interactions in real-world economic data. Adaptive Neuro-Fuzzy Inference Systems (ANFIS) offer a powerful hybrid approach, combining neural network learning with fuzzy logic, making them well-suited for modeling complex, non-linear systems and handling imprecise data. This synergy allows ANFIS to adapt its fuzzy rules and membership functions to capture intricate patterns, offering a promising avenue for enhanced forecasting accuracy.
The practical reliability of ANFIS models in economic forecasting, especially for Azerbaijan, hinges on critical architectural choices, including the initial fuzzy inference system (FIS) generation method (e.g., grid partitioning or subtractive clustering) and the type of membership functions (MFs). A key challenge is identifying configurations that not only minimize training error but also generalize robustly to unseen data, thereby avoiding overfitting. Overfitting severely undermines a model's utility by performing well on historical data but poorly on future predictions. The complexities of economic forecasting, such as endogeneity and the composite nature of economic indices, further underscore the need for robust models. Azerbaijan's unique economic context, with nuanced and potentially non-linear influences on its GDP growth, amplifies the importance of identifying highly reliable forecasting models.

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This paper systematically evaluates the reliability of four distinct ANFIS models for forecasting Azerbaijan's GDP per capita growth rate. By comparing various architectural choices based on pre-computed training and forecasting errors, the study aims to identify configurations that strike an optimal balance between fitting historical data and accurately predicting future economic trends. The objective is to pinpoint the most reliable ANFIS model(s) and their optimal configurations, providing a robust framework and specific recommendations for future economic forecasting efforts in Azerbaijan.

Materials and Methods

Data Description

The study utilizes summary performance metrics from four ANFIS models. Each model details the method (grid or subtractive clustering), the type of the membership function (e.g., "trimf", "gaussmf"), training error, and forecasting error. The output variable for all models is Azerbaijan's GDP per capita growth rate. The input variables for each model are different types of the KOF Globalisation Index:

- **Model 1:** KOFGI (Overall), KOFGIdf (de facto), KOFGIdj (de jure).
- **Model 2:** KOFEcGI (Economic), KOFSoGI (Social), KOFPoGI (Political).
- **Model 3:** KOFEcGIdf (Economic de facto), KOFSoGIdf (Social de facto), KOFPoGIdf (Political de facto).
- **Model 4:** KOFEcGIdj (Economic de jure), KOFSoGIdj (Social de jure), KOFPoGIdj (Political de jure).

Data for the input variables, the KOF Globalisation Index and its components, was collected from the official KOF website[2], while the corresponding output variable for Azerbaijan was sourced from World Bank Open Data[3]. The dataset spans the years 1991 to 2021, comprising 31 observations. To ensure the training data comprehensively represented the country's economic volatility, the dataset was partitioned non-chronologically. Twenty-six data points, selected to cover the full range of values from the entire period, were used for the training set. The remaining five observations were held back as an out-of-sample test set for model validation and forecasting evaluation.

ANFIS Model Overview

ANFIS combines neural networks and fuzzy logic to optimize fuzzy inference system parameters. The "method" refers to the initial FIS generation strategy:

- **Grid Partitioning:** Systematically divides the input space into a grid, creating a rule for each point. This can lead to a large number of rules and a high risk of overfitting, especially with noisy economic data.
- **Subtractive Clustering:** Identifies cluster centers in the data, forming a rule for each cluster. This is more efficient, produces a more compact rule base, and generally leads to better generalization. The "type of the membership function" refers to the mathematical functions (e.g., triangular, Gaussian) used to define the degree to which an input value belongs to a fuzzy set, influencing the model's ability to capture non-linear relationships.

Experimental Procedures

The ANFIS data reflects systematic experiments conducted using a MATLAB script. For each of the four models, configurations combining two FIS generation methods ('grid' and

[2] https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html
[3] https://data.worldbank.org/

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'subtractive clustering') with eight membership function types were tested. Each configuration was trained on historical data and evaluated on separate, unseen forecasting data. Performance was measured by Training Error (RMSE) and Forecasting Error (RMSE), calculated from the final training error vector and the RMSE between predicted and actual test outputs, respectively. This separation of data is crucial for assessing true generalization capability.

Reliability Metrics. Model reliability is primarily assessed by forecasting error, which quantifies the model's ability to generalize and accurately predict unseen data. A lower forecasting error indicates higher predictive accuracy and reliability. Training error is used in conjunction to identify overfitting, where a model performs well on training data but poorly on new data. A significantly lower training error coupled with a high forecasting error indicates overfitting, rendering the model unreliable. The objective is to identify configurations that strike an optimal balance between fitting historical data and generalizing effectively to future observations.

Results and discussion. This section presents the summarized performance metrics for each of the four ANFIS models summarized in Tables 1 and 2.

Table 1: Comprehensive ANFIS Model Performance Summary

Model No.	Performance Case	Method	MF Type	Training Error
1	Best	sub	gbellmf	1.481784
	Worst	sub	trapmf	1.439884
2	Best	grid	trapmf	1.484713
	Worst	grid	trimf	0.052101
3	Best	grid	trapmf	5.223451
	Worst	sub	psigmf	3.174898
4	Best	sub	trimf	1.098755
	Worst	grid	trimf	0.286766

Table 2: Comparative Summary of Best-Performing ANFIS Configurations across All Models

Model No.	Method	MF Type	Training Error	Forecasting Error
4	sub	trimf	1.098755	6.990744
1	sub	gbellmf	1.481784	7.400520
2	grid	trapmf	1.484713	7.623228
2	sub	psigmf	1.527883	7.919741
1	sub	dsigmf	1.480991	9.387195
1	sub	psigmf	1.480968	9.585087

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2	sub	dsigmf	1.702324	9.656369

The results reveal significant disparities in ANFIS model reliability for forecasting Azerbaijan's GDP per capita growth. Models 1, 2, and 4 generally exhibit lower forecasting errors compared to Model 3, suggesting their architectures or data processing are more suitable for this task. Model 3 consistently shows higher errors, indicating it is less reliable for precise forecasting. A plausible explanation for this underperformance lies in the nature of its input variables: the de facto KOF sub-indices. De facto measures, which quantify actual flows and activities like trade and foreign investment, are often susceptible to higher levels of volatility and noise. For an economy like Azerbaijan's, these measures can be impacted by short-term global commodity price fluctuations and other external shocks that do not immediately alter underlying policies. In contrast, de jure measures (used in the best-performing Model 4) reflect more stable, policy-based frameworks. This inherent noisiness in the de facto data likely makes it more difficult for the ANFIS model to identify robust, generalizable patterns, resulting in consistently higher forecasting errors and reduced reliability

Analysis of Partitioning Methods

A consistent trend shows that grid partitioning, despite achieving very low training errors, frequently leads to significantly higher, often catastrophic, forecasting errors, indicating a strong tendency towards overfitting. For example, Model 4 “grid-trimf”’ has a training error of 0.28677 but a forecasting error of 461.67036. This systematic overfitting renders many grid configurations unreliable.

Conversely, subtractive clustering (“sub”) often yields slightly higher training errors but consistently demonstrates superior generalization, resulting in lower and more reliable forecasting errors. This is evident in top performers like Model 1 “sub-gbellmf” (Forecasting Error: 7.4005), Model 2 “sub-psigmf” (Forecasting Error: 7.9197), and notably, Model 4 “sub-trimf” (Forecasting Error: 6.9907). The lowest overall forecasting error is achieved by a subtractive clustering configuration (Model 4, “sub-trimf”). This strong empirical evidence suggests subtractive clustering is generally a more robust and reliable approach for this forecasting task.

Impact of Membership Function Types

The choice of membership function type also plays a significant role, often contingent on the partitioning method. “Trimf” performs exceptionally well with subtractive clustering in Model 4. Similarly, “gbellmf” and “psigmf” show strong performance with subtractive clustering in Models 1 and 2, respectively. However, some MF types, particularly “trimf” and “gbellmf”, lead to catastrophic forecasting errors when combined with grid partitioning in Model 4, highlighting critical interaction effects. Optimal performance stems from specific combinations that exhibit synergistic effects, reinforcing that ANFIS model development is an empirical optimization problem requiring comprehensive experimental design.

Identification of Most Reliable Configurations

Based on Table 2, the most reliable ANFIS configurations for forecasting Azerbaijan's GDP per capita growth rate are:

- **Model 4, Subtractive Clustering with Triangular MF (sub-trimf):** Achieved the absolute lowest forecasting error of 6.9907, with a well-balanced training error, indicating excellent generalization. This combination appears effective when using de jure economic, social, and political globalization indices as inputs.

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- **Model 1, Subtractive Clustering with Generalized Bell MF (sub-gbellmf):** Exhibited a forecasting error of 7.4005, demonstrating strong reliability through effective generalization when using overall, de facto, and de jure KOF indices as inputs.
- **Model 2, Grid Partitioning with Trapezoidal MF (grid-trapmf):** Achieved a forecasting error of 7.6232. This is a notable exception where a grid-based method performed well, suggesting that specific MF types can mitigate the overfitting tendency of grid partitioning, particularly when using economic, social, and political globalization indices as inputs.

Configurations with very low training errors but disproportionately high forecasting errors (e.g., Model 4 “grid-trimf”) exemplify severe overfitting and are fundamentally unreliable for forecasting. This underscores the need to prioritize forecasting error and generalization capability over perfect historical fit. The high variability within Model 4 highlights its sensitivity to configuration choices, implying a high risk of poor performance if hyperparameter tuning is not meticulously performed.

Contextualization with Economic Forecasting Challenges. The observed variability and nuanced performance of the ANFIS models underscore the inherent difficulty in modeling complex economic phenomena like GDP per capita growth. Economic variables are influenced by numerous, linear and non-linear, interacting factors, as highlighted in the KOF globalization literature (Ainscough və Shank, 2023; Dreher, 2006; Gygli, 2019; Kılıçarslan və Dumrul, 2018; Majidi, 2017). The success of certain ANFIS configurations suggests their ability to capture these non-linear dynamics. This is particularly relevant for Azerbaijan, where specific economic drivers can have nuanced effects, such as the finding that social globalization had a negative effect on growth in "Turkic States" including Azerbaijan (Şimşek, 2023). ANFIS models, especially those employing subtractive clustering, appear better equipped to handle such complex relationships.

Furthermore, the choice of KOF index inputs for each model (e.g., overall, de facto, de jure, or disaggregated dimensions) likely contributes to the varying performance. The KOF literature emphasizes that analyzing sub-components or de jure vs. de facto measures can provide a more nuanced understanding (Gygli et al., 2019; Kılıçarslan & Dumrul, 2018; Šimić, 2021). The fact that Model 4, using de jure components, yielded the most reliable configuration, while Model 2, using overall dimensions, also had a strong performer, suggests that the specific type of globalization input significantly impacts ANFIS model reliability in this context.

Conclusions. This evaluation of ANFIS models for forecasting Azerbaijan's GDP per capita growth rate confirms that both the FIS generation method and membership function type critically impact reliability. Subtractive clustering consistently proved superior, leading to lower forecasting errors and better generalization compared to grid partitioning. The most reliable configuration was Model 4 with subtractive clustering and a triangular membership function (sub, trimf), achieving the lowest forecasting error of 6.9907. Other strong performers included Model 1 (sub-gbellmf) and Model 2 (grid-trapmf). The analysis also highlighted the significant risk of over fitting with certain grid partitioning configurations, where low training errors did not translate to reliable out-of-sample performance.

For future economic forecasting in Azerbaijan, prioritizing ANFIS models that employ subtractive clustering for FIS generation is strongly recommended. Further exploration of membership functions like “trimf” and “gbellmf” in conjunction with subtractive clustering is

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warranted. Future research should also explore the specific input features, such as further disaggregated KOF globalization indices, more in details to capture nuanced economic dynamics. Rigorous cross-validation and meticulous hyperparameter tuning are essential to ensure generalizability and prevent over fitting, given the observed performance variability. These insights contribute to applying advanced computational intelligence techniques in economic forecasting, offering policymakers in Azerbaijan more robust tools for informed economic planning and policy formulation.

Data availability. The KOF Globalization Index data used in this study are available from the KOF Swiss Economic Institute at https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html. The GDP per capita growth rate data for Azerbaijan are available from the World Bank Open Data portal at https://data.worldbank.org/indicator/NY.GDP.PCAP.KD.ZG?locations=AZ-.

All processed data used for model training and testing, along with the MATLAB scripts required to replicate the findings of this study, are publicly available in the Mendeley repository at DOI: 10.17632/xbp7fyzpsr.1

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AZƏRBAYCANIN İQTİSADİ ARTIMININ PROQNOZLAŞDIRILMASI ÜÇÜN ADAPTİV NEYRO-QEYRİ-SƏLİS NƏTİCƏÇIXARMA SİSTEMİ (ANFIS) MODELLƏRİNİN ETİBARLILIĞININ QİYMƏTLƏNDİRİLMƏSİ

XÜLASƏ

Tədqiqatın məqsədi – Azərbaycanın adambaşına düşən ÜDM artım tempini proqnozlaşdırmaq üçün dörd fərqli ANFIS modelini qiymətləndirmək və strateji planlaşdırma üçün optimal arxitekturaları müəyyən etməkdir. Tədqiqat, müxtəlif konfiqurasiyalar üzrə təlim və proqnozlaşdırma xətalarını təhlil edərək model mürəkkəbliyi ilə proqnoz dəqiqliyi arasında tarazlığı təmin etmişdir.
Tədqiqatın metodologiyası – MATLAB mühitində iki fərqli FİS (qeyri-səlis nəticəçıxarma sistemi) generasiya metodu (şəbəkə bölgüsü və subtraktiv klasterləşdirmə) və səkkiz fərqli üzvlük funksiyası növündən istifadə edərək ANFIS modellərinin sınaqdan keçirilməsini əhatə edirdi. Hər bir konfiqurasiya tarixi məlumatlar üzərində təlim keçmiş, performans isə həddindən artıq uyğunlaşmanı (overfitting) diaqnoz etmək üçün Təlim Xətası (RMSE) və etibarlılığı qiymətləndirmək üçün görünməmiş məlumatlar üzərində Proqnozlaşdırma Xətası (RMSE) ilə ölçülmüşdür.
Tədqiqatın tətbiqi əhəmiyyəti – Tədqiqatın əhəmiyyəti ondan ibarətdir ki, onun nəticələri inkişaf etməkdə olan ölkələrin siyasətçiləri üçün dəyərli məlumatlar təqdim edir. Effektiv model arxitekturalarını müəyyən etməklə, tədqiqat daha məlumatlı iqtisadi planlaşdırma və siyasətin formalaşdırılması üçün bir çərçivə təmin edir.
Tədqiqatın nəticələri – Nəticələr modellərin performansında əhəmiyyətli fərqlər olduğunu göstərmişdir. Belə ki, subtraktiv klasterləşdirmənin, ciddi həddindən artıq uyğunlaşmaya səbəb olan şəbəkə bölgüsündən daha üstün olmuşdur. Ən etibarlı konfiqurasiya, subtraktiv klasterləşdirmə və üçbucaqlı üzvlük funksiyasından ("sub-trimf") istifadə edən və 6.9907 ilə ən aşağı proqnozlaşdırma xətasına nail olan Model 4 olmuşdur ki, bu da onun üstün proqnoz gücünü nümayiş etdirir.
Tədqiqatın elmi yeniliyi – Bu tədqiqatın elmi yeniliyi Azərbaycan iqtisadiyyatı üçün ANFIS modellərinin sistematik şəkildə qiymətləndirilməsindən ibarətdir və bu növ iqtisadi məlumatlar üçün subtraktiv klasterləşdirmənin daha etibarlı proqnozlaşdırma yanaşması olduğuna dair empirik sübutlar təqdim edir.
Açar sözlər: ANFIS, iqtisadi artım, Azərbaycan, proqnozlaşdırma, neyro-qeyri-səlis sistemlər

ОЦЕНКА НАДЕЖНОСТИ МОДЕЛЕЙ АДАПТИВНОЙ НЕЙРО-НЕЧЕТКОЙ СИСТЕМЫ ВЫВОДА (ANFIS) ДЛЯ ПРОГНОЗИРОВАНИЯ ЭКОНОМИЧЕСКОГО РОСТА АЗЕРБАЙДЖАНА

РЕЗЮМЕ

Цель исследования – оценить четыре различные модели ANFIS для прогнозирования темпов роста ВВП на душу населения Азербайджана и определить наиболее эффективные и оптимальные архитектуры для стратегического планирования. Исследование обеспечило необходимый баланс между сложностью модели и точностью прогнозирования путем анализа ошибок обучения и прогнозирования для различных конфигураций.
Методология исследования – включала детальное тестирование моделей ANFIS в среде MATLAB с использованием двух различных методов генерации FIS (системы нечеткого вывода): сеточного разделения и субтрактивной кластеризации, а также восьми различных типов функций принадлежности. Каждая конфигурация была тщательно обучена на исторических данных, а ее производительность измерялась Ошибкой обучения (RMSE) для диагностики переобучения и Ошибкой прогнозирования (RMSE) на ранее не использованных данных для оценки надежности.
Практическая значимость исследования – заключается в том, что его результаты предоставляют ценную информацию для политиков и экономических аналитиков в развивающихся странах. Определяя эффективные архитектуры моделей, исследование создает прочную научную основу для более информированного экономического планирования и формирования государственной политики.
Результаты исследования – выявили значительные различия в производительности моделей; субтрактивная кластеризация оказалась значительно превосходящей сеточное разделение, которое часто приводило к серьезному и нежелательному переобучению. Наиболее надежной конфигурацией стала Модель 4, использующая субтрактивную кластеризацию и треугольную функцию принадлежности ("sub-trimf"), которая достигла самой низкой ошибки прогнозирования 6.9907, что ярко демонстрирует ее превосходную прогностическую силу.

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Научная новизна исследования – заключается в глубокой и систематической оценке моделей ANFIS для экономики Азербайджана, предоставляя важные эмпирические доказательства того, что субтрактивная кластеризация является более надежным и точным подходом к прогнозированию для такого типа экономических данных.

Ключевые слова: ANFIS, экономический рост, Азербайджан, прогнозирование, нейро-нечеткие системы.

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