Article

Neural DE: an evolutionary method based on Differential Evolution suitable for neural network training

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Abstract: Artificial neural networks have proven to be an important machine learning model that has been widely used in recent decades in a number of difficult problems of classification or data fitting from real - world areas. Due to their importance, a number of techniques have been developed that efficiently identify the parameter vector for these models. These techniques usually come from the field of optimization and, by minimizing the training error of artificial neural networks, estimate the vector of their parameters. However, many times these techniques either get trapped in local minima of the training error or lead to overfitting the artificial neural network, resulting in poor performance when applied to data that was not present during the training process. This paper presents an innovative training technique for artificial neural networks based on the Differential Evolution optimization method. This new technique creates an initial population of artificial neural networks that evolve and periodically applies a local optimization technique in order to accelerate the training of these networks. The application of the local minimization technique is done in such a way as to avoid the phenomenon of overfitting. This new method was successfully applied to a series of classification and data fitting problems and a comparative study was made with other training techniques from the relevant literature.

Keywords: Neural networks; Evolutionary methods; Differential Evolution; Machine learning

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1. Introduction

An artificial neural network [1,2] is defined commonly as a function $N(\overrightarrow{x},\overrightarrow{w})$, where the vector $\overrightarrow{x}$ stands for the input pattern and the vector $\overrightarrow{w}$ (weight vector) represents the vector of parameters for this particular network. This function is used in classification and regression problems and the training procedure refers to the adaptation of $\overrightarrow{w}$ by minimizing the so-called training error defined as:

$$E\left(N\left(\overrightarrow{x},\overrightarrow{w}\right)\right)=\sum_{i=1}^{M}\left(N\left(\overrightarrow{x}_i,\overrightarrow{w}\right)-y_i\right)^2 \quad (1)$$

Where the set $\left(\overrightarrow{x_i},y_i\right),\ i=1,\ldots,M$ stands for the train set for the training process. The values y_i denote the expected outputs for the $\overrightarrow{x_i}$ patterns. These model have been applied successfully on a variety of cases from real world problems, such as problems found in physics [3–5], problems related to the solution of differential equations [6], problems related to solar radiation[7], agriculture problems [8], problems appeared in chemistry [9,10], economics problems [11,12], medicine problems [13,14] etc.

Due to the widespread use of artificial neural networks, a significant range of methods has been developed that identify the optimal parameter vector by minimizing equation 1. This set of methods included the Back Propagation method [15,16], the RPROP method [17], the Adam optimizer[18] etc. Also, more recent approaches have been used to train artificial neural networks such as the Simulated Annealing method [19], modified version of the Genetic Algorithm [20], the Particle Swarm Optimization (PSO) method [21], the Ant

Colony Optimization technique [22] etc. Moreover, Sexton et al. proposed the incorporation of the tabu search algorithm for neural network training [23] and Zhang et al. suggested a hybrid algorithm [24] that utilizes the PSO method and the Back Propagation method for efficient neural network training. Also, Karaboga suggested the application of the Artificial Bee Colony (ABC) algorithm to train artificial neural networks [26]. Recently, Zhao et al proposed a new Cascaded Forward Algorithm to train artificial neural networks [25].

However, in many cases, although the above techniques can significantly reduce the error of equation 1, they lead the artificial neural network to overfitting, that is, the network exhibits significantly reduced performance on data that was not present during training. This problem has been studied extensively in the relevant literature and a number of methods have been proposed to address it, such as weight sharing [27,28], pruning [29,30], early stopping [31,32], weight decaying [33,34] etc.

This paper proposed a new evolutionary optimization technique based on Differential Evolution [35] to efficiently train artificial neural networks. The Differential Evolution (DE) method was initially proposed by Storn and Price [36,37] and it has been applied successfully on a variety of optimization problems, such as community detection [38], structure prediction [39], motor fault diagnosis [40], clustering techniques [41] etc. The method also has been used in machine learning applications, such as as classification methods [43,44], feature selection techniques [45,46], deep learning [47,48], etc. In the current work a series of modifications are incorporated in the DE method in order to efficient train artificial neural networks. Among these modifications one finds the periodic and controlled application of a local optimization method to randomly selected neural networks from the population of the DE method. The application of the local technique is done by ensuring that the parameters of the neural network remain within a specific value range, thus avoiding, to the extent possible, any overfitting that could occur. Furthermore, in the modifications there is a termination rule that, on the one hand, is based on stochastic observations regarding the evolution of the population of the DE method and, on the other hand, uses the special characteristics of the error function of the artificial neural network.

The rest of this article is organized as follows: in section 2 the proposed algorithm is fully outlined, in section 3 the datasets used in the experiments are listed accompanied by a series of experiments regarding various aspects of the proposed method and finally some conclusions are presented in section 4.

2. The proposed method

The Differential Evolution method involves a series of candidate solutions called agents. These agents evolve through a series of iterations aiming to obtain the global minimum of the corresponding objective function. In the present method, each agent also constitutes a vector of parameters of an artificial neural network and the objective function to be minimized is the error function presented previously. The neural networks used in the current work are expressed through the equation:

$$N(\overrightarrow{x},\overrightarrow{w})=\sum_{i=1}^{H}w_{(d+2)i-(d+1)}\sigma\left(\sum_{j=1}^{d}x_jw_{(d+2)i-(d+1)+j}+w_{(d+2)i}\right) \tag{2}$$

that was initially suggested in [49]. The constant H denotes the number of processing units for the neural network and the constant d stands for the number of elements in the input pattern $\overrightarrow{x}$. Hence, the number of elements in the parameter vector $\overrightarrow{w}$ are calculated as $n=(d+2)H$. The main steps of the proposed method are as follows:

1. **Initialization Step**.
   - (a) **Set** as NP the number of agents.
   - (b) **Create** randomly the NP agents $g_i,\ i=1,\ldots,\mathrm{NP}$
   - (c) **Compute** the fitness value f_i of each agent g_i using the objective function as $f_i=f(g_i)$.
   - (d) **Set** as p_l the local search rate.

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    (e) Set as $a \geq 1$ the weight parameter for the method.
    (f) Set as $N_g$ the maximum number of iterations allowed.
    (g) Set as $N_I$ the number of iterations used in the stopping rule.
    (h) Set the parameter CR, which represents the crossover probability with CR$\leq 1$.
    (i) Set $k = 0$, the iteration counter.
2. Main Step.
    (a) For $i = 1, \ldots ,$NP do
        i. Obtain the agent $g_i$
        ii. Select randomly three distinct agents $g_a, g_b, g_c$.
        iii. Draw a random integer $R \in [1, n]$.
        iv. Create a trial point $x_t$.
        v. For $j = 1, \ldots .n$ do
            A. Draw a random number $r \in [0, 1]$.
            B. If $r \leq$ CR or $i = R$ then $x_{t,j} = g_{a,j} + F \times \left(g_{b,j} - g_{c,j}\right)$ else $x_{t,j} = g_{i,j}$. The value $F$ represents the differential weight of the DE method and it is calculated as
               $$F = -0.5 + 2r \quad (3)$$
               with $r$ a random number number in $[0, 1]$. This calculation was introduced in the paper of Charilogis et al [50].
        vi. End For
        vii. Set $f_t = f(x_t)$
        viii. If $f_t \leq f_i$ then $g_i = x_t$.
        ix. Draw a random number $r \in [0, 1]$.
        x. If $r \leq p_l$ then
            A. Create the vectors $\overrightarrow{L}, \overrightarrow{R}$ with the properties
               $$\begin{array}{ccc} L_i & = & -a|g_i| \\ R_i & = & a|g_i| \end{array}, \ i = 1, \ldots, n$$
               .
            B. Minimize the error function
               $$E\left(N\left(\overrightarrow{x}, \overrightarrow{g_i}\right)\right) = \sum_{j=1}^{M} \left(N\left(\overrightarrow{x}_j, \overrightarrow{g_i}\right) - y_j\right)^2 \quad (4)$$
               inside the bounds $\overrightarrow{L}, \overrightarrow{R}$ using some local optimization method. In the current work the BFGS variant of Powell [51] was selected as the local optimization method.
            C. Set $f_i = E\left(N\left(\overrightarrow{x}, \overrightarrow{g_i}\right)\right)$.
        xi. End if
    (b) End For
3. Termination check Step.
    (a) Set $k = k + 1$.
    (b) If $k \geq N_g$ then goto step 4.
    (c) Check the termination rule specified in the work of Charilogis et al [50]. In this work the value
        $$\delta^{(k)} = \left| \sum_{i=1}^{\mathrm{NP}} \left| f_i^{(k)} \right| - \sum_{i=1}^{\mathrm{NP}} \left| f_i^{(k-1)} \right| \right| \quad (5)$$
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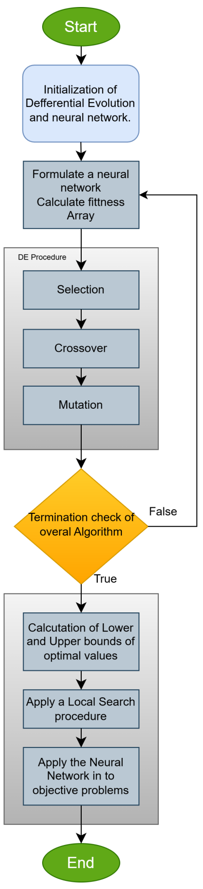
is calculated, where the value $f_i^{(k)}$ represents the fitness value of agent i at iteration k. If $\delta^{(k)} \leq \epsilon$ for a number of N_I iterations, then goto step 4.

   (d) **Obtain** the agent g^* with the lowest fitness value f^*.
   (e) **If** $f^* \leq e$ then goto step 4.
   (f) **Goto** step 2.

4. **Testing step**.
   (a) **Obtain** the agent g^* with the lowest fitness value f^*.
   (b) **Apply** the neural network $N\left(\overrightarrow{x}, \overrightarrow{g^*}\right)$ and report the associated test error.

The main steps of the proposed method are also outlined graphically in Figure 1.



Start
Initialization of Defferential Evolution and neural network.
Formulate a neural network Calculate fittness Array
DE Procedure
Selection
Crossover
Mutation
Termination check of overal Algorithm
False
True
Calcutation of Lower and Upper bounds of optimal values
Apply a Local Search procedure
Apply the Neural Network in to objective problems
End

Figure 1. The flowchart of the proposed method.

3. Experiments

A series of experiments were carried out to determine the effectiveness of the proposed technique and its ability to achieve low generalization errors in classification and data fitting problems. In addition, a series of experiments were performed to determine the stability of the method when critical parameters take different values. In order to perform the experiments a series of classification and regression datasets from the relevant literature was obtained. These datasets can be found in the following websites:

1. The UCI website, https://archive.ics.uci.edu/(accessed on 9 January 2025)[42]
2. The Keel website, https://sci2s.ugr.es/keel/datasets.php(accessed on 9 January 2025)[52].
3. The Statlib URL https://lib.stat.cmu.edu/datasets/index(accessed on 9 January 2025).

3.1. *Experimental datasets*

The following series of classification datasets was used:

1. **Alcohol**, which is related to some experiments regarding alcohol consumption [53].
2. **Australian**, which is related to bank transactions [54].
3. **Bands,** regarding printing problems [55].
4. **Balance** dataset [56], which is related to psychological experiments.
5. **Cleveland**, a medical dataset which was thoroughly studied in the past in a series of research papers [57,58].
6. **Circular** dataset, which created artificially.
7. **Dermatology**, a medical dataset related to dermatology problems [59].
8. **Ecoli**, which is related to protein issues [60].
9. **Haberman**, a medical dataset used for breast cancer detection.
10. **Hayes-roth** dataset [61].
11. **Heart**, a dataset related to heart diseases [62].
12. **HeartAttack**, a dataset related to heart diseases
13. **Hepatitis**, a medical dataset regarding hepatitis.
14. **Housevotes**, that was used in the Congressional voting in USA [63].
15. **Ionosphere**, a dataset related to measurements from the ionosphere [64,65].
16. **Liverdisorder**, which is a medical dataset studied in a series of papers[66,67].
17. **Lymography** [68].
18. **Magic**, this dataset contains measurements from physics simulations [69].
19. **Mammographic**, a medical dataset related to breast cancer [70].
20. **Page Blocks** dataset [74], related to the page layout of documents.
21. **Parkinsons**, a medical dataset for the detection of Parkinson's disease [71,72].
22. **Pima**, a medical dataset related to the presence of diabetes[73].
23. **Phoneme**, a dataset regarding sounds.
24. **Popfailures**, a dataset related to measurements from climate experiments [75].
25. **Regions2**, a medical dataset used for the detection of issues in the liver [76].
26. **Ring**, a dataset related to a series of multivariate normal distributions.
27. **Saheart**, used for the detection of heart diseases.[77].
28. **Segment** dataset [78].
29. **Statheart**, a medical dataset used for the detection of heart diseases.
30. **Sonar** dataset [79].
31. **Spambase**, a dataset used to recognize spam emails.
32. **Spiral**, which is an artificial dataset.
33. **Student**, a dataset concerning experiments in schools [80].
34. **Tae**, used to evaluate teaching performance.
35. **Transfusion**, which is a medical dataset [81].
36. **Wdbc**, a medical dataset which is used to detect breast cancer [82,83].
37. **Wine**, a dataset used to detect the quality of wines [84,85].
38. **EEG** dataset, which is a medical dataset about EEG recordings[86,87]. The following cases from this dataset were adopted here: Z_F_S, ZO_NF_S and ZONF_S.
39. **Zoo**, a dataset used for animal classification [88] .

Additionally, the following series of regression datasets was adopted:

1. **Abalone**, a dataset related to the age of abalones [89].
2. **Airfoil**, a dataset provided by NASA [90].
3. **Auto**, a dataset related to the fuel consumption of cars.
4. **BK**, a dataset which is related to basketball games.
5. **BL**, a dataset related to electricity experiments.
6. **Baseball**, a dataset used to estimate the income of baseball players.
7. **Concrete**, a civil engineering dataset [91].
8. **DEE**, used for the prediction of electricity prices.
9. **FA**, that contains measurements about body fat.
10. **Friedman**, an artificial dataset[92].
11. **FY,** this dataset used in experiments regarding the longevity of fruit flies.
12. **HO**, a dataset with 13 features obtained from the STATLIB repository.

13. **Housing**, used to estimate the price of houses [93].
14. **Laser**, used in a series of laser experiments.
15. **LW**, a dataset used to detect the weight of babes.
16. **Mortgage**, an dataset related to economic measurements.
17. **Plastic**, a dataset related to problems regarding pressure on plastics.
18. **PY** dataset, (Pyrimidines problem). The task of this dataset is the learning of Learning Quantitative Structure Activity Relationships (QSARs)[94].
19. **Quake**, a dataset used to measure earthquakes.
20. **SN**, a dataset related to trellising and pruning.
21. **Stock**, a dataset related to the prices of stocks.
22. **Treasury**, which is related to economics.

3.2. Experimental results

The code used in the current work was implemented using the C++ programming language and the Optimus optimization library, freely available from https://github.com/itsoulos/OPTIMUS (accessed on 9 January 2025). Every experiment was repeated 30 times, using different seed for the random number generator each time. For the validation of the experiments the 10 - fold cross validation technique was incorporated. The machine used in the experiments was an AMD Ryzen 5950X with 128GB of ram, running Debian Linux as the operating system. The values for the parameters of the proposed method are listed in Table 1.

Table 1. The values for the parameters of the proposed method.

PARAMETER	MEANING	VALUE
N_g	Number of maximum allowed generations.	200
NP	Number of agents	500
CR	Crossover probability	0.9
N_I	Number of iterations for termination rule	10
p_l	Local search rate	0.005
a	Weight parameter	2.0
H	Number of processing nodes for neural network	10

The table 2 depicts the experimental results for the classification datasets and Table 3 shows the experimental results for the regression datasets. The used formula for the classification error is:

$$E_C(M(x)) = 100 \times \frac{\sum_{i=1}^{N} \left(\text{class}(M(x_i)) - y_i\right)}{N} \tag{6}$$

where $M(x)$ denotes the used model and the set T represents the train dataset. Likewise, the regression error is defined as:

$$E_R(M(x)) = \frac{\sum_{i=1}^{N} \left(M(x_i) - y_i\right)^2}{N} \tag{7}$$

In all experimental tables the following notation was adopted:

1. The column DATASET denotes the name of the used dataset.
2. The column ADAM represents the incorporation of the ADAM optimizer for the training of a neural network with $H = 10$ processing nodes.
3. The column BFGS stands for the usage of the BFGS optimization method provided by Powell [51] for the training of a neural network with $H = 10$ processing nodes.
4. The column GENETIC represents the usage of a genetic algorithm for the training of a neural network with $H = 10$ processing nodes. The number of chromosomes in this genetic algorithm are equal with the number of agents in the proposed method.

5. The column NEAT stands for the usage of the NEAT method (NeuroEvolution of Augmenting Topologies) [95] for the training of a neural network. This method was implemented in https://github.com/BiagioFesta/EvolutionNet(accessed on 9 January 2025).
6. The column RBF represents the usage of a Radial Basis Function (RBF) network [96,97] with $H = 10$ processing nodes.
7. The row AVERAGE stands for the average classification or regression error for all datasets in the corresponding table.

Table 2. Experimental results for the classification datasets using the series of optimization methods. The numbers in cells represent average classification error measured on the corresponding test set.

DATASET	ADAM	BFGS	GENETIC	NEAT	RBF	NEURALDE
ALCOHOL	57.78%	41.50%	39.57%	66.80%	49.32%	19.15%
AUSTRALIAN	35.65%	38.13%	32.21%	31.98%	34.89%	15.31%
BALANCE	12.27%	8.64%	8.97%	23.14%	33.53%	6.92%
BANDS	36.92%	36.67%	34.92%	34.30%	37.17%	35.00%
CLEVELAND	67.55%	77.55%	51.60%	53.44%	67.10%	45.07%
CIRCULAR	19.95%	6.08%	5.99%	35.18%	5.98%	4.23%
DERMATOLOGY	26.14%	52.92%	30.58%	32.43%	62.34%	10.38%
ECOLI	64.43%	69.52%	54.67%	43.44%	59.48%	45.22%
HABERMAN	29.00%	29.34%	28.66%	24.04%	25.10%	27.55%
HAYES-ROTH	59.70%	37.33%	56.18%	50.15%	64.36%	35.59%
HEART	38.53%	39.44%	28.34%	39.27%	31.20%	17.60%
HEARTATTACK	45.55%	46.67%	29.03%	32.34%	29.00%	19.70%
HEPATITIS	68.13%	72.47%	62.12%	67.04%	64.63%	57.46%
HOUSEVOTES	7.48%	7.13%	6.62%	10.89%	6.13%	7.48%
IONOSPHERE	16.64%	15.29%	15.14%	19.67%	16.22%	16.17%
LIVERDISORDER	41.53%	42.59%	31.11%	30.67%	30.84%	31.72%
LYMOGRAPHY	39.79%	35.43%	28.42%	33.70%	25.50%	28.86%
MAGIC	40.55%	17.30%	21.75%	24.85%	21.28%	11.73%
MAMMOGRAPHIC	46.25%	17.24%	19.88%	22.85%	21.38%	17.52%
PARKINSONS	24.06%	27.58%	18.05%	18.56%	17.41%	14.32%
PAGE BLOCKS	34.27%	8.49%	6.84%	10.22%	10.09%	6.04%
PHONEME	29.43%	15.58%	15.55%	22.34%	23.32%	15.50%
PIMA	34.85%	35.59%	32.19%	34.51%	25.78%	24.85%
POPFAILURES	5.18%	5.24%	5.94%	7.05%	7.04%	6.09%
REGIONS2	29.85%	36.28%	29.39%	33.23%	38.29%	28.77%
RING	28.80%	29.44%	28.80%	30.85%	21.67%	22.90%
SAHEART	34.04%	37.48%	34.86%	34.51%	32.19%	29.63%
SEGMENT	49.75%	68.97%	57.72%	66.72%	59.68%	15.60%
SONAR	30.33%	25.85%	22.40%	34.10%	27.90%	19.80%
SPAMBASE	48.05%	18.16%	6.37%	35.77%	29.35%	4.95%
SPIRAL	47.67%	47.99%	48.66%	48.66%	44.87%	42.06%
STATHEART	44.04%	39.65%	27.25%	44.36%	31.36%	18.53%
STUDENT	5.13%	7.14%	5.61%	10.20%	5.49%	4.86%
TAE	60.20%	51.58%	49.84%	60.67%	60.02%	45.62%
TRANSFUSION	25.68%	25.84%	24.87%	24.87%	26.41%	23.59%
WDBC	35.35%	29.91%	8.56%	12.88%	7.27%	4.29%
WINE	29.40%	59.71%	19.20%	25.43%	31.41%	10.39%
Z_F_S	47.81%	39.37%	10.73%	38.41%	13.16%	6.81%
ZO_NF_S	47.43%	43.04%	21.54%	43.75%	9.02%	4.73%
ZONF_S	11.99%	15.62%	4.36%	5.44%	4.03%	2.41%
ZOO	14.13%	10.70%	9.50%	20.27%	21.93%	6.63%
AVERAGE	**35.88%**	**33.43%**	**26.19%**	**32.66%**	**30.08%**	**19.78%**

Table 3. Experimental results for the provided regression datasets using the series of methods. Numbers in cells represents average regression error calculated on the corresponding test set.

DATASET	ADAM	BFGS	GENETIC	NEAT	RBF	NEURALDE
ABALONE	4.30	5.69	7.17	9.88	7.37	5.04
AIRFOIL	0.005	0.003	0.003	0.067	0.27	0.0014
AUTO	70.84	60.97	12.18	56.06	17.87	16.21
BK	0.0252	0.28	0.027	0.15	0.02	0.019
BL	0.622	2.55	5.74	0.05	0.013	0.016
BASEBALL	77.90	119.63	103.60	100.39	93.02	60.56
CONCRETE	0.078	0.066	0.0099	0.081	0.011	0.003
DEE	0.63	2.36	1.013	1.51	0.17	0.35
FA	0.048	0.426	0.025	0.19	0.015	0.083
FRIEDMAN	22.90	1.263	1.249	19.35	7.23	1.22
HO	0.035	0.62	2.78	0.17	0.03	0.017
HOUSING	80.99	97.38	43.26	56.49	57.68	24.82
LASER	0.03	0.015	0.59	0.084	0.03	0.0026
LW	0.028	2.98	1.90	0.17	0.03	0.021
MORTGAGE	9.24	8.23	2.41	14.11	1.45	0.54
PLASTIC	11.71	20.32	2.791	20.77	8.62	3.27
PY	0.321	0.578	0.56	0.075	0.012	0.11
QUAKE	0.07	0.42	0.04	0.298	0.07	0.042
SN	0.026	0.40	2.95	0.174	0.027	0.027
STOCK	180.89	302.43	3.88	215.82	12.23	3.40
TREASURY	11.16	9.91	2.93	15.52	2.02	1.021
AVERAGE	**22.47**	**30.31**	**9.29**	**24.35**	**9.91**	**5.56**

The analysis of Table 2 evaluates the error rates of various machine learning models across multiple classification datasets. Each row corresponds to a dataset, and each column represents a specific model. The values indicate the error percentages, where lower values signify better performance. The last row provides the average error rate for each model, offering an overall performance summary. Starting with the averages, the NEURALDE model exhibits the best overall performance, achieving the lowest mean error rate of 19.78%. It is followed by GENETIC with an average error rate of 26.19% and RBF at 30.08%. The NEAT model has an average error rate of 32.66%, while BFGS and ADAM display the highest average error rates, 33.43% and 35.88%, respectively. This makes NEURALDE the most efficient model among those compared. On a dataset-specific level, NEURALDE consistently delivers the lowest error rates in numerous cases. For instance, in the ALCOHOL dataset, it achieves the best result with an error rate of 19.15%. Similarly, in the CIRCULAR dataset, NEURALDE outperforms all other models with an error rate of 4.23%, demonstrating its effectiveness in handling complex data structures. In the MAGIC and MAMMOGRAPHIC datasets, NEURALDE again proves superior, with error rates of 11.73% and 17.52%, respectively. There are, however, a few datasets where NEURALDE does not perform as dominantly. For example, in the HOUSEVOTES dataset, it ties with other models at 7.48%. In the ZONF_S dataset, it records its worst performance with an error rate of 2.41%, indicating that its efficiency can vary with certain data characteristics. Other models, such as GENETIC, show strong performance in isolated cases, such as in the SPIRAL dataset (48.66%). However, they generally fall short of NEURALDE's consistent excellence. RBF demonstrates strong stability, with notable results in the DERMATOLOGY (62.34%) and PHONEME (23.32%) datasets. Meanwhile, ADAM and BFGS tend to underperform, particularly in datasets like SPAMBASE, where they record high error rates of 48.05% and 18.16%, respectively. In conclusion, the NEURALDE model stands out as the most effective model overall, achieving the lowest average error rate and excelling in the majority of datasets. While other models, such as RBF and GENETIC, perform well in specific scenarios, NEURALDE demonstrates superior consistency and effectiveness across a wide range of datasets.

The Table 3 presents the performance of various machine learning models on regression problems, where the values represent the error. Lower error values indicate better performance. Each row corresponds to a specific dataset, while the last row shows the average error for each model, providing an overall view of their effectiveness.Based on the average error, NEURALDE demonstrates the best performance, with the lowest overall error of 5.56. This result suggests that the model consistently performs well across most datasets. Following NEURALDE are GENETIC with an average error of 9.29 and RBF with an average error of 9.91. ADAM, NEAT, and BFGS exhibit higher average errors, at 22.47, 24.35, and 30.31 respectively, indicating lower performance compared to the other models. Analyzing the results dataset by dataset, NEURALDE records the smallest error in several cases. For instance, in the AIRFOIL dataset, it achieves an error of 0.0014, outperforming all other models. In the CONCRETE dataset, its error is only 0.003, the lowest among all models. Similarly, in the LASER dataset, it achieves an exceptionally low error of 0.0026. In the TREASURY dataset, NEURALDE demonstrates superior performance with an error of 1.021, better than all other models. GENETIC shows competitive performance in several datasets. For example, in the HOUSING dataset, it achieves an error of 43.26, which is better than ADAM and NEAT but not as strong as NEURALDE. In the PLASTIC dataset, its error is 2.791, which is significantly lower than most other models except NEURALDE.

RBF achieves low errors in some datasets, such as MORTGAGE, where it records an error of 1.45, the second-best result after NEURALDE (0.54). However, in other datasets like STOCK, where it has an error of 12.23, RBF underperforms compared to GENETIC and NEURALDE. ADAM and NEAT exhibit higher errors across many datasets. For example, in the STOCK dataset, ADAM records the highest error at 180.89, followed by NEAT at 215.82. Conversely, in the AIRFOIL dataset, ADAM achieves a relatively low error of 0.005, though it still falls short of NEURALDE. BFGS generally shows higher errors, such as in the BASEBALL dataset (119.63), reflecting its limited performance. In summary, NEURALDE stands out as the most effective regression model, with consistently low errors and the lowest average error overall. GENETIC and RBF display competitive performance in some datasets but lack the same consistency. ADAM, NEAT, and BFGS exhibit significantly higher errors, indicating their inferior performance compared to NEURALDE.

An extensive analysis was conducted on the performance of different machine learning models using various optimization methods, with pairwise comparisons made through the Wilcoxon Test. The study was carried out on a set of well-known datasets and focused on the NEURALDE model, comparing it with other popular optimization methods such as ADAM, BFGS, GENETIC, NEAT, and RBF. The Wilcoxon Test, a non-parametric statistical method, is ideal for evaluating performance differences, especially when the data does not follow a normal distribution Figure 2. The results revealed significant performance differences between NEURALDE and other models. Specifically, the p-value for the comparison between NEURALDE and ADAM was p=4.7e-08, a very low value that indicates the differences between the two models are statistically significant and unlikely to be due to chance. The p-value for the comparison between NEURALDE and BFGS was even lower, at p=1e-18, suggesting substantial performance differences, with NEURALDE outperforming BFGS by a wide margin. Similarly, the comparison between NEURALDE and GENETIC yielded p=2.9e-09, confirming that the two methods show distinct performance, with NEURALDE being superior. The comparison between NEURALDE and NEAT showed p=2.3e-10, while the comparison with RBF resulted in p=1.3e-08. In both cases, the p-values were extremely low, proving that the performance differences are statistically significant. This analysis highlights NEURALDE as a standout model among the datasets used, showing significant performance differences compared to the other methods. The very low p-values in all comparisons demonstrate that the observed differences are not due to random chance, but rather reflect the true superiority or differentiation of NEURALDE. The methods ADAM, BFGS, GENETIC, NEAT, and RBF are widely used and effective in many cases, but this analysis suggests that NEURALDE excels in specific problems or datasets. This statistical analysis provides valuable insight into the selection of appropriate models and optimization methods for machine learning tasks. Although the specific p-values and results pertain to the datasets used in this study, the significance of the findings underscores the importance of careful evaluation when selecting models.

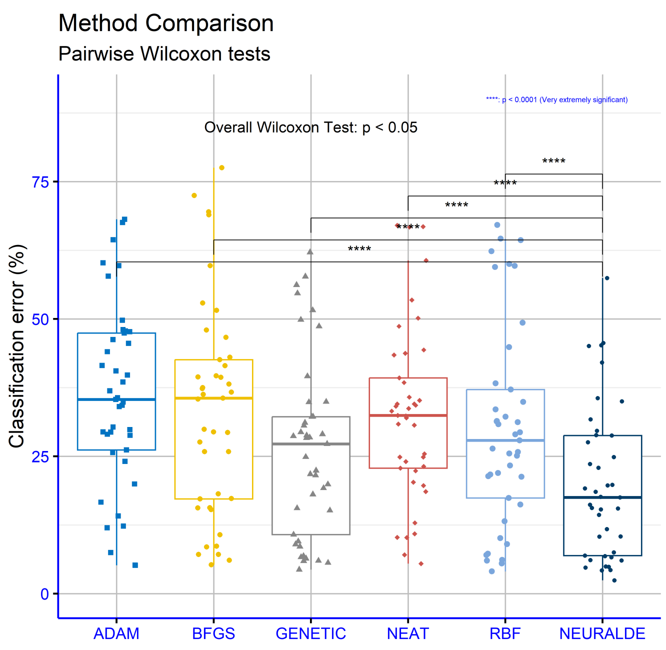


Figure 2. Statistical comparison of the used machine learning models for the classification datasets.

Furthermore, an analysis was conducted to compare various machine learning models employing different optimization methods in terms of regression error. The study was performed using a script in R, employing the Wilcoxon Test for pairwise comparisons. This non-parametric statistical test is suitable for data that do not follow a normal distribution Figure 3. The experiments were conducted on a series of well-known datasets, ensuring diversity across problem domains. The results revealed significant differences in regression error between the NEURALDE model and other optimization methods. Specifically, the comparison between NEURALDE and ADAM yielded a p-value of 0.00051, indicating a statistically significant difference in favor of NEURALDE. Similarly, the comparison with BFGS showed an even smaller p-value of 9.5e-07, highlighting the clear superiority of NEURALDE in this context. The analysis of NEURALDE against GENETIC resulted in a p-value of 0.0033, further supporting the significance of the observed difference. Likewise, the comparison with NEAT gave a p-value of 2.9e-06, and with RBF, the p-value was 0.0048, demonstrating statistically significant differences in all cases. These findings indicate that NEURALDE consistently outperforms the other optimization methods analyzed in terms of reducing regression error. The exceptionally low p-values across all comparisons suggest that these differences are unlikely to be due to random variation and reflect a genuine advantage. While other methods such as ADAM, BFGS, GENETIC, NEAT, and RBF are generally effective across various tasks, the results show that NEURALDE exhibits superior performance in minimizing regression error for the datasets analyzed. This analysis provides valuable insights for selecting appropriate models and optimization techniques in regression tasks. Although the results are specific to the datasets used in the study, the statistical significance of the findings highlights the importance of careful evaluation when choosing a model.

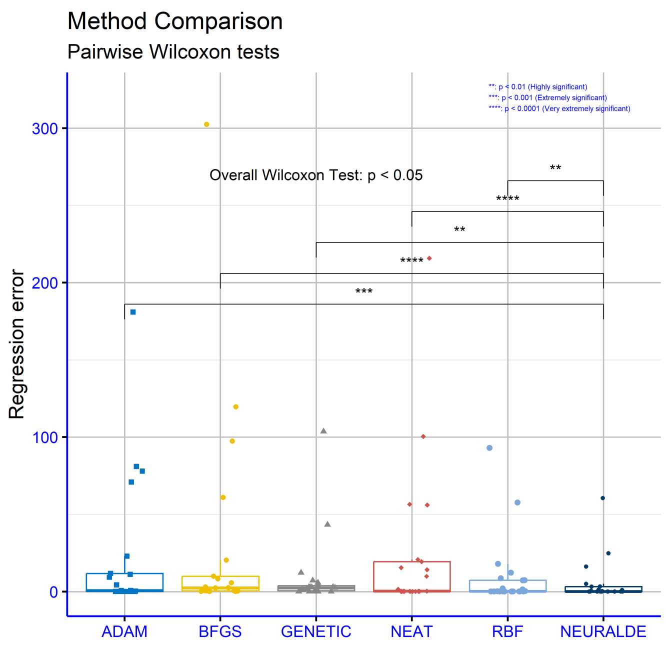


Figure 3. Statistical comparison between the machine learning models for the regression datasets.

3.2.1. Experiments with the differential weight

Another series of experiments was carried out in order to determine the effect that the specific differential weight calculation mechanism has on the accuracy of the proposed technique. For this reason the following methods for the calculation of the differential weight (parameter F) were used:

- The method denoted as MIGRANT in the experimental tables. In this case the differential weight mechanism proposed in [98] was used.
- The method denoted as ADAPTIVE in the experimental tables. This method uses the differential weight calculation proposed in [99].
- The method represented as RANDOM in the experimental tables. This method is the default method, suggested by Charilogis [50].

The table 4 provides the performance of three differential weight computation methods (MIGRANT, ADAPTIVE, and RANDOM) on the series of classification datasets. The analysis reveals that the MIGRANT method achieves the smallest average error rate of 19.34%, indicating the best overall performance among the three methods. The RANDOM method follows closely with an average error rate of 19.78%, while the ADAPTIVE method has the highest average error rate of 19.98%, suggesting it is the least effective on average. Examining individual datasets, MIGRANT outperforms the other methods in several cases. For example, in the HEART dataset, MIGRANT records an error rate of 19.01%, better than ADAPTIVE (17.29%) and RANDOM (17.60%). Similarly, in the MAGIC dataset, MIGRANT achieves a competitive error rate of 11.83%, which is close to RANDOM (11.73%) but higher than ADAPTIVE (11.28%). MIGRANT also has the lowest error in datasets such as ALCOHOL (19.62%), REGIONS2 (26.26%), and SPAMBASE (5.87%). ADAPTIVE demonstrates strong performance in specific datasets, achieving the lowest error rates in cases such as MAGIC (11.28%) and HEART (17.29%). However, in many datasets, it performs worse than MIGRANT or RANDOM, such as in SPAMBASE, where it records a lower error rate of 4.78% but is generally outperformed in other critical datasets. The RANDOM method exhibits competitive performance in several datasets, achieving the lowest error rates in examples like ZOO (6.63%) and ZONF_S (2.41%). However, its performance fluctuates more significantly, with higher error rates in datasets such as HEARTATTACK (19.70%) and REGIONS2 (28.77%), where it is outperformed by MIGRANT and ADAPTIVE. Notable observations include cases where the error rates are very close across the methods, such as in datasets like CIRCULAR, where the differences are minimal (MIGRANT at 4.28%, ADAPTIVE at 4.34%, and RANDOM at 4.23%). In other cases, the differences are more pronounced, as in SEGMENT, where MIGRANT achieves 9.71%, significantly better than ADAPTIVE (15.99%) and RANDOM (15.60%). Overall, MIGRANT demonstrates the most consistent and robust performance across the datasets, with the lowest average error and competitive results in many individual datasets. RANDOM and ADAPTIVE have comparable average errors but show more variability in their performance.

Table 4. Experimental results for the classification datasets using a list of proposed differential weight mechanisms found in the literature.

DATASET	MIGRANT	ADAPTIVE	RANDOM
ALCOHOL	19.62%	18.44%	19.15%
AUSTRALIAN	14.77%	16.14%	15.31%
BALANCE	6.79%	6.94%	6.92%
BANDS	33.28%	35.42%	35.00%
CLEVELAND	45.74%	44.60%	45.07%
CIRCULAR	4.28%	4.34%	4.23%
DERMATOLOGY	11.41%	9.83%	10.38%
ECOLI	42.61%	47.51%	45.22%
HABERMAN	27.76%	28.35%	27.55%
HAYES-ROTH	35.92%	36.31%	35.59%
HEART	19.01%	17.29%	17.60%
HEARTATTACK	21.31%	20.28%	19.70%
HEPATITIS	56.37%	56.46%	57.46%
HOUSEVOTES	7.47%	7.54%	7.48%
IONOSPHERE	15.88%	16.40%	16.17%
LIVERDISORDER	32.56%	32.54%	31.72%
LYMOGRAPHY	26.52%	28.95%	28.86%
MAGIC	11.83%	11.28%	11.73%
MAMMOGRAPHIC	17.69%	17.44%	17.52%
PARKINSONS	13.28%	14.21%	14.32%
PAGE BLOCKS	5.48%	5.93%	6.04%
PHONEME	15.39%	15.17%	15.50%
PIMA	25.04%	23.28%	24.85%
POPFAILURES	5.55%	6.55%	6.09%
REGIONS2	26.26%	28.98%	28.77%
RING	21.04%	25.54%	22.90%
SAHEART	29.94%	29.80%	29.63%
SEGMENT	9.71%	15.99%	15.60%
SONAR	18.83%	18.93%	19.80%
SPAMBASE	5.87%	4.78%	4.95%
SPIRAL	41.36%	41.54%	42.06%
STATHEART	20.79%	19.32%	18.53%
STUDENT	4.36%	5.28%	4.86%
TAE	45.09%	44.78%	45.62%
TRANSFUSION	23.01%	24.51%	23.59%
WDBC	3.80%	4.55%	4.29%
WINE	8.22%	12.84%	10.39%
Z_F_S	7.16%	7.15%	6.81%
ZO_NF_S	4.19%	4.70%	4.73%
ZONF_S	2.47%	2.44%	2.41%
ZOO	5.23%	6.87%	6.63%
AVERAGE	**19.34%**	**19.98%**	**19.78%**

The Table 5 presents the performance of three differential weight computation methods (MIGRANT, ADAPTIVE, and RANDOM) on the regression datasets. The RANDOM method achieves the lowest average error, 5.56, making it the most effective overall. ADAPTIVE follows with an average error of 6.23, while MIGRANT exhibits the highest average error at 8.03, indicating the least effective performance. For specific datasets, RANDOM often outperforms the others. For instance, in the HOUSING dataset, it records an error of 24.82, lower than MIGRANT (14.58) and ADAPTIVE (32.62). Similarly, in the PLASTIC dataset, RANDOM achieves the smallest error of 3.27 compared to MIGRANT (5.36) and ADAPTIVE (3.57). RANDOM also shows superior performance in datasets like MORTGAGE (0.54) and STOCK (3.4). ADAPTIVE demonstrates strong performance in certain datasets, such as FRIEDMAN, where its error is 1.32, outperforming MIGRANT (1.66) and RANDOM (1.22). In the QUAKE dataset, ADAPTIVE records the lowest error of 0.041. However, its performance is noticeably weaker in other datasets, like HOUSING, where it registers the highest error of the three. MIGRANT outperforms in a few cases, such as the BL dataset, where its error is 0.007, significantly lower than ADAPTIVE (0.019) and RANDOM (0.016). However, it generally records higher errors in many datasets, such as AUTO (45.37) and BASEBALL (79.24), where the other methods perform better. In some cases, such as the LASER dataset, all methods perform similarly, with errors of 0.0026 for MIGRANT and RANDOM, and 0.0027 for ADAPTIVE. In the QUAKE dataset, the differences are also minimal, with RANDOM having the highest error (0.042), but very close to the others. Overall, RANDOM emerges as the most reliable and effective method, with the lowest average error and frequent superiority across individual datasets. ADAPTIVE performs well in selected datasets but shows greater variability, while MIGRANT demonstrates the least effective performance, with higher errors across numerous datasets.

Table 5. Experimental results for the regression datasets using a variety of differential weigh methods.

DATASET	MIGRANT	ADAPTIVE	RANDOM
ABALONE	4.57	5.97	5.04
AIRFOIL	0.002	0.0011	0.0014
AUTO	45.37	18.89	16.21
BK	0.28	0.02	0.019
BL	0.007	0.019	0.016
BASEBALL	79.24	61.89	60.56
CONCRETE	0.0028	0.0029	0.003
DEE	0.27	0.35	0.35
FA	0.051	0.10	0.083
FRIEDMAN	1.66	1.32	1.22
HO	0.009	0.014	0.017
HOUSING	14.58	32.62	24.82
LASER	0.0026	0.0027	0.0026
LW	0.0189	0.044	0.021
MORTGAGE	0.43	0.93	0.54
PLASTIC	5.36	3.57	3.27
PY	0.12	0.14	0.11
QUAKE	0.038	0.041	0.042
SN	0.023	0.031	0.027
STOCK	15.94	3.58	3.40
TREASURY	0.70	1.24	1.021
AVERAGE	**8.03**	**6.23**	**5.56**

An analysis was conducted to compare different methods for computing differential weights in a proposed machine learning approach, focusing on classification error. The analysis employed the Wilcoxon Test for pairwise comparisons and was applied to the classification datasets. The goal was to examine whether statistically significant differences exist among the three approaches: MIGRANT, ADAPTIVE, and RANDOM Figure 4. The results showed that the comparison between MIGRANT and ADAPTIVE yielded a p-value of 0.085. Although this value suggests a trend of differentiation, it does not fall below the conventional significance threshold of 0.05, indicating that the difference is not statistically significant. Similarly, the comparison between MIGRANT and RANDOM produced a p-value of 0.064, which, while closer to significance, also does not meet the required threshold. Finally, the comparison between ADAPTIVE and RANDOM resulted in a p-value of 0.23, indicating no statistically significant difference between these two methods. Overall, the findings suggest that while there are indications of differences in behavior among the three approaches, none of these differences are statistically significant based on the data analyzed. This implies that the three methods for computing differential weights may be considered equivalent in terms of their impact on classification error, at least for the datasets used in this study.

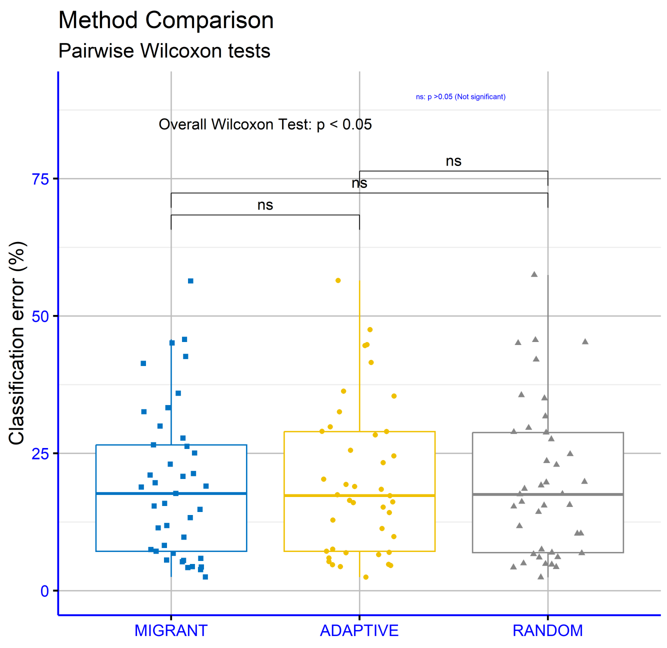


Figure 4. Statistical comparison for the obtained results on the classification datasets using a series of differential weight mechanisms.

An analysis was conducted to compare different methods for calculating differential weight in the proposed machine learning approach on the regression datasets. The Wilcoxon Test was used for pairwise comparisons, applied across the series of regression datasets, with a focus on regression error. The aim was to determine the statistical significance of the observed differences between the methods Figure 5. The results showed that the comparison between MIGRANT and ADAPTIVE yielded a p-value of 0.68, indicating no statistically significant difference between these two methods. Similarly, the comparison between MIGRANT and RANDOM resulted in a p-value of 0.9, confirming the absence of a statistically significant difference in this case as well. However, the comparison between ADAPTIVE and RANDOM produced a p-value of 0.00095, which is below the standard threshold for statistical significance (commonly 0.05). This suggests a statistically significant difference between these two approaches. Overall, the findings indicate that the MIGRANT and ADAPTIVE methods, as well as the MIGRANT and RANDOM methods, exhibit similar performance regarding regression error. In contrast, the ADAPTIVE method shows a clear and statistically significant differentiation from the RANDOM method.

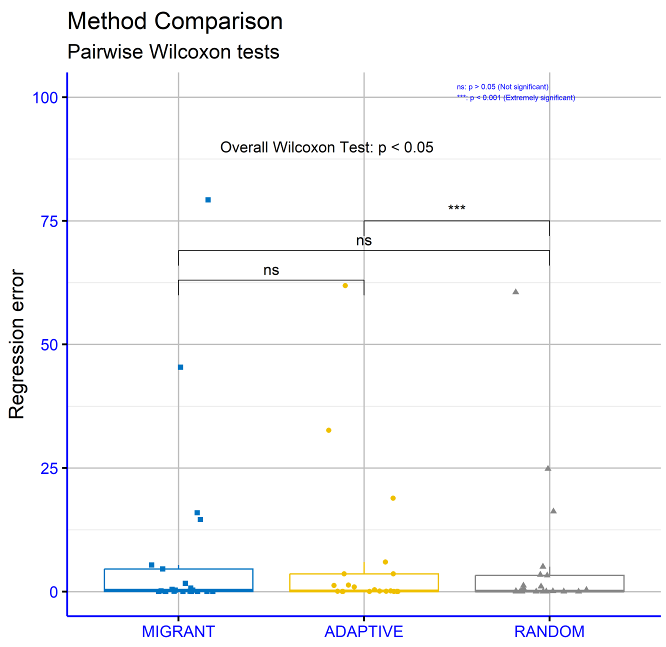


Figure 5. Statistical comparison between the various differential weight mechanisms for the regression datasets.

3.2.2. Experiments with the factor a

In the next series of experiments, the effect of the parameter a on the behavior of the method on classification and data fitting data was studied. In this series of experiments, different values of this parameter were studied. This parameter determines the allowable range of values within which the local minimization method can vary the parameters of the artificial neural network.

The Table 6 presents error percentages across the used classification datasets for different values of the parameter a (1.25, 1.5, 2, 4, and 8). The lowest overall average error is observed for $a = 2$ with an average of 19.78%. This suggests that $a = 2$ provides the most balanced performance across datasets. The other parameter values—1.25, 1.5, 4, and 8—yield average errors of 19.98%, 19.95%, 20.00%, and 19.95%, respectively. These results indicate that $a = 2$ has a slight advantage in minimizing the overall error compared to other values. For individual datasets, the performance varies depending on the parameter value. For example, in the ALCOHOL dataset, the smallest error is achieved at $a = 2$ with 19.15%, while other values result in slightly higher errors. Similarly, in the SEGMENT dataset, the error is minimized at $a = 8$ with 14.27%. However, in datasets like SPIRAL, the errors across all parameter values are close, with no significant advantage for any specific value. In certain datasets, there is a clear trend in error reduction as the parameter value changes. For example, in the SEGMENT dataset, errors decrease consistently from $a = 1.25$ to $a = 8$. Conversely, in the ZOO dataset, the error decreases for lower values of a but increases again at higher values, indicating that performance is not always linear with changes in a. Some datasets exhibit minimal variability in performance across parameter values. For example, the error for the LIVERDISORDER dataset remains relatively stable, ranging from 31.41% to 32.33%. Similarly, the SPIRAL dataset shows little variation, with errors consistently around 42%. In other cases, specific parameter values consistently underperform. For instance, in the Z_F_S dataset, $a = 1.5$ achieves the lowest error of 6.67%, while $a = 2$ and $a = 4$ result in slightly higher errors. Similarly, $a = 8$ achieves the smallest error for certain datasets like SEGMENT but performs poorly for datasets like WINE. Overall, $a = 2$ emerges as the most effective parameter value, yielding the smallest average error across datasets. While other values of a perform well in individual cases, their overall performance is less consistent.

Table 6. Experimental results for the classification datasets using different values for the critical parameter a

DATASET	$a = 1.25$	$a = 1.5$	$a = 2$	$a = 4$	$a = 8$
ALCOHOL	21.49%	20.20%	19.15%	22.34%	19.86%
AUSTRALIAN	16.43%	16.89%	15.31%	15.90%	16.16%
BALANCE	7.49%	7.56%	6.92%	7.01%	7.16%
BANDS	34.88%	35.09%	35.00%	35.61%	35.01%
CLEVELAND	44.86%	46.08%	45.07%	44.67%	45.07%
CIRCULAR	4.17%	4.26%	4.23%	4.49%	4.61%
DERMATOLOGY	10.77%	10.65%	10.38%	9.87%	8.94%
ECOLI	44.13%	45.87%	45.22%	46.65%	47.46%
HABERMAN	27.24%	27.02%	27.55%	27.91%	28.40%
HAYES-ROTH	36.95%	36.46%	35.59%	35.82%	33.21%
HEART	17.43%	17.17%	17.60%	17.19%	17.19%
HEARTATTACK	19.50%	19.27%	19.70%	19.69%	19.69%
HEPATITIS	59.00%	57.38%	57.46%	60.21%	60.96%
HOUSEVOTES	7.07%	7.90%	7.48%	7.06%	7.07%
IONOSPHERE	14.24%	15.48%	16.17%	16.17%	15.43%
LIVERDISORDER	31.41%	31.59%	31.72%	32.23%	32.33%
LYMOGRAPHY	27.00%	27.07%	28.86%	27.57%	27.09%
MAGIC	12.18%	11.94%	11.73%	11.78%	12.25%
MAMMOGRAPHIC	17.42%	17.46%	17.52%	17.56%	17.54%
PARKINSONS	13.67%	13.40%	14.32%	14.19%	13.83%
PAGE BLOCKS	6.32%	6.28%	6.04%	5.83%	5.92%
PHONEME	16.07%	15.69%	15.50%	15.00%	15.00%
PIMA	24.59%	24.61%	24.85%	24.57%	24.79%
POPFAILURES	4.90%	5.28%	6.09%	7.50%	6.94%
REGIONS2	29.35%	28.94%	28.77%	28.79%	28.69%
RING	27.65%	26.97%	22.90%	23.92%	23.20%
SAHEART	29.33%	29.37%	29.63%	29.97%	30.47%
SEGMENT	18.18%	16.86%	15.60%	14.53%	14.27%
SONAR	19.27%	19.62%	19.80%	18.87%	20.16%
SPAMBASE	4.67%	5.07%	4.95%	5.00%	5.87%
SPIRAL	41.92%	41.76%	42.06%	41.49%	42.13%
STATHEART	19.22%	18.91%	18.53%	19.30%	20.22%
STUDENT	4.76%	4.55%	4.86%	5.84%	6.43%
TAE	47.54%	46.22%	45.62%	46.07%	44.38%
TRANSFUSION	23.74%	23.87%	23.59%	23.95%	24.15%
WDBC	4.48%	4.50%	4.29%	4.12%	4.14%
WINE	9.24%	9.67%	10.39%	10.39%	11.88%
Z_F_S	7.26%	6.67%	6.81%	6.64%	6.70%
ZO_NF_S	4.82%	4.91%	4.73%	4.42%	4.33%
ZONF_S	2.42%	2.55%	2.41%	2.68%	2.60%
ZOO	6.23%	6.93%	6.63%	7.07%	6.40%
AVERAGE	**19.98%**	**19.95%**	**19.78%**	**20.00%**	**19.95%**

The Table 7 presents error rates for the regression datasets across different values of the critical parameter a (1.25, 1.5, 2, 4, and 8). The lowest average error is observed for $a = 1.5$, with an average of 5.39, suggesting it offers the best overall performance. $a = 1.25$ ranks second with an average of 5.46, and $a = 2$ slightly higher at 5.56. The values $a = 4$ and $a = 8$ show a marked increase in errors, with averages of 5.94 and 7.44, respectively. This indicates that higher values of a are less effective compared to smaller ones. For individual datasets, performance varies with the value of a. For instance, in the AIRFOIL dataset, the error consistently decreases as a increases, with the smallest error (0.0007) observed at $a = 8$. Conversely, in the FRIEDMAN dataset, the error rises sharply at $a = 8$ (19.74), signaling a significant performance decline. In some datasets, such as BASEBALL, the error steadily increases with higher values of a rising from 57.67 at a=1.25 to 72.37 at $a = 8$. In contrast, in the HOUSING dataset, the smallest error occurs at $a = 4$ (22.86), although larger values like $a = 8$ show only a slight increase. Certain datasets exhibit minimal sensitivity to changes in a. For example, in the LASER dataset, errors remain almost constant regardless of the parameter value, ranging from 0.0025 to 0.0035. Similarly, in the DEE dataset, the errors are nearly identical across all values of a showing minimal variation. Interestingly, the PLASTIC dataset shows a gradual decrease in error from 3.37 at a=1.25 to 2.8 at a=8, indicating improved performance with increasing a. Conversely, in the STOCK dataset, the error increases significantly from 2.82 at a=1.25 to 5.42 at $a = 8$. In conclusion, $a = 1.5$ emerges as the optimal choice for minimizing overall error in this analysis. Higher values of a demonstrate reduced effectiveness, especially at $a = 8$, where the average error rises notably. However, the results reveal that the impact of a varies by dataset, with some benefiting from smaller values and others exhibiting relative insensitivity to parameter changes.

Table 7. Experimental results for the regression datasets using different values for the critical parameter a.

DATASET	$a = 1.25$	$a = 1.5$	$a = 2$	$a = 4$	$a = 8$
ABALONE	4.36	4.66	5.04	7.63	8.84
AIRFOIL	0.002	0.0018	0.0014	0.0009	0.0007
AUTO	14.97	14.72	16.21	16.04	16.58
BK	0.02	0.02	0.019	0.11	0.21
BL	0.011	0.012	0.016	0.037	0.11
BASEBALL	57.67	58.42	60.56	67.70	72.37
CONCRETE	0.003	0.003	0.003	0.004	0.005
DEE	0.35	0.34	0.35	0.34	0.34
FA	0.067	0.056	0.083	0.24	0.42
FRIEDMAN	1.30	1.24	1.22	1.41	19.74
HO	0.011	0.012	0.017	0.043	0.17
HOUSING	28.09	25.93	24.82	22.86	26.45
LASER	0.0026	0.0025	0.0026	0.0027	0.0035
LW	0.019	0.019	0.021	0.073	0.77
MORTGAGE	0.50	0.45	0.54	0.75	0.62
PLASTIC	3.37	3.10	3.27	3.02	2.80
PY	0.12	0.13	0.11	0.09	0.09
QUAKE	0.04	0.041	0.042	0.048	0.096
SN	0.024	0.024	0.027	0.087	0.17
STOCK	2.82	3.13	3.40	3.21	5.42
TREASURY	0.87	0.81	1.021	1.06	1.06
AVERAGE	**5.46**	**5.39**	**5.56**	**5.94**	**7.44**

In Figure 6, a comparison of various values of the parameter a which defines the bounds of optimal values in the proposed machine learning method, is presented. The comparisons were conducted using the Wilcoxon Test across the series of used datasets to evaluate the classification error. The results indicate that the p-values for all pairwise comparisons between different values of a are above the significance level of 0.05, suggesting no statistically significant differences. For instance, comparisons between $a = 1.25$ and other values (1.5, 2, 4, 8) yielded p-values ranging from 0.6 to 0.73, while comparisons between $a = 1.5$ and other values (2, 4, 8) produced p-values ranging from 0.32 to 0.8. Similarly, comparisons between $a = 2$ and higher values (4 and 8) resulted in p-values of 0.22 and 0.31, respectively, whereas the comparison between $a = 4$ and $a = 8$ yielded a p-value of 0.69. In conclusion, the results suggest that variations in the parameter a within the specified range do not lead to statistically significant differences in classification error, as all p-values remain well above the conventional significance threshold. Therefore, the choice of a specific value for a is likely to have little or no impact on the method's performance, based on the current data.

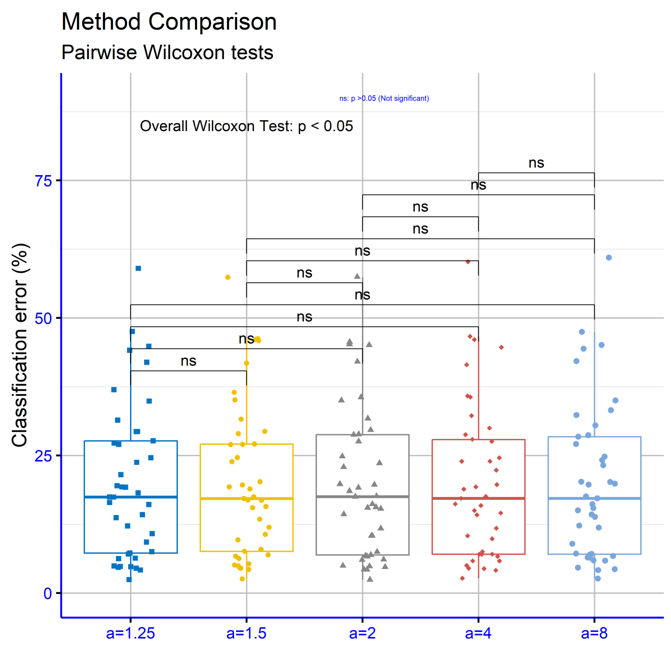


Figure 6. Statistical comparison for the experiments with different values for the parameter a. The method was applied on the classification datasets.

In Figure 7, the comparison of different values of parameter a for the regression error is presented. The results showed that statistically significant differences were observed in some comparisons, as the p-values were below the significance level of 0.05. For example, the comparison between $a = 1.25$ and $a = 4$ yielded p=0.024, while between $a = 1.25$ and $a = 8$, p=0.017 was observed. Similarly, the comparison between $a = 1.5$ and $a = 8$ resulted in p=0.0021, indicating strong statistical significance. Conversely, some comparisons did not show statistically significant differences, as the p-values were above the significance level. For instance, the comparison between $a = 2$ and $a = 4$ yielded p=0.22, while the comparison between $a = 1.25$ and $a = 2$ resulted in p=0.15. In conclusion, the results suggest that the choice of parameter a affects the regression error in certain cases, with statistically significant differences primarily observed in comparisons between smaller and larger values of the parameter. However, the differences are not always consistent and depend on the specific combinations of values being compared.

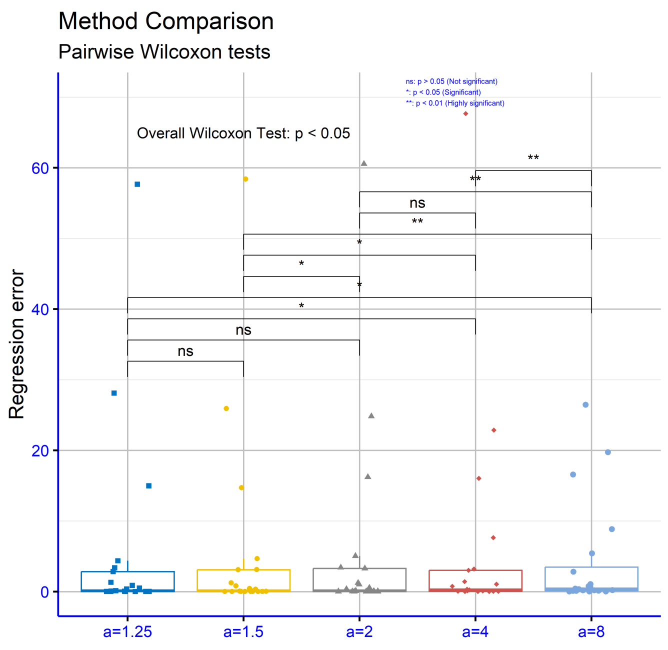


Figure 7. Statistical comparison for the experiments using different values for the parameter a. The method was applied on the regression datasets.

3.2.3. Experiments with the local search rate

In the last series of experiments, the effect of the execution rate of local optimization methods was studied. For this reason, values ranging from 0.25% to 2% were studied.

The Table 8 provides error rates for the used classification datasets under different values of periodic local search p_l (0.0025, 0.005, 0.01, and 0.02). The analysis reveals that the lowest average error is observed $p_l = 0.02$, with an error rate of 19.43%, suggesting that this value yields the best overall performance. This is closely followed by $p_l = 0.01$ with an average error of 19.66% and $p_l = 0.005$ with 19.78%. The highest average error occurs at $p_l = 0.0025$ with 20.48%, indicating comparatively poorer performance. Examining individual datasets, the impact of p_l varies. For instance, in the ALCOHOL dataset, the smallest error is observed at $p_l = 0.02$ with 16.49%, whereas larger values such as $p_l = 0.01$ and $p_l = 0.005$ result in higher errors (21.81% and 19.15%, respectively). Conversely, in the SEGMENT dataset, the error consistently decreases as p_l increases, reaching its lowest value at $p_l = 0.02$ with 11.70%. This trend is also evident in datasets such as SPAMBASE and WINE, where the errors decrease significantly with higher p_l values. Some datasets exhibit minimal sensitivity to changes in p_l. For example, in the HEART and LIVERDISORDER datasets, the error rates remain relatively stable across all p_l values, showing only marginal fluctuations. In other cases, such as CIRCULAR and HOUSEVOTES, the variations in error rates are similarly minor. However, certain datasets show exceptions to the general trend. For example, in the SONAR dataset, the error rate is lowest at $p_l = 0.02$ with 18.53%, but higher p_l values like $p_l = 0.01$ produce increased errors (20.38%). Similarly, the REGIONS2 dataset achieves its best performance at $p_l = 0.02$ with an error rate of 28.02%, but other p_l values yield comparable results, such as 28.77% at both $p_l = 0.005$ and $p_l = 0.01$. The data suggests that higher p_l values, particularly $p_l = 0.02$, generally result in improved performance across most datasets. Nevertheless, the optimal p_l value may vary depending on specific dataset characteristics, and some datasets show negligible or inconsistent responses to changes in p_l. Overall, $p_l = 0.02$ is recommended for achieving the lowest average error.

Table 8. Experimental results for the classification datasets using different values of local search rate p_l.

DATASET	$p_l = 0.0025$	$p_l = 0.005$	$p_l = 0.01$	$p_l = 0.02$
ALCOHOL	19.15%	19.15%	21.81%	16.49%
AUSTRALIAN	17.93%	15.31%	14.17%	14.14%
BALANCE	7.44%	6.92%	6.63%	6.54%
BANDS	35.66%	35.00%	35.01%	34.44%
CLEVELAND	46.45%	45.07%	45.39%	45.32%
CIRCULAR	4.21%	4.23%	4.16%	4.31%
DERMATOLOGY	11.25%	10.38%	9.96%	9.07%
ECOLI	46.64%	45.22%	44.34%	44.66%
HABERMAN	27.99%	27.55%	27.66%	27.43%
HAYES-ROTH	36.33%	35.59%	34.03%	31.44%
HEART	17.05%	17.60%	17.35%	17.51%
HEARTATTACK	19.62%	19.70%	19.43%	20.37%
HEPATITIS	60.13%	57.46%	58.79%	60.34%
HOUSEVOTES	7.81%	7.48%	8.02%	7.47%
IONOSPHERE	15.52%	16.17%	16.33%	16.72%
LIVERDISORDER	31.92%	31.72%	32.06%	32.40%
LYMOGRAPHY	27.48%	28.86%	29.55%	29.98%
MAGIC	12.00%	11.73%	11.55%	11.57%
MAMMOGRAPHIC	17.23%	17.52%	17.34%	17.57%
PARKINSONS	14.70%	14.32%	13.39%	14.04%
PAGE BLOCKS	6.02%	6.04%	5.66%	5.76%
PHONEME	15.67%	15.50%	15.29%	15.04%
PIMA	25.52%	24.85%	24.63%	24.87%
POPFAILURES	5.46%	6.09%	6.30%	6.75%
REGIONS2	30.41%	28.77%	28.77%	28.02%
RING	27.01%	22.90%	24.05%	23.85%
SAHEART	29.91%	29.63%	29.54%	29.89%
SEGMENT	19.36%	15.60%	13.88%	11.70%
SONAR	19.62%	19.80%	20.38%	18.53%
SPAMBASE	6.30%	4.95%	5.43%	4.78%
SPIRAL	42.22%	42.06%	41.16%	40.35%
STATHEART	19.90%	18.53%	19.72%	20.47%
STUDENT	4.97%	4.86%	5.13%	5.01%
TAE	47.05%	45.62%	43.93%	45.05%
TRANSFUSION	24.41%	23.59%	23.11%	22.64%
WDBC	4.88%	4.29%	4.17%	4.07%
WINE	12.39%	10.39%	9.02%	8.41%
Z_F_S	7.11%	6.81%	6.26%	6.62%
ZO_NF_S	5.69%	4.73%	4.23%	3.93%
ZONF_S	2.45%	2.41%	2.45%	2.38%
ZOO	6.93%	6.63%	6.00%	6.50%
AVERAGE	**20.48%**	**19.78%**	**19.66%**	**19.43%**

The Table 9 presents error rates for the used regression datasets under different values of periodic local search p_l (0.0025, 0.005, 0.01, and 0.02). The analysis indicates that the lowest average error is observed at $p_l = 0.01$ with a value of 5.04, suggesting that this setting offers the best overall performance. This is followed by $p_l = 0.02$ with an average error of 5.10, $p_l = 0.005$ with 5.56, and $p_l = 0.0025$ with 6.34, which has the highest average error and the poorest performance. Examining individual datasets reveals variations in the impact of different p_l values. In the AUTO dataset, the error decreases steadily as p_l increases, dropping from 17.63 at $p_l = 0.0025$ to its lowest point of 10.11 at $p_l = 0.02$.

Similarly, in the HOUSING dataset, the error significantly reduces from 32.72 at $p_l = 0.0025$ to 14.02 at $p_l = 0.02$. This decreasing trend is also evident in other datasets, such as MORTGAGE, where the error falls from 1.22 at $p_l = 0.0025$ to just 0.032 at $p_l = 0.02$, and STOCK, where the error reduces from 6.58 to 1.47. In some datasets, the p_l parameter has minimal impact. For instance, in the CONCRETE dataset, the error remains constant across all p_l values at 0.003. Similar stability is observed in the QUAKE and SN datasets, where variations are minimal. However, some datasets exhibit less predictable trends. In the BASEBALL dataset, the error initially decreases from 63.05 at $p_l = 0.0025$ to 60.56 at $p_l = 0.005$, but then increases again to 71.93 at $p_l = 0.02$. Similar inconsistent results are observed in the PY and BL datasets. Overall, the analysis suggests that $p_l = 0.01$ delivers the best average performance. Nevertheless, the effect of the p_l parameter varies across datasets, with some benefiting more from higher or lower p_l values.

Table 9. Experimental results for the regression datasets using different values of the local search rate parameter p_l.

DATASET	$p_l = 0.0025$	$p_l = 0.005$	$p_l = 0.01$	$p_l = 0.02$
ABALONE	4.48	5.04	5.27	4.93
AIRFOIL	0.0019	0.0014	0.0009	0.0006
AUTO	17.63	16.21	12.50	10.11
BK	0.027	0.019	0.03	0.029
BL	0.031	0.016	0.05	0.017
BASEBALL	63.05	60.56	62.57	71.93
CONCRETE	0.003	0.003	0.003	0.003
DEE	0.36	0.35	0.32	0.31
FA	0.056	0.083	0.066	0.091
FRIEDMAN	1.36	1.22	1.18	1.19
HO	0.015	0.017	0.017	0.016
HOUSING	32.72	24.82	18.24	14.02
LASER	0.0025	0.0026	0.0023	0.0024
LW	0.026	0.021	0.026	0.033
MORTGAGE	1.22	0.54	0.18	0.032
PLASTIC	3.61	3.27	2.66	2.43
PY	0.13	0.11	0.17	0.22
QUAKE	0.042	0.042	0.045	0.041
SN	0.025	0.027	0.027	0.025
STOCK	6.58	3.40	2.14	1.47
TREASURY	1.83	1.021	0.38	0.11
AVERAGE	**6.34**	**5.56**	**5.04**	**5.10**

In Figure 8, the pairwise comparisons using the Wilcoxon Test are presented to examine the impact of different values of the local optimization parameter (p_l) on the proposed machine learning method, based on a series of well-known datasets, with the aim of evaluating the classification error. The Wilcoxon Test results showed that comparisons between $p_l = 0.0025$ and $p_l = 0.005$, $p_l = 0.01$, and $p_l = 0.02$ demonstrated statistically significant differences, as the p-values were lower than the significance level of 0.05. Specifically, the p-value for the comparison between $p_l = 0.0025$ and $p_l = 0.005$ was 0.0001, between $p_l = 0.0025$ and $p_l = 0.01$ was 0.00034, and between $p_l = 0.0025$ and $p_l = 0.02$ was 0.00048. Conversely, the comparisons between $p_l = 0.005$ and $p_l = 0.01$, as well as between $p_l = 0.01$ and $p_l = 0.02$, did not show statistically significant differences, with p-values of 0.21 and 0.57, respectively. The comparison between $p_l = 0.005$ and $p_l = 0.02$ yielded a p-value of 0.052, indicating a marginal lack of significance. Overall, the results suggest that the choice of the pl parameter value affects the classification error primarily in comparisons involving the value $p_l = 0.0025$, while the other comparisons do not exhibit clear statistically significant differences.

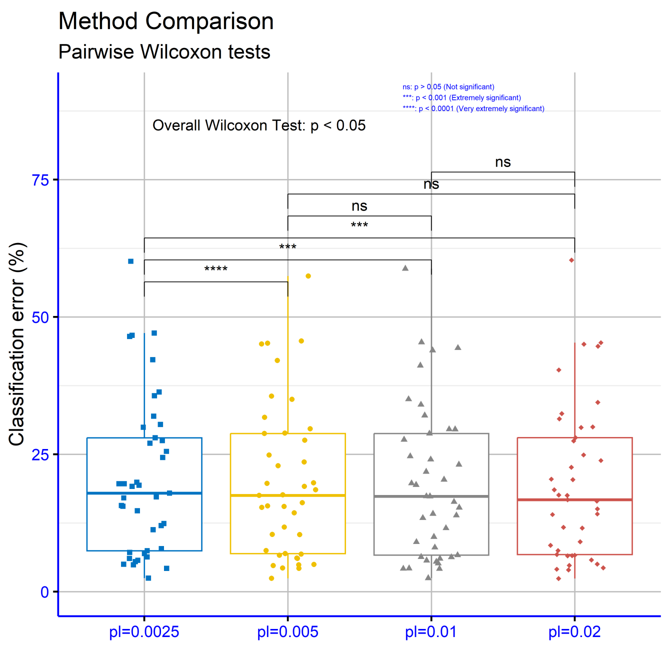


Figure 8. Statistical comparison for the conducted experiments on the classification datasets using the proposed method and different values of local search rate p_l.

In Figure 9, the regression error for different values of the periodic local search parameter is presented. In the comparisons between $p_l = 0.0025$ and $p_l = 0.005$, the p-value was 0.011, indicating a statistically significant difference, as it is below the significance level of 0.05. In contrast, the comparisons between $p_l = 0.0025$ and $p_l = 0.01$, $p_l = 0.0025$ and $p_l = 0.02$, $p_l = 0.005$ and $p_l = 0.01$, and $p_l = 0.005$ and $p_l = 0.02$ did not show statistically significant differences, with p-values of 0.12, 0.18, 0.22, and 0.097, respectively, all of which are above the significance level of 0.05. Finally, the comparison between $p_l = 0.01$ and $p_l = 0.02$ yielded a p-value of 0.086, which is close to but above the significance level of 0.05, suggesting borderline non-significance. Overall, the results indicate that only the comparison between $p_l = 0.0025$ and $p_l = 0.005$ showed a statistically significant difference, while the remaining comparisons did not present clear statistically significant differences.

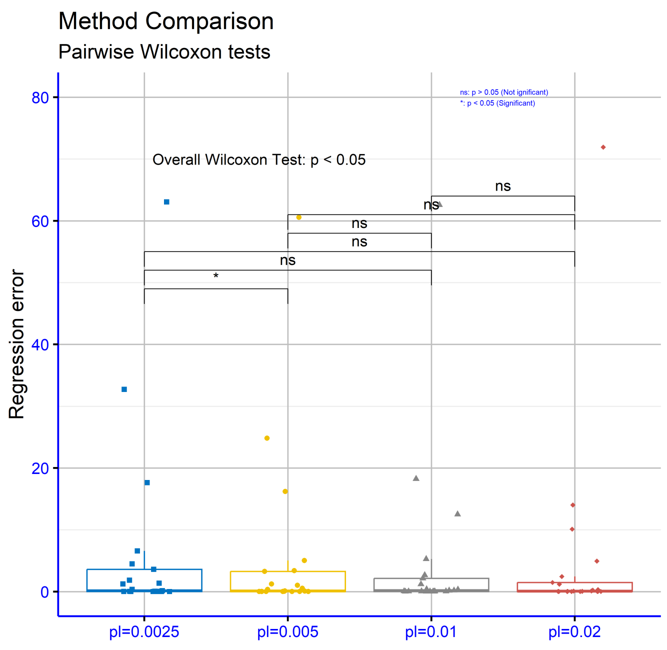


Figure 9. Statistical comparison for the conducted experiments on the regression datasets using the proposed method and different values of local search rate p_l.

4. Conclusions

The study focuses on the development and evaluation of the NEURALDE method, an innovative approach to optimizing neural network training based on Differential Evolution (DE). The results demonstrate that NEURALDE outperforms traditional optimization techniques such as ADAM, BFGS, GENETIC, NEAT, and RBF in both classification and regression tasks. Across a wide range of datasets, NEURALDE consistently achieved the lowest error rates, confirming its robustness and efficiency. Statistical analyses, including the Wilcoxon Test, were used to validate the significance of the differences between NEURALDE and other methods. The extremely low p-values indicate that the observed differences are not random but reflect the actual superiority of NEURALDE. Furthermore, the method proved resilient to common neural network training challenges, such as overfitting and entrapment in local minima.

NEURALDE is established as a reliable and high-performance optimization method for machine learning applications. Its exceptional performance in both classification and regression, combined with statistical validation of its superiority, positions it as a strong contender for broader adoption in various machine learning applications. The method is particularly useful for complex datasets or scenarios where traditional approaches fail to deliver satisfactory results.

This study opens multiple avenues for further research. Firstly, exploring the scalability of NEURALDE on larger and more diverse datasets could provide valuable insights into its generalizability and practical utility. Incorporating adaptive mechanisms within the Differential Evolution framework is another promising direction, as it could dynamically adjust parameters based on dataset characteristics, further enhancing the method's performance. Another interesting avenue is applying NEURALDE to unsupervised learning tasks, such as clustering, to evaluate its adaptability across different machine learning paradigms. Furthermore, integrating NEURALDE with cutting-edge techniques like transfer learning and reinforcement learning could unlock new potential, particularly for real-time applications and complex decision-making environments. Future research could also focus on reducing the computational cost of the method to make it more accessible for large-scale problems. Overall, NEURALDE provides a robust foundation for further improvements and extensions, aiming to establish it as a key optimization method in machine learning.

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