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REVIEW ARTICLE

PREDICTION OF THE ELECTRICAL RESISTIVITY OF SOILS IN TROPICAL AREAS BASED ON METEOROLOGICAL VARIABLES USING GENETIC ALGORITHMS AND FUZZY INFERENCE SYSTEM APPROACHES

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ABSTRACT

The safety of property and people against risks and electrical faults is essentially ensured by an earthing system. The essential element of the latter is the electrical resistivity of the soil. This is influenced by several factors. In this work, we used the georeference coordinates of the point (A), state of nature the day before the measurement (B), state of nature on the day of the measurement (C), and the ambient temperature at the measurement point (D). 9513 in-situ measurement samples on selected sites in Lomé constitute the database. Genetic algorithms and fuzzy inference systems made it possible to create models taking into account the bibliographic review. Evaluation criteria such as: RMSE, RRMSE, MAPE and R^2 are used to evaluate these models. The results give RMSE = 16.20%, RRMSE = 10.94%, MAPE = 9.27%, R^2 = 97.93% for Genetic Algorithms with the BCD configuration and for fuzzy inference systems, we have RMSE = 71.48, RRMSE = 48.29%, MAPE =35.29%, R^2 =61.53% by ACD configuration. We conclude that Genetic Algorithms give a very good result given the value of its correlation coefficient with the BCD combination, which justifies that the parameters used are well suited to predicting the electrical resistivity of the soil in the area considered.

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INTRODUCTION

The search for ease and speed in human activities has led to the implementation of several automated devices. Most of these devices only run on electricity. To provide electricity to populations living in increasingly diverse places, linked to ever-increasing demographics, several means of producing electrical energy are used [46]. Conventional power plants using polluting primary energy sources (coal, oil and natural gas) are more exploited [27]. To remedy the pollution of the environment and nature caused by these power plants, new research has been developed in the production of electricity based on renewable and clean sources (Solar, wind, Geothermal), [14] ,[31], [37], [38]. This was recently confirmed by the COP28 in Dubai, which allocated 100 million dollars to Africa in this context, [11], [15]. Given that the production centers are not concentrated in a single location, so that the supply of electricity is stable, at an acceptable price and to ensure customers have the power they need; we interconnect the power plants to the places of consumption, [1], [9], [13], [40]. These various means of production are only possible by setting up an electrical network, [46], [50]. In reality the whole Production – Transport – Distribution – Consumption (Electric networks), [12], [40], set up to supply electricity to places where the needs are essential, presents dangers during its operation without forget that the use of electricity is also dangerous, both for the installations and the users [6], [7], [19], [36], [40]. To avoid these dangers, protection devices are found almost everywhere in electrical installations, [4], [33]. In the latter, the most important is the earthing system, [48], because it is the only device capable of ensuring both the protection of people and property, [28], [7]. The soil being at the heart of its implementation, [18]. It is important to note that when the current passes through a person's body, the after-effects remain there for their entire life, [3] [7], [35], [36]. Furthermore, for grounding to be efficient and effective, and to play its role well, its conductivity must be very high (its electrical resistance tends towards 0), [4], [5], [30] ,[51]. The value of this resistance is closely linked to the resistivity of the ground where it is installed, [17], [8], [36]. The resistivity of the soil varies from one place to another and is influenced by many factors: intrinsic (porosity, salinity, water content, clay content, temperature etc.), [22], and external factors, can even change throughout the days or seasons, [37], [38], [48]. Of all the work related to this field which has made it possible to find ranges of values for each type of soil [39], new research has focused on the use of extrinsic factors in the determination of soil resistivity in tropical areas., [7], [16], [39], [41], [49]. Inspired by this work, Apaloo Bara *et al.* (2020), [6], [23], [24], [43], focused on the use of a few codified meteorological variables to predict the electrical resistivity of soils using algorithms like: ANN (RBF, MLP); ANFIS;

SVM (Gaussian, linear function); Naive Bayesian classifier and random forests. The georeference coordinates of the location (A), the state of nature the day before the measurement (B), the state of nature on the day of the measurement (C), and the ambient temperature at the measurement point (D)are the input variables. This work produced very interesting results in places, acceptable in some cases and mediocre in the rest. The effectiveness and extension of the results provided by Artificial Intelligence today, [20], [42], leads us to resume this work but this time by exploring other algorithms such as Genetic Algorithms (GA) [21], [29], [44] and Fuzzy Inference Systems (FIS), [26], [32], [34], in order to revisit this work. This being the objective pursued in this document, the aim is to consider the performance evaluation criteria such as the Mean Absolute Percentage Error (MAPE), the Square Root of the Mean Square Error (RMSE), the Square Root of the relative normalized root mean square error (RRMSE) and the Correlation Coefficient (R^2), to judge the results of this work. Data collected from 9 sites over a period of three (03) will be used in this work.

MATERIALS AND METHODS

Materials: All the data used for our study comes from nine (09) sites in the city of Lomé which is the capital and main city of Togo. The electrical resistivity values are associated with the geo-referenced coordinates, the state of nature the day before the measurement, the state of nature on the day of the measurement and the ambient temperature in the field. We thus have 4 variables which will serve as input variables to our model. These variables and the coding of the four input variables used and all their possible combinations are presented in Tables 1 and 2, respectively.

Table 1. List of input variables for model simulation, [6], [23]

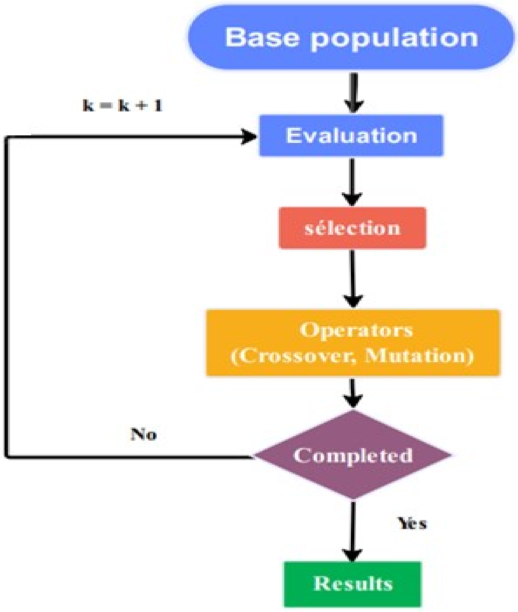
Input variables	Values	Mathematical explanations	Codes
Geo referenced coordinates of the point	Longitude	-	A
	Latitude		
	Altitude		
State of nature the day before the measurement	Very sunny	1	B
	Sunny	2	
	Less sunny	3	
	Partially covered	4	
	Cloudy	5	
	Rainy	6	
State of nature on the day of measurement	Very sunny	1	C
	Sunny	2	
	Less sunny	3	
	Partially covered	4	
	Cloudy	5	
	Rainy	6	
Ambient temperature (in ° C) at the point of measurement	25 ; 26 ; 27 ; 28 ; 29 ; 30 ; 31 ; 32 ; 33 ;34 ; 35.	-	D

Table 2. Combination for model simulation, [6], [23]

Combination numbers	Related configurations
1	[AB]
2	[AC]
3	[AD]
4	[BC]
5	[BD]
6	[CD]
7	[ABC]
8	[ABD]
9	[ACD]
10	[BCD]
11	[ABCD]

Prediction models: The methods used in this study for the prediction of soil electrical resistivity are genetic algorithms (GA) and fuzzy inference system (FIS).

Genetic algorithm [3], [21], [25], [44]: Genetic algorithms are based on the idea of biological evolution and use the concept of genetics to solve optimization problems. Figure 1 illustrates the operating principle of the genetic algorithm. In order to take full advantage of the potential of a genetic algorithm, we followed each step of its flowchart methodically and efficiently.



Genetic algorithm flowchart: The main formula used in genetic algorithms is the fitness function which measures the quality of each candidate solution. Indeed, AGs work on the maximization of an objective function. In many problems, the objective is to minimize a given function $f(x)$. We thus transform this objective function into an adaptation function $f_a(x)$ defined by relation (1).

$$f_a(x) = f_{\max}(x) - f(x) \qquad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

où : $f_{\max}(x) = \max(f(x))$

In the case where the objective function to be maximized takes negative values, relation (1) is replaced by relation (2).

$$f_a(x) = f(x) - f_{\min}(x) \qquad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

où : $f_{\min}(x) = \min(f(x))$.

The adaptation function has intrinsic characteristics that must be exploited to best effect when adapting to the relevant research domain. This allowed us to take into account the evaluation strategy, the selection method, and the type of operation which takes into account mutation and crossing. Because of this characteristic we adapt it here to the forecasting problem despite it being an optimization algorithm. The operation of the genetic algorithm also arises from its flowchart structure, as is the case for any algorithm.

Fuzzy Inference System [26], [32], [36]: Fuzzy inference systems are not based on mathematical functions in the strict sense. They use the concepts of fuzzy logic, which is an extension of classical logic allowing modeling and reasoning about vague or imprecise concepts. These are fuzzy linguistic variables, membership functions for each fuzzy variable and fuzzy inference rules. These three (03) parameters make it possible to create a fuzzy inference system. Figure 2 illustrates the general operating structure of a fuzzy inference system.

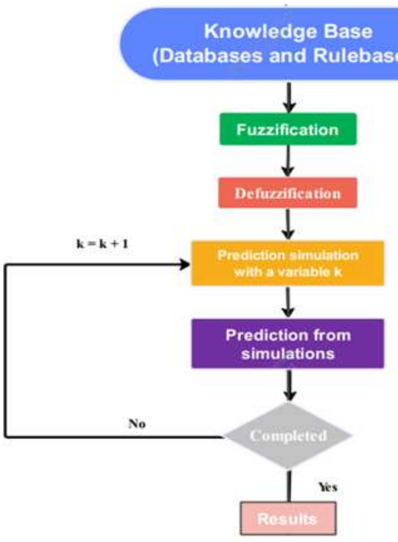


Figure 2. General structure of a fuzzy inference system

To carry out its operations, the FIS performs fuzzification then defuzzification in order to predict the data to be studied. During fuzzification it converts numerical values into linguistic terms, thus enabling the application of fuzzy set theory to measurable quantities. Linguistic variables express input data values in natural language. Each linguistic term is associated with a membership function that evaluates the extent to which a given numerical value belongs to that term. Regarding defuzzification (quantitization), it transforms fuzzy information into determined information. During this step, it uses the center of gravity method, also known as the centroid method, which transforms a fuzzy distribution resulting from the inference into a precise numerical value which will serve as a command. In the defuzzification process, the center of gravity method calculates the point at which the center of gravity of the fuzzy distribution lies and thus representing the digital output value. The abscissa of the center of gravity is determined using relation (3).

$$Z^* = \frac{\int_{z_0}^{z_1} \mu_z(z) z dz}{\int_{z_0}^{z_1} \mu_z(z) dz} \qquad (3)$$

Where :

- Z^* is the determined output value (center of gravity point).
- $\mu_z(z)$ ismembership function of the output variable to the value
- z_0 and z_1 terminals of the output variable.

If it happens that the function μ(z) is discretized, relation (3) is replaced by relation (4).

$$Z^* = \frac{\sum_{i=1}^{n} \mu_i(z) z_i}{\sum_{i=1}^{n} \mu_i(z)} \qquad (4)$$

Where :

- n is the number of quancritization level;
- z_i is the output value for level i;
- μ_i the membership value.

Evaluation criteria: Certain parameters intended to highlight the behavior of the models when faced with the data are taken into account in order to properly judge the results, as observed in most of the literature [2], [10], [45], [47]. This is the mean absolute percentage error (MAPE), expressed by relation (5); the square root of the root mean square error (RMSE) as shown in relation (6); relation (7) indicates the expression of the square root of the relative mean square error (RRMSE) and the correlation coefficient (R²) exposed by relation (8) were used.

$$RMSE = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(\rho_{j,p} - \rho_{j,r}\right)^2} \qquad \text{…………(5)}$$

$$RRMSE = \frac{\sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(\rho_{j,p} - \rho_{j,r}\right)^2}}{\frac{1}{N}\sum_{j=1}^{N} P_{j,r}} \qquad \text{…………(6)}$$

$$MAPE = \sum_{j=1}^{N}\left|\frac{\rho_{j,p} - \rho_{j,r}}{\rho_{j,r}}\right| \times 100 \qquad \text{…………(7)}$$

$$R^2 = \frac{\sum_{j=1}^{N}\left(\rho_{j,P} - \rho_{p,avg}\right) * \left(\rho_{j,r} - \rho_{j,avg}\right)}{\sqrt{\left[\sum_{j=1}^{N}\left(\rho_{j,p} - \rho_{p,avg}\right)^2\right] * \left[\sum_{j=1}^{N}\left(\rho_{j,r} - \rho_{r,avg}\right)^2\right]}} \qquad \text{…………(8)}$$

Where:

- $\rho_{j,p}$ represent the estimated or predicted values;
- $\rho_{j,r}$ are measured values;
- $P_{p,avg}$ being the predicted mean values;
- $\rho_{j,avg}$ is the average measured value;
- N is the number of points sampled.

RESULTS

The results are grouped into two (02) steps. First concerning the characterization, certain statistical parameters such as the mean, the standard deviation, the median, the mode, the minimum, the maximum, the asymmetry coefficient and the flattening coefficient were used. Table 3 groups the results and Figure 3. represents its graphical view.

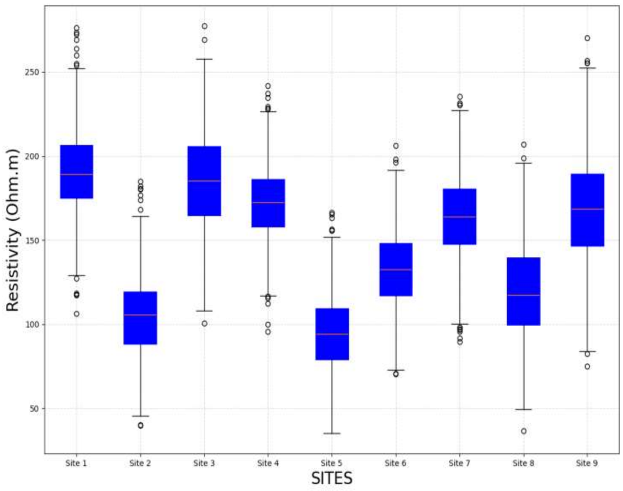


Figure 3. Graphical view of the characterization values of the nine (9) sites

Table 3. Statistical characteristics of electrical resistivity according to the nine (09) sites

SITE	Mean (Ohm.m)	Mode (Ohm.m)	Median (Ohm.m)	STD	Min. (Ohm.m)	Max. (Ohm.m)	Skewness	Kurtosis
1	190.711	188.496	189.386	23.737	106.448	276.463	0.091	3.425
2	104.014	39.998	105.523	23.002	39.998	185.102	0.040	3.188
3	185.633	100.635	185.243	27.943	100.635	277.560	0.033	2.608
4	172.213	188.496	172.609	20.794	95.727	241.948	-0.027	3.259
5	95.249	35.212	94.267	21.581	35.212	166.585	0.181	2.918
6	133.213	70.495	132.803	21.384	70.495	206.447	0.034	2.815
7	164.184	89.628	164.094	24.918	89.628	235.661	-0.033	2.972
8	119.694	36.526	117.503	26.248	36.526	206.903	0.263	2.797
9	168.144	74.989	168.553	30.820	74.989	270.363	0.007	3.027

Table 4. Summary of models by Algorithms according to performance evaluation criteria

	Performance evaluation criteria and their values							
	Genetic Algorithm				Fuzzy Inference System			
Combinaisons	RMSE (%)	RRMSE (%)	MAPE (%)	R² (%)	RMSE (%)	RRMSE (%)	MAPE (%)	R² (%)
[AB]	20.69	13.98	13.00	97.80	61.65	41.65	32.52	48.26
[AC]	20.69	13.98	13.00	97.80	61.60	41.61	32.48	48.88
[AD]	20.73	14.00	13.03	97.80	52.09	35.19	30.77	33.95
[BC]	18.81	12.70	11.49	97.92	85.22	57.57	45.52	41.71
[BD]	18.84	12.73	11.52	97.92	56.86	38.41	30.77	31.35
[CD]	18.84	12.73	11.52	97.92	55.75	37.66	30.10	26.94
[ABC]	20.43	13.80	12.78	97.80	71.42	48.25	35.21	53.25
[ABD]	20.46	13.82	12.80	97.80	71.61	48.37	35.38	61.27
[ACD]	20.46	13.82	12.80	97.80	*71.48*	*48.29*	*35.29*	*61.53*
[BCD]	16.20	10.94	9.27	97.93	67.95	45.90	36.73	54.45
[ABCD]	17.75	11.99	10.55	97.82	50.39	34.04	27.76	22.76

Table 5. Best model performance by AG and FIS

Algorithms	Performance evaluation criteria and their values			
	RMSE (%)	RRMSE (%)	MAPE (%)	R² (%)
AG	16.20	10.94	9.27	97.93
FIS	71.48	48.29	35.29	61.53

Table 6. Low performance of models by AG and FIS

Table 7. Summary of best performances by algorithms and configurations

		Performance evaluation criteria and their values				**Types of configurations affected**
Modeling algorithm	**Function or kernel**	**RMSE (en %)**	**RRMSE (en %)**	**MAPE (en %)**	**R² (en %)**	
AG	Adaptation	16,20	10,94	9,27	97,93	BCD
FIS	Abscissa of the center of gravity	71,48	48,29	35,29	61,53	ACD
ANN	MLP	20,779	14,032	12,620	77,569	ABCD (80 Neural)
	RBF	37,161	25,094	25,267	76,009	ACD (100 Neural)
ANFIS	gbellmf	22,450	15,160	13,645	70,605	ACD et BCD
	gaussmf	22,896	19,238	15,294	70,497	ACD
SVM	Linear	24,656	20,200	23,219	72,717	ABCD
	Gaussian	20,723	19,303	26,475	74,026	ABCD
Random Forests	Choice Trees	22.419	15.185	17.372	70.4	ABCD
Naive Bayesian Classifier	Classification	49.79	51.71	24.75	37.34	ABCD
Best performance (model selected)	Adaptation	16,20	10,94	9,27	97,93	BCD

In the second step, as observed in Table 2, the model results of the eleven (11) configurations, after simulation by the AG and the FIS are grouped in Table 4. After the eleven (11) simulations, we obtained the best performance with the [BCD] combination for the genetic algorithm and the [ACD] combination for the Fuzzy Inference System. Table 5 shows us the best performances. For low performances per model, (see table 6), we have the configuration [ABCD] for the FIS and for AG we have the combination [AD].

ANALYSIS AND DISCUSSIONS

Analyzing the results of the characterization, the smallest electrical resistivity value of the soil obtained is 39.908 Ω.m on site 2, while the largest is 277.560 Ω.m on site 3. Which shows a large disparity between the modeling output values.

The asymmetry coefficients being all close to zero (0) and those of flattening close to three (03) indicate on the other hand a good distribution of the data from a statistical point of view. Referring to Table 4, we observe that the correlation coefficients obtained for all the models by AG are greater than 97%, moreover the RRMSE obtained have values greater than 14% (see configuration [AD]). Considering these results, the AGs which are well rated for the optimization problems give us very good performance here for the predictions of the electrical resistivity of soils. Its best performance is obtained by the [BCD] configuration indicating: RMSE = 16.20%; RRMSE = 10.94%; MAPE = 9.27% and an R² = 97.93%. This result overwhelms other results obtained in the literature in terms of performance for predicting the electrical resistivity of soils. In order to better refine the comparison with these results, we have gathered all the best performances obtained with all the algorithms explored in table 7, [4], [6], [23], [24], [43]. These results also take into account the configurations retained by algorithm. Inspired by this table 7, the [ACD] configurator returns for several algorithms, namely: Artificial neural networks with basic radial function; adaptive neuro-fuzzy inference system with functions gbellmf and gaussmf; fuzzy inference system by abscissa of the center of gravity. Concerning the BCD configuration, it is obtained by adaptive neuro-fuzzy inference system by gbellmf, genetic algorithm by adaptation. Several other best results bringing together the configuring [ABCD] are obtained by: the multilayer perceptron function of artificial neural networks, the linear and Gaussian kernels of Support Vector Machines; random forests and naive Bayesian classifiers. We point out here that no other configuration gave better results than those mentioned above. In summary, we indicate here that the adaptation of genetic algorithms for the prediction of the electrical resistivity of soils in the tropical zone is extremely effective given these results.

CONCLUSION

This work takes into account meteorological variables which have very important influences in the exploitation of electricity in this modern world to explore the prediction of the electrical resistivity of soils. Before tackling it, a literary review allowed us to discover that several algorithms are used on the subject. These are: Artificial Neural Networks with Radial Base Function and Multilayer Perceptron, [6]; Adaptive Neuro Fuzzy Inference System [24]; Support Vector Machines with Gaussian kernels and linear function [6], [43]; Naive Bayesian classifier and random forests, [23]. To do this, the Fuzzy Inference System which made it possible to obtain very relevant results [34] in terms of forecasting caught our attention. Also, having seen that Genetic Algorithms, specially designed for the analysis of optimization problems, can be adapted to explore forecasting work. We also took it as an opportunity and applied it in this work. The data used remains the same, [6], [24], namely: the georeference coordinates of the place (A), the state of nature the day before the measurement (B), the state of nature on day of measurement (C), and the ambient temperature at the measurement point (D) are the input variables. Given the lack of a correlation coefficient close to 1 to definitively validate the existing models, we used the same performance evaluation criteria such as the mean absolute percentage error (MAPE); the square root of the root mean square error (RMSE); the square root of the relative mean square error (RRMSE) and the correlation coefficient (R^2), observed in previous work in order to properly judge our results. The results of our work are as follows: RMSE = 16.20%; RRMSE = 10.94%; MAPE = 9.27% and an R^2 = 97.93% obtained using Genetic Algorithms by the configuration [BCD] and RMSE = 71.48%; RRMSE = 48.29%; MAPE = 35.29% and an R^2 = 97.93% for the fuzzy inference system with the [ACD] configuration. We notice that the [ACD] configuration is obtained as the best combination with several algorithms. Likewise for the [ABCD] configuration. Other results also validated the [BCD] configuration but did not achieve the performance of this work. Given the correlation coefficient very close to 1, the RRMSE which is around 13 and the possibility of adapting genetic algorithms for the processing of forecasting work, then we retain this algorithm as the best for predicting the electrical resistivity of soils. However, it will be necessary to confirm the quality of this work by finding the optimization function and then integrating it into an automated system in order to experiment with the results of all this work.

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