

## Article

# Predicting the forest fire duration enriched with meteorological data using Feature Construction Techniques

Constantina Kopitsa<sup>1</sup>, Ioannis G. Tsoulos<sup>2\*</sup>, Andreas Miltiadous<sup>3</sup>, Vasileios Charilogis<sup>4</sup>

<sup>1</sup> Department of Informatics and Telecommunications, University of Ioannina, Greece; k.kopitsa@uoi.gr

<sup>2</sup> Department of Informatics and Telecommunications, University of Ioannina, Greece; itsoulos@uoi.gr

<sup>3</sup> Department of Informatics and Telecommunications, University of Ioannina, Greece; a.miltiadous@uoi.gr

<sup>4</sup> Department of Informatics and Telecommunications, University of Ioannina, Greece; v.charilog@uoi.gr

\* Correspondence: itsoulos@uoi.gr

**Abstract:** The spread of contemporary artificial intelligence technologies, particularly Machine Learning, has significantly enhanced the capacity to predict natural disasters. Wildfires constitute a prominent example, as machine learning can be employed to forecast not only their spatial extent but also their environmental and socio-economic impacts, propagation dynamics, and even their duration. Such predictive capabilities are of critical importance for effective wildfire management, as they inform the strategic allocation of material resources, and the optimal deployment of human personnel in the field. The necessity of leveraging machine learning tools has become imperative in our era, as climate change has disrupted traditional wildfire management models due to prolonged droughts, rising temperatures, and the increasing frequency of extreme weather events. For this reason, our research seeks to fully exploit the potential of Principal Component Analysis (PCA), Minimum Redundancy Maximum Relevance (MRMR), and Grammatical Evolution, both for constructing Artificial Features and for generating Neural Network Architectures. For this purpose, we utilized the highly detailed and publicly available datasets provided by the Hellenic Fire Service for the years 2014–2021, which we further enriched with meteorological data, corresponding to the prevailing conditions at both the onset, and the suppression of each wildfire event. The research concluded that the Feature Construction technique, using Grammatical Evolution, outperforms other methods in terms of stability and accuracy. Specifically, the model accuracy of wildfire duration using Feature Construction, the mean error was 8.79%, indicating an overall accuracy of 91.21%.

**Keywords:** Forest fires; Machine learning; Neural networks; Feature Construction; Genetic Programming; Grammatical Evolution

**Citation:** Kopitsa, C.; Tsoulos, I.G.; Miltiadous, A.; Charilogis V. Predicting the forest fire duration enriched with meteorological data using Feature Construction Techniques. *Journal Not Specified* **2024**, 1, 0. <https://doi.org/>

Received:

Revised:

Accepted:

Published:

**Copyright:** © 2025 by the authors. Submitted to *Journal Not Specified* for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

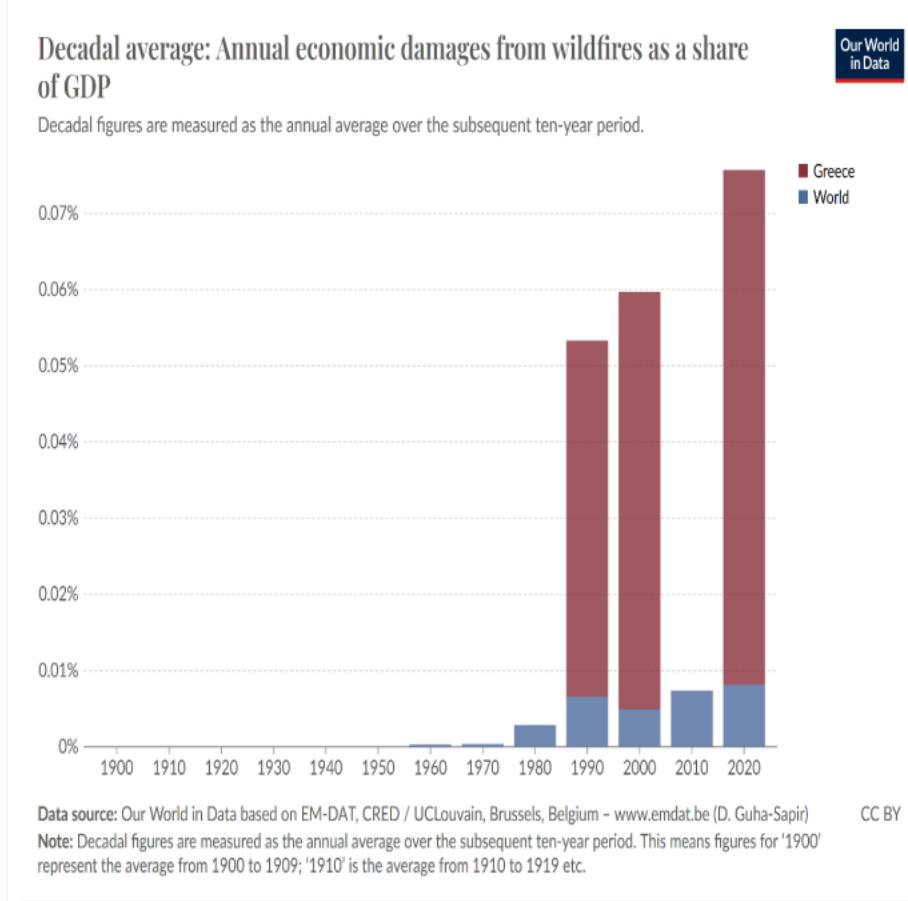
## 1. Introduction

Fire has always had a dual nature, in human history. On one hand, it has had the power to destroy civilizations, while on the other, it has significantly contributed to the evolution, of human society. From its destructive potential in warfare, and natural disasters, to its transformative role in technological, and cultural advancement, fire has shaped both, the rise, and fall of human civilizations. The ability to harness fire for cooking, metallurgy, and warmth played a crucial role in the development, of early human societies [1], while its unchecked force, has also led to widespread devastation. This duality, underscores fire's paradoxical role, in human progress: a force capable of both creation and destruction.

This notion is also evident in ancient Greek mythology, particularly in the tale of Prometheus, who defied the gods by stealing fire, and gifting it to humanity. This act symbolizes the transfer of divine knowledge and power to humans, enabling progress and civilization. The myth, underscores fire's dual role as a tool for human advancement and as a source of conflict illustrating the tension between progress and its ethical implications as well as the costs of rebellion and innovation [2]. On this matter, fire has played a multifaceted role in human history, both through myths and through its tangible impacts.

Nevertheless, in the modern era, wildfires are ranked among the most significant natural hazards [3] with immense effects on Earth's ecosystems, and human societies. Beyond that according the Chair of ISO/TC 92 fire safety Mr. P. Van Hees: '*With losses caused by fire estimated at 1% of the global GDP each year, fire safety must be viewed in the broader perspective of risk management and disaster mitigation*' [4].

In Figure 1 it is illustrated, through a graphical representation the economic burden from forest fires on the annual GDP.



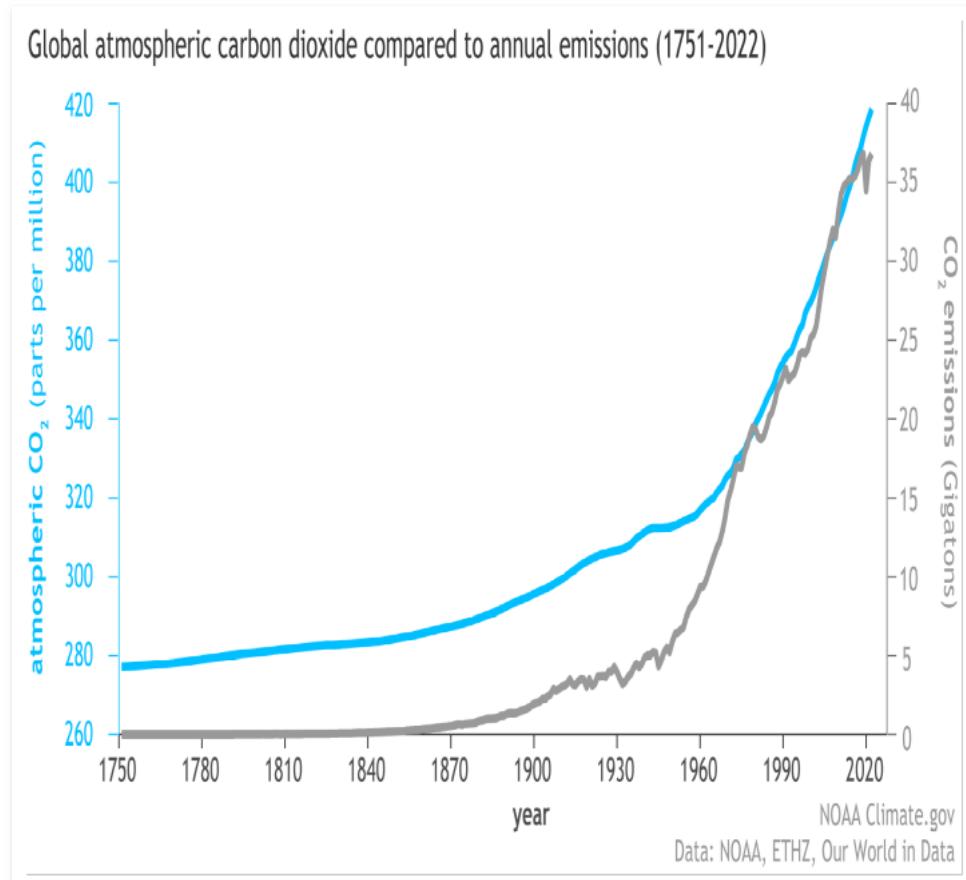
**Figure 1.** The economic impact of forest fires in Greece, and around the world.

The following numbers show the extent of the destruction caused by fires:

- The cost of fire is estimated at about 1% to 2% of the annual GDP
- About 1% of fires are responsible for more than 50% of the costs
- The number of people dying in fire is estimated at 2.2 deaths per 100,000 inhabitants (based on 35 countries)[4].

In other words wildfires and climate change intensify each other. Climate change exacerbates wildfires by increasing drought, high temperatures, low humidity, lightning, and strong winds, leading to more severe, and prolonged fire seasons. Conversely, wildfires contribute to worsening climate change [5]. Thus, wildfires (along with the extraction and burning of fossil fuels, and volcanic eruptions) exacerbate Climate Change, by further releasing carbon dioxide, into the atmosphere [6]. Also, the Mediterranean region is recognized as a key "hot-spot" for the impacts of climate change [8]. At the same time, the critical need to address climate changes, effects on wildfire patterns is highlighted as essential for protecting both the environment, and public health in Greece [7].

In Figure 2, we observe the continuous increase in carbon dioxide levels, beginning in 1751.



**Figure 2.** The environmental impact of carbon dioxide. Available from: <https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide> (accessed on November 29, 2024).

Concerning this, the United Nations of Environment Programme, are calling the governments: "to radically shift their investments in wildfires to focus on prevention and preparedness" [5]. Therefore, despite the challenging circumstances posed by Climate Change, driven by continuous human expansion and technological progress we aim to transform this disadvantage into an advantage by focusing our efforts on advancing technology itself. On this Artificial intelligence, particularly Machine learning, emerges as

a valuable ally in addressing this global issue, offering innovative solutions and supporting sustainable development [9,10].

Machine learning, refers to a collection of techniques and algorithms that enable systems to identify patterns and make decisions based on data improving their performance over time without explicitly being programmed for specific tasks [11]. This was the vision, of Alan Turing, when, in 1936 he wrote his PhD ‘On Computable Numbers, with an application to the Entscheidung problem’ [12]. Namely, Machine learning, is a pivotal branch of artificial intelligence, presents endless opportunities for businesses and society alike. Beyond its numerous advantages it plays a critical role in driving groundbreaking advancements in Climate Change adaptation and mitigation. By accelerating, the development of solutions, to some of the most pressing challenges facing the planet, machine learning is reshaping the way we address global environmental issues [11]. Although, modeling complex environmental variables, often presents challenges due to the significant computational resources required and the diversity or complexity of data formats [13]. Machine learning algorithms, however, can bypass these challenges by deriving mappings and relationships directly from the data eliminating the need for predefined expert rules. This capability is particularly beneficial when dealing with scenarios involving a large number of parameters with intricate physical properties, such as in forest fires. Consequently, adopting a machine learning approach to fire management can help overcome many of the limitations associated with traditional physics-based simulation models.

Regarding this, in the recent literature, significant interest has been developed, in the role of machine learning in the field of fire management [14]. Forest fires, however, have not been extensively studied as research on forest fires constitutes only 2.9% of the global literature, according to a study conducted between 2017 and 2021 [15]. More specifically, floods have received the most attention in research (20.3%), followed by earthquakes and hurricanes, each accounting for 18.8%. Studies on general disaster types make up 15.9%, while landslides account for 10.1%. Notably, depending on the area of focus, researchers employ corresponding algorithms to address specific challenges.



**Figure 3.** Machine learning methods used in fire management.

Figure 3 summarizes the machine learning methods used in various fields of fire management, as obtained from the relevant literature. A number of recent publications have appeared in recent years, which utilize machine learning techniques for forest fire management. For example, Bayesian networks have been widely utilized in the context of forest fires, particularly for predicting, and analyzing, potential causes of fires [16]. Additionally, a recent study employed Bayesian networks to model the cascading effects of drought and forest fires [17]. Also, Bayesian networks were integrated with deep learning techniques to detect fires, from video frames [18].

Naïve Bayes, has been also applied to forest fire-related challenges in numerous studies. For instance, Nugroho developed a forest fire prevention system, that combines a wireless sensor network with a Naïve Bayes classifier [19]. Zainul's work proposes a method for classifying hotspots responsible for forest fires using the naïve Bayes algorithm [20]. Karo, proposed a methodology for wildfire classification, that incorporates feature selection and employs Naïve Bayes alongside other machine learning techniques [21].

Moreover, Logistic Regression, has been applied to various forest fire-related issues, including estimating human-caused wildfire risk [22], predicting wildfire vulnerability [23], probabilistic modeling of wildfire occurrence [24] and analyzing wildfire danger [25].

94  
95  
96  
97  
98  
99  
100  
101  
102  
103  
104  
105  
106  
107  
108  
109  
110

Several studies, have utilized Artificial Neural Networks (ANNs), in the field of forest fire prediction, and monitoring. For instance, Hossain, employed ANNs to detect flames and smoke based on static image features [26]. Lall and Mathibela applied neural networks to predict wildfire risk in Cape Town [27]. Similarly, Sayad utilized neural networks along with other machine learning techniques for wildfire predictive modeling, using data from NASA's Land Processes Distributed Active Archive Center (LP DAAC) [28]. Additionally, Gao recently published a case study, on predicting wildfires, in a Chinese province, using neural networks [29].

Also, Random Forest, has been widely utilized in forest fire prediction. For instance, Latifah applied Random Forest, to predict forest fires in Borneo [30]. Similarly, Malik proposed the usage of Random Forest to estimate the wildfire risk in Northern California [31]. Additionally, Gao conducted a forest fire risk prediction study in China, combining Random Forest with a neural network trained using the back-propagation method [32].

This paper addresses a key issue in forest fire management, such as predicting the duration of fires, utilizing information from already caused forest fires in combination with the weather conditions that prevailed during the development of this phenomenon. Regarding this topic a series of research papers have been published during the past years, such as the work of Xiao et al [14], who developed a wildfire duration prediction model, based on historical fire data and geospatial information. The algorithms employed included: RF (Random Forest), KNN, and XGBoost regression models as well as image-based approaches such as CNN and Encoder. The model, achieved an accuracy exceeding 80% for fires lasting longer than 10 days. In the same direction of research, Andela validated the fire data from the Global Fire Atlas, using independent datasets from the United States. The study utilized satellite data and highlighted that the duration of fires is significantly influenced among others by the fire season [33]. Ujjwal settled a surrogate model to capture the dynamic spread of a wildfire over time. The surrogate model, designed to simulate the relationship between the burned area and key meteorological parameters (such as relative humidity, temperature, and wind speed), provides valuable insights, into fire behavior across different [34]. Wang, also conducted research that while capable of yielding results for predicting, wildfire duration, primarily, focused on forecasting the scale of a forest fire. The study utilized neural network algorithms, including Backpropagation Neural Network (BPNN), Recurrent Neural Network (RNN) and Long Short-Term Memory (LSTM). Among these classification methods, LSTM demonstrated the highest accuracy, achieving 90.9% [35]. Xi settled a framework, for jointly, modeling fire duration, and size using a bivariate finite mixture model. Four subpopulations (normal or extreme in duration and size) were analyzed, incorporating, variables such as: location, month, and environmental factors. The analysis, revealed a strong correlation between: duration, and size, and identified key predictors, influencing these subpopulations [36].

Predicting, the duration of a fire is crucial, as it allows for estimating the potential damage, to the affected area and determining the necessary human resources, for its suppression. Besides that, forest fires and climate change are commonly exacerbating. The Western fire chief's association, from the U.S. emphasizes that climate change is drastically impacting the fire season. As a result, fire seasons now last six to eight months, compared to the four months, they previously spanned. Face the Facts USA reports that in the U.S. the average duration of wildfires increased from 8 days, before 1986, to 37 days by 2013 [37].

The current work utilizes a series of feature construction and selection methods in order to improve the ability of various machine learning techniques to predict the duration of forest fires. These methods involve creating new, meaningful variables by combining or transforming existing data attributes [38]. For example, integrating material resources deployed during a forest fire event into a single metric constitutes feature construction, enabling models, to better capture the complexity, of fire incidents, and resource allocation. Another example, for Feature Construction, during a forest fire, is combining weather attributes, in order to form, a fire risk index. Such, approaches enhance data representation,

facilitating more robust, and interpretable predictive models, in disaster management. The feature construction or selection methods were applied on data collected for the Greek case that contained weather information.

The remaining of this manuscript is divided as follows: section 2 described the used dataset and it provided a detail discussion on the used methods, section 3 outlines the conducted experiments and some statistical tests on them and finally section 4 discusses some conclusions on the experimental results.

## 2. Materials and Methods

This section initiates with a description of the used datasets and continues with a detailed description of the used feature construction and selection techniques, that will be applied on the datasets incorporated in the conducted experiments.

### 2.1. The used dataset

In this research, open data provided by the Hellenic Fire Service were utilized, available at the link [https://www.fireservice.gr/en\\_US/synola-dedomenon](https://www.fireservice.gr/en_US/synola-dedomenon). The datasets used included information on all fires that occurred in Greece during the years 2014–2021. The data encompassed the location of the fire, the date and time of ignition and extinguishment, the burned areas categorized by land type, and the firefighting forces deployed for suppression efforts.

The datasets comply with the European transparency legislation (Directive 2013/37/EU), ensuring that the data are unbiased in terms of type and location, and represent all fires in the Hellenic region. The information provided by the Hellenic Fire Service is easily accessible, regularly updated, accurate, and comprehensive, facilitating analysis and covering all involved entities.

Regarding burned areas, the dataset included measurements for the following categories: forests, forested areas, groves, grasslands, reed beds and wetlands, agricultural lands, crop residues, and landfills.

As for the firefighting units deployed, the dataset included measurements for the following resources: firefighters, ground-based teams, volunteers, military forces, other supporting units, fire trucks, service vehicles, tankers, machinery, CL-215 aircraft, PZL aircraft, GRU aircraft, as well as contracted helicopters and aircraft.

#### 2.1.1. Data Preprocessing and Weather Feature Extraction

The first step in data preprocessing involved removing rows with missing values. Subsequently, using the OpenCage Geocoding API, the location data, initially formatted as "Municipality, Area, Address," were converted into geolocation data in the form of latitude and longitude coordinates.

Next, weather information was extracted for each fire event using the OpenWeather API, capturing data for both the ignition and extinguishment times. OpenWeather is a widely used service that provides detailed weather data, including historical, real-time, and forecasted weather information. The extracted weather features included the following:

1. **Temperature at 2 meters:** The air temperature near the ground level.
2. **Relative Humidity at 2 meters:** The percentage of moisture in the air relative to its maximum capacity.
3. **Dew Point at 2 meters:** The temperature at which air reaches saturation and moisture condenses.
4. **Precipitation:** The amount of rainfall during the specific time interval.
5. **Weather Code:** A classification of the general weather conditions (e.g., clear, cloudy, rainy).
6. **Cloud Cover:** The percentage of the sky obscured by clouds.
7. **Evapotranspiration (ET0):** The potential evapotranspiration measured using the FAO Penman-Monteith method, indicating water loss from the surface and vegetation.

8. **Vapour Pressure Deficit (VPD):** The difference between the amount of moisture in the air and the maximum it can hold. 215
9. **Wind Speed** at 10m and 100m: Wind velocity measured at heights of 10 meters and 216  
100 meters. 217
10. **Wind Direction** at 10m and 100m: The directional angle of the wind at the respective 218  
heights. 219

220  
Additionally, daily-level weather data were included, such as:

1. **Daylight Duration:** The total hours of daylight during the day. 221
2. **Sunshine Duration:** The total hours of direct sunlight during the day. 222

223  
These features were aggregated and matched with each fire record, ensuring 224  
comprehensive weather context for both the ignition and extinguishment phases 225  
of the fires. 226

### 2.1.2. Definition of the output variable 227

To define the output variable, the duration of each forest fire was converted from hours 228  
or other time units into minutes, ensuring greater precision in classification. A logarithmic 229  
transformation of fire duration in minutes was then applied to manage the wide range 230  
of values effectively, preventing excessive influence from extreme durations. Based on 231  
this transformation, three distinct categories were established, serving as target values for 232  
experimental analysis. This approach enabled the classification of forest fires according to 233  
their duration. For the Greek forest fire data used in this study, the following classification 234  
scheme was adopted: 235

1. Up to 360 minutes (6 hours) is considered to be a fire, of short duration. 236
2. From 361 – 7200 minutes (6 hours – 5 days) is a fire of medium duration. 237
3. More than 7201 minutes (5 days - and more), which is considered a long duration fire. 238

## 2.2. *The used feature construction and selection methods* 239

### 2.2.1. The PCA method 240

The Principal Component Analysis (PCA) technique, introduced by mathematician 241  
Karl Pearson in 1901 [39], and developed by Harold Hotelling (1933). This technique 242  
operates on the principle that when data from a higher-dimensional space is transformed 243  
into a lower-dimensional space, the resulting lower-dimensional representation should 244  
retain the maximum variance of the original data. 245

Notably, it is worth mentioning that the use of PCA, on larger datasets, became 246  
practical only after the advent of electronic computers, which made it computationally 247  
feasible, to handle datasets, beyond trivial sizes [40]. Continuing, with the applications of 248  
PCA, it is a widely utilized technique in exploratory data analysis, and machine learning, 249  
particularly, in building predictive models. It is an unsupervised learning method, designed 250  
to analyze, the relationships among a set of variables. Often referred to as a form of general 251  
factor analysis, it involves regression to determine a line of best fit. The primary objective, 252  
of PCA, is to reduce the dimensionality of a dataset, while retaining the most significant 253  
patterns, and relationships, among the variables, all without requiring prior knowledge, of 254  
the target variables [41]. 255

Next, we will briefly reference studies, that have utilized PCA, covering different 256  
areas, such as: statistical physics, genetic improvement, face recognition, economic & 257  
environmental sciences, medical prediction, e.t.c. Explicitly, the research conducted, by 258  
Park [42], highlights the reasons behind the success of the PCA technique, for lattice systems. 259  
The study's primary limitation lies in the dependency of the proposed formula's accuracy 260  
on the dataset size. Specifically, the results achieve full precision, only under the condition 261  
of an infinite dataset. This constraint restricts the practical applicability, of the method, 262  
when working with finite or limited data, a common scenario, in real-world analyses. 263

264  
Additionally, the work of Sarma et al. [43] utilizes PCA, in order to evaluate, morphometric traits, under a multivariate approach. The findings suggest, that PCA could 265

significantly enhance the genetic improvement. Noteworthy, is the fact, that the 64.29%, of the total variance explained, can be considered relatively low. This suggests, that a significant amount of unexplained information remains, which is not captured, by the four principal components. Moreover, Gambardella et al. used the PCA technique for monitoring the cultivation, of cannabis, in Albania. Specifically, with PCA they remove redundant spectral information from multiband datasets [44]. The article, by Slavkovic and Jevtic [45], presents the implementation of a face recognition system based on the Principal Component Analysis (PCA) algorithm. The PCA technique was utilized by Hargreaves [46], for stock selection, specifically to identify, a limited number of stock variables, that could effectively aid, in determining winning stocks.

Moreover, Xu et al. presents an interesting example of a modified application of Principal Component Analysis (PCA), utilizing, both linear and non-linear methods, through Kernel PCA (KPCA), in combination, with the Adaptive Boosting (AdaBoost) algorithm [47]. In the study of Zhang [48], a neural network model, combining PCA and Levenberg-Marquardt [49] was developed, to efficiently, and accurately analyze, and predict the interaction between IAQ and its influencing factors. In particular, it was examined indoor air quality (IAQ), and its relationship, with building features, and environmental conditions.

In the work of Akinnuwesi et al [50], a hybrid approach was suggested combining Principal Component Analysis (PCA), and Support Vector Machine (SVM) [51]. They create, the Breast Cancer Risk Assessment and Early Diagnosis (BC-RAED) model, designed to accurately detect BCa, in its early stages. PCA, was initially applied to extract features, during the first preprocessing stage, followed by further feature reduction, in the second stage. The multi-preprocessed data, were analyzed for breast cancer risk, and diagnosis using SVM. The BC-RAED model, achieved, an accuracy of 97.62%, a sensitivity of 95.24%, and a specificity of 100% in assessing, and diagnosing breast cancer risk.

Subsequently, we will briefly mention certain studies, that have been conducted, in the field of Forest Fires. Guan's research focuses on forest fire prediction using PCA-preprocessed data. The preprocessing step removed irrelevant information, simplifying analysis. Linear regression and random forest methods were then applied, revealing temperature, relative humidity, wind, and rain as the most influential factors in forest fire occurrence [52].

A novel model was developed, by Nikolov, using meteorological forecast data as input. Principal Component Analysis (PCA), with orthogonal rotation, was applied to reduce 195 meteorological variables, from the NARR dataset, to a smaller set of significant fire-ignition predictors, later used in logistic regression, to calculate wildfire ignition probabilities [53]. Also, a recent publication focuses on predicting wildfire ignitions, caused by lightning strikes, which account for the largest area burned annually, in the extratropical Northern Hemisphere. Principal Component Analysis (PCA), played a key role, in reducing 611 potential predictors, to 13 principal components, which were used in logistic regression to identify the primary factors influencing lightning occurrence [54].

### 2.2.2. The MRMR method

The min-redundancy max-relevance (MRMR) algorithm, introduced by Chris Ding and Hanchuan Peng [55]. This method aims to optimize feature selection, by minimizing redundancy, and maximizing relevance [56]. In sum, MRMR enhances relevance-only methods, such as using an f-test between the target, and the features. When two features are similar, MRMR prioritizes only the one, with the highest relevance.

The study, by Zhao, extends traditional MRMR methods, by introducing a non-linear feature redundancy measure and a model-based feature relevance measure, which are tested on synthetic and real-world datasets. Based on its empirical success, MRMR is integrated into Uber's marketing machine learning platform to automate the creation and deployment of scalable targeting and personalization models [57].

Moreover, Wu et al. proposed that the MRMR algorithm is utilized in conjunction with a Random Forest model [58] to perform feature selection in the context of air quality prediction. MRMR, is employed to determine which variables have the most significant impact, on the air quality index (AQI), while minimizing redundancy among them [59].

The article, by Elbeltagi is an innovative approach for estimating maize chlorophyll by integrating hyperspectral indices with cutting-edge, six advanced machine learning techniques. The MRMR algorithm was incorporated into the process to enhance feature selection by pinpointing the most significant spectral bands, minimizing data redundancy and boosting model efficiency [60].

In the energy sector, Liu conducted the following research offering an improved method for predicting transient stability in power systems. The MRMR algorithm is applied for feature selection with minimal redundancy and maximum relevance providing an enhanced approach for forecasting transient stability, in power systems. This approach addresses the limitations of previous methods, such as low accuracy, difficult applicability and high computational cost, while incorporating the "winner take all" (WTA) technique for ensemble learning and enhanced precision [61].

Eristi also refers to the energy sector. Specifically, this paper presents, a new PD detection system, that combines spectral analysis, spectrogram analysis, deep learning algorithms, MRMR and ensemble machine learning (EML) [62]. The most impactful features, are identified, by performing MRMR feature selection analysis, on the extracted deep features [63].

Zhang employed an Acoustic Emission (AE) technique to monitor inaccessible areas of large storage tank floors utilizing AE sensors positioned externally to the tank. The implemented algorithm effectively distinguishes corrosion signals from interference signals, particularly drop-back signals induced by condensation. Experimental studies were conducted both in laboratory settings and in field environments, focusing on Q235 steel. Seven characteristic AE features derived from signal hits and frequency were extracted and subsequently selected for pattern recognition, using the MRMR method [64].

Additionally, Karamouz et al., proposed a methodology to examine the effects of climate change on sea level variations in coastal areas using an artificial neural network model. Feature selection techniques, including MRMR and Mutual Information (MI) are employed to identify the most suitable predictors for the neural network input [65].

### 2.2.3. The Neural Network Construction method

Another machine learning method introduced recently that is based on Grammatical Evolution [66] is the construction of artificial neural networks [67]. In this work the architecture of the neural network is produced through a series of generations of the underlying genetic algorithm by reducing the training error of the neural network. Furthermore, the method is able to identify the best set of parameters for the neural network. This method can also retain only a small portion of features from the original objective problem, significantly reducing the information required to reduce the training error. This method was used in a series of practical problems, such as the identification of amide I bonds [68], solution of differential equations [69], incorporation in the detection of Parkinson's disease [70], usage in the estimation of performance of students [71], autism screening [72] etc.

The used grammar for the construction of neural networks expressed in Backus–Naur (BNF) form [73] is shown in Figure 4. Numbers in parentheses represent the sequence number of each production rule. The constant  $n$  stands for the number of input features.

```

S ::= <sigexpr> (0)
<sigexpr> ::= <Node> (0)
| <Node> + <sigexpr> (1)
<Node> ::= <number> * sig(<sum> + <number>) (0)
<sum> ::= <number> * <xxlist> (0)
| <sum> + <sum> (1)
<xxlist> ::= x1 (0)
| x2 (1)
.....
| xn (n-1)
<number> ::= (<digitlist>. <digitlist>) (0)
| (-<digitlist>. <digitlist>) (1)
<digitlist> ::= <digit> (0)
| <digit><digitlist> (1)
<digit> ::= 0 (0)
| 1 (1)
.....
| 9 (9)

```

**Figure 4.** The grammar incorporated in the construction of neural networks.

This grammar produces artificial neural networks in the following form:

$$\text{NN}(\vec{x}, \vec{w}) = \sum_{i=1}^H w_{(n+2)i-(n+1)} \sigma \left( \sum_{j=1}^n x_j w_{(n+2)i-(n+1)+j} + w_{(n+2)i} \right) \quad (1)$$

The symbol  $H$  defines the number of processing nodes (weights). The sigmoid function  $\sigma(x)$  is used as the activation function of neural network and it is defined as:

$$\sigma(x) = \frac{1}{1 + \exp(-x)} \quad (2)$$

The main steps of the algorithm are:

1. **Initialization step.**

- (a) Set the number of used chromosomes  $N_c$ . Each chromosome is a set of randomly selected integers. These integer values represent rule number in the extended BNF grammar previously presented.
- (b) Set the maximum number of allowed generations  $N_g$ .
- (c) Set the selection rate  $p_s \in [0, 1]$  and the mutation rate  $p_m \in [0, 1]$ .
- (d) Set  $k = 0$ , the generation number.

2. **Fitness calculation step.**

- (a) For each chromosome  $g_i, i = 1, \dots, N_c$  do
  - i. Create using the grammar of figure 4 the corresponding neural network  $\text{NN}_i(\vec{x}, \vec{w})$
  - ii. Set as  $f_i = \sum_{j=1}^M (\text{NN}_i(\vec{x}_j, \vec{w}_i) - y_j)^2$  the fitness of chromosome  $i$ . The set  $(\vec{x}_j, y_j), j = 1, \dots, M$  stands for the train set of the objective problem.

(b) **End For**

3. **Genetic operations step.**

- (a) Application of Selection operator. The chromosomes of the population are sorted according to their fitness values and the best  $(1 - p_s) \times N_c$  chromosomes are copied to the next generation. The remaining are replaced by new chromosomes produced during crossover and mutation.
- (b) Application of Crossover operator. In this step  $p_s \times N_c$  new chromosomes will be created from the original ones. For each set  $c_1, c_2$  of new chromosomes

that will be created, two chromosomes  $g_a$  and  $g_b$  are selected from the old population using tournament selection. The new chromosomes are created using one - point crossover between  $g_a$  and  $g_b$ . An example of this operation is shown graphically in Figure 5.

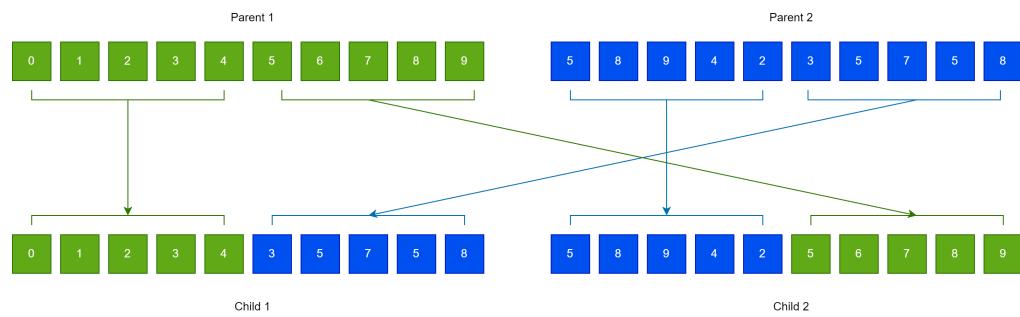
- (c) Application of Mutation operator. For each element of every chromosome a random number  $r \in [0, 1]$  is selected. The corresponding element is changed randomly when  $r \leq p_m$ .

#### 4. Termination check step.

- (a) Set  $k = k + 1$   
 (b) If  $k \leq N_g$  then goto Fitness Calculation Step.

#### 5. Application to the test set.

- (a) Obtain the best chromosome  $g^*$  from the genetic population.  
 (b) Create the corresponding neural network  $NN^*(\vec{x}, \vec{w})$   
 (c) Apply this neural network to the test set of the objective problem and report the corresponding error (test error).



**Figure 5.** An example of the one - point crossover operation used in Grammatical Evolution.

#### 2.2.4. The Feature Construction method

Another approach discussed here and used in the conducted experiments is the feature construction technique initially proposed in [74]. This approach creates artificial features from the original ones using the Grammatical Evolution procedure. The new features are non - linear mappings of the original ones. This method has been used in a series of practical cases during the past years, such as Spam Identification [75], Fetal heart classification [76], EEG signal processing [77,78] etc. The extended version of BNF grammar used during the feature construction process is outlined in Figure 6.

**Figure 6.** The extended BNF grammar used in the feature construction process.

```

S ::= <expr>      (0)
<expr> ::=  (<expr> <op> <expr>)  (0)
           | <func> ( <expr> )      (1)
           | <terminal>          (2)
<op>  ::=   +     (0)
           | -     (1)
           | *     (2)
           | /     (3)
<func> ::=  sin   (0)
           | cos   (1)
           | exp   (2)
           | log   (3)
<terminal> ::= <xlist>          (0)
               | <digitlist>. <digitlist> (1)
<xlist> ::= x1    (0)
           | x2    (1)
           .....
           | xn    (n-1)
<digitlist> ::= <digit>        (0)
                | <digit><digit>    (1)
                | <digit><digit><digit> (2)
<digit>  ::=  0 (0)
           | 1 (1)
           .....
           | 9 (9)

```

The main steps of the used algorithm have as follows:

1. **Initialization step.**
  - (a) Define the number of used chromosomes  $N_c$ .
  - (b) Define the maximum number of allowed generations  $N_g$ .
  - (c) Set the selection rate  $p_s \in [0, 1]$  and the mutation rate  $p_m \in [0, 1]$ .
  - (d) Set as  $N_f$  the number of desired features that will be created.
  - (e) Set  $k = 0$ , the generation number.
2. **Fitness calculation step.**
3. **For**  $i = 1, \dots, N_c$  **do**
  - (a) Create with the assistance of Grammatical Evolution, a set of  $N_f$  artificial features from the original ones, for chromosome  $g_i$ .
  - (b) Transform the original train set using the previously produced features. Represent the new set as  $\text{TR} = (x_{g_i,j}, t_j), j = 1,..M$
  - (c) Apply a machine learning model denoted as  $C$  on set TR and train this model and denote as  $C(x)$  the output of this model for any input pattern  $x$ .
  - (d) Calculate the fitness  $f_i$  as:

$$f_i = \sum_{j=1}^M (C(x_{g_i,j}) - t_j)^2 \quad (3)$$

The Radial Basis Function (RBF) networks [79,80] were used as the machine learning models  $C(x)$  in the current work. This machine learning model was chosen because of the significantly shorter training time it requires compared to other machine learning models.

4. **End For**

5. **Genetic operations step.** Perform the same genetic operators as in the case of construction neural networks, discussed previously. 434  
435
6. **Termination check step.** 436  
437  
438
- (a) Set  $k = k + 1$  437
- (b) If  $k \leq N_g$  then goto Fitness Calculation Step. 438
7. **Application to the test set.** 439  
440  
441  
442  
443  
444  
445  
446  
447  
448  
449
- (a) Obtain the chromosome  $g^*$  with the lowest fitness value. 440
- (b) Create the  $N_f$  artificial features that correspond to this chromosome 441
- (c) Apply the  $N_f$  features to the train set and produce the mapped training set 442  
 $TR = (x_{g_i,j}, t_j), j = 1,..M$  443
- (d) Train a machine learning model on the produced training set. An artificial 444  
neural network [81,82] with  $H = 10$  processing nodes is used in the current 445  
work. This neural network was trained using a BFGS variant of Powell [83]. 446
- (e) Apply the new features to the test set of the objective problem and create the 447  
set  $TT = (x_{g_i,j}, t_j), j = 1,..K$  448
- (f) Apply the machine learning model on set TT and report the test error. 449

### 3. Results

The experiments were executed using the freely available optimization environment of Optimus, that can be downloaded from <https://github.com/itsoulos/GlobalOptimus.git> 451  
as well as the WEKA programming tool [84]. The WEKA software has been incorporated in 452  
a series of problems [85–88]. Each experiment was conducted 30 times, using different seed 453  
for the random generator each time and the ten - fold cross validation procedure was used 454  
to validate the experimental results. The values of parameters for the used methods are 455  
shown in Table 1. The following notation is used in the tables presenting the experimental 456  
results: 457  
458

1. The column YEAR denotes the year of recording. 459
2. The column BAYES the application of the Naive Bayes [89] method to the corresponding 460  
dataset. 461
3. The column ADAM represents the usage of the ADAM optimizer [90] for the training 462  
of a neural network with  $H = 10$  processing nodes. 463
4. The column BFGS denotes the incorporation of the BFGS optimizer [83] to train a 464  
neural network with  $H = 10$  processing nodes. 465
5. The column MRMR denotes the results obtained by the application of a neural network 466  
trained with the BFGS optimizer on two features selected using the MRMR technique. 467
6. The column PCA stands for the results obtained by the application of a neural network 468  
trained with the BFGS optimizer on two features created using the PCA technique. 469  
The PCA variant implemented in MLPACK software [91] was incorporated to create 470  
these features. 471
7. The column NNC denotes the usage of the method of Neural Network Construction 472  
on the proposed datasets. The software that implements this method was obtained 473  
from [92]. 474
8. The column FC represents the usage of the previously mentioned method for 475  
constructing artificial features. For the purposes of this article two artificial features were 476  
created. These features were produced and evaluated using the QFc software [93]. 477

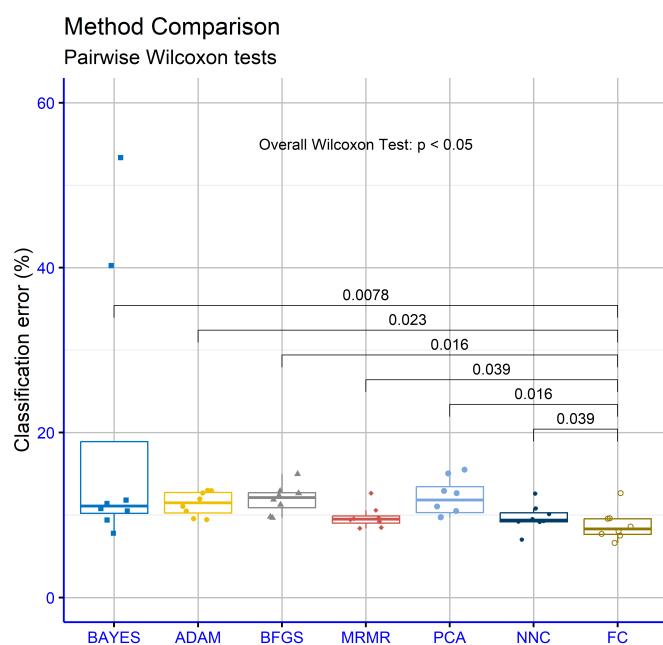
**Table 1.** Experimental results using a series of machine learning methods for the prediction of forest fire duration.

YEAR	BAYES	ADAM	BFGS	MRMR	PCA	NNC	FC
2014	11.41%	13.00%	12.38%	9.68%	15.50%	9.21%	8.04%
2015	10.49%	11.94%	11.25%	8.49%	15.03%	9.17%	7.51%
2016	10.79%	12.95%	11.88%	9.45%	12.93%	10.12%	8.60%
2017	53.36%	12.68%	12.65%	12.65%	12.64%	12.61%	12.66%
2018	9.39%	10.48%	14.97%	9.21%	10.49%	9.29%	7.72%
2019	7.79%	9.44%	9.66%	8.39%	9.72%	7.03%	6.62%
2020	40.26%	9.56%	9.80%	9.55%	9.76%	9.50%	9.61%
2021	11.81%	11.06%	12.90%	10.57%	11.03%	10.80%	9.55%
AVERAGE	19.41%	11.39%	11.94%	9.75%	12.14%	9.72%	8.79%

Table 1 presents the percentage values of classification error for various machine learning models from 2014 to 2021, as well as the average error rate for each model. The analysis reveals significant insights regarding the performance and stability of the methods. The BAYES model exhibits the highest variability, with a particularly high error rate in 2017 (53.36%). This is a clear outlier, possibly due to specific conditions in the data or the evaluation framework. In other years, its error rates range between 7.79% and 11.81%. The average error rate for BAYES is 19.41%, the highest in the table, indicating the lowest overall accuracy compared to the other models. The ADAM model shows an average error rate of 11.39%, with values ranging from 9.44% to 13.00%. Its stability is evident, as there are no significant deviations in specific years. ADAM's performance is considered relatively good compared to other methods. The BFGS model has an average error rate of 11.94%, slightly higher than ADAM's. Its error rates range from 9.66% to 14.97%. Although it demonstrates stable performance, its higher average value suggests slightly lower accuracy in certain cases. The MRMR model has an average error rate of 9.75%, ranking it among the most accurate methods. However, its error rate reaches 12.65% in 2017, while remaining low in other years, making it a reliable option overall. The PCA model has an average error rate of 12.14%, which is among the highest in the table. It shows relatively stable values, with a slight increase to 15.50% in 2014. Despite its generally good performance, its accuracy is lower compared to other methods such as MRMR or FC. The NNC model has an average error rate of 9.72%, one of the lowest in the table. Its values range from 7.03% to 12.61%, with small deviations, demonstrating stability and reliability. The FC model has the lowest average error rate in the table, at 8.79%, making it the most accurate method overall. Its error rates range between 6.62% and 12.66%, indicating stable performance with minor fluctuations. In conclusion, FC is the most accurate model, with the lowest average error rate, while BAYES demonstrates the lowest accuracy due to its high average error rate and significant variability. Methods such as MRMR and NNC are also reliable, with low error rates and relatively stable performance. The observed deviations in specific years might be related to changes in the data or evaluation parameters.

In Figure 7, the results of the Wilcoxon test for pairwise comparisons of the classification models are presented, providing valuable insights into the statistical significance of their performance differences. Below is a more in-depth analysis, focusing on the interpretation of results and a deeper understanding of the relationships between the models. The overall result of the Wilcoxon test ( $p < 0.5$ ) confirms that statistically significant differences exist among the models' performances. This indicates that the models are not equivalent in terms of their accuracy, with some clearly outperforming others. The comparison between FC and NNC ( $p = 0.039$ ) reveals a statistically significant difference, though the p-value is relatively close to the significance threshold (commonly  $p < 0.05$ ). This suggests that while FC outperforms NNC, the difference is not exceedingly pronounced. This outcome might be influenced by specific data characteristics or variations in the models' stability. The comparison between FC and PCA ( $p = 0.016$ ) shows a clearer statistically significant difference. FC's performance is evidently superior to PCA's, which may be attributed to the fundamental differences in their methodologies. PCA, as a dimensionality reduction technique, might lose critical information in the data, leading to lower accuracy in certain

scenarios. For the comparison between FC and MRMR ( $p = 0.039$ ), a statistically significant difference is observed once again. Similar to the FC-NNC comparison, this difference exists but is not highly pronounced. MRMR, which selects features based on mutual information, might not perform as consistently across all datasets, giving FC an edge. The comparison between FC and BFGS ( $p = 0.016$ ) indicates an even more distinct difference. BFGS, as an optimization method, may lack the flexibility or precision required for classification tasks, allowing FC to demonstrate more stable and superior performance in this case. The difference between FC and ADAM ( $p = 0.023$ ) is also statistically significant. While ADAM is generally considered an effective algorithm in many contexts, FC appears to outperform it in this analysis, possibly due to better adaptability to the specific characteristics of the dataset. The most striking difference is seen in the comparison between FC and BAYES ( $p = 0.0078$ ). The very low p-value strongly confirms a statistically significant difference, highlighting FC's clear superiority over BAYES. Notably, BAYES has exhibited high variability in its performance, especially in 2017, when it recorded a very high error rate. This variability likely reduces its overall reliability, which is reflected in this comparison. In summary, FC consistently outperforms all other models in this analysis, with statistically significant differences observed in all pairwise comparisons. The differences are not only numerical but also conceptual, as FC's superior performance can likely be attributed to its stability, flexibility, and ability to handle the data's nuances more effectively. In contrast, models like BAYES and PCA seem more affected by changes in the data or problem conditions. This analysis highlights FC as the most reliable and high-performing model among those evaluated.



**Figure 7.** Statistical comparison of the used machine learning techniques.

The data in Table 2 present the classification error rates for the "FC" machine learning model across different numbers of constructed features ( $N_f = 1$ ,  $N_f = 2$ , and  $N_f = 3$ ) generated using Grammatical Evolution, spanning the years 2014 to 2021. These results provide insights into the impact of the number of features on the model's performance over time. For  $N_f = 1$ , the classification error rates exhibit variability across the years, ranging from a minimum of 6.77% in 2019 to a maximum of 12.68% in 2017. The average error rate for this configuration is 9.03%, indicating a relatively moderate level of accuracy overall. The peak error in 2017 suggests possible challenges in that year's data or specific interactions between the model and the constructed feature set. For  $N_f = 2$ , the classification error rates show a slightly improved overall performance compared to  $N_f = 1$ , with an average

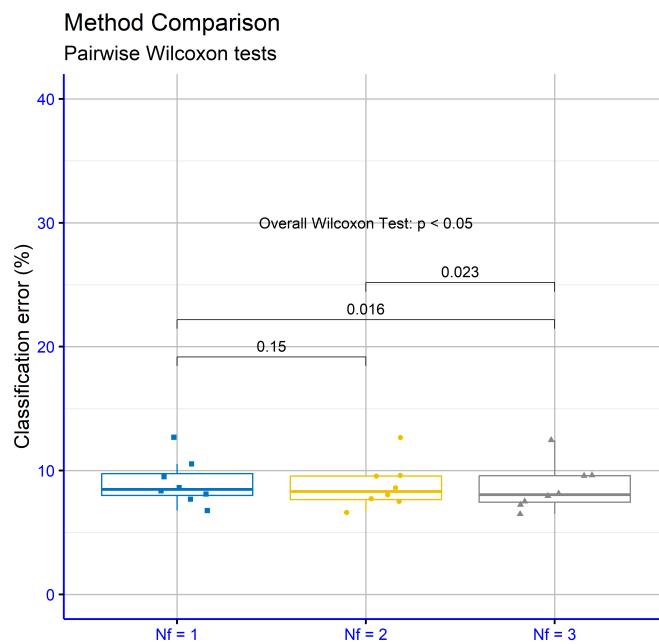
error of 8.79%. The error rates range from 6.62% in 2019, marking the lowest rate for this configuration, to 12.66% in 2017, the highest. These results indicate that adding one more feature generally leads to improved accuracy, although the improvement is not uniform across all years. For  $N_f = 3$ , the classification error rates demonstrate further improvement, with an average error of 8.63%, which is the lowest among the three configurations. The error rates range from a minimum of 6.49% in 2019 to a maximum of 12.46% in 2017. The slightly lower peak error compared to  $N_f = 1$  and  $N_f = 2$  suggests that the inclusion of a third constructed feature enhances the model's ability to capture data patterns more effectively. Across all configurations, the year 2017 consistently exhibits the highest classification error rates, irrespective of the number of features. This outlier suggests specific data-related challenges or unique model behavior during that year. Conversely, 2019 consistently shows the lowest error rates, indicating favorable conditions for accurate classification during that period. The trend in the average classification error rates decreasing from 9.03% for  $N_f = 1$  to 8.63% for  $N_f = 3$  demonstrates that the addition of constructed features through Grammatical Evolution positively impacts the model's accuracy. However, the diminishing returns between  $N_f = 2$  and  $N_f = 3$  suggest that the incremental benefit of adding more features may plateau after a certain point. In conclusion, the analysis reveals that increasing the number of constructed features generally improves the accuracy of the "FC" model. The results highlight the importance of balancing feature complexity and model performance while considering the specific characteristics of the data across different years.

**Table 2.** Experiments with different number of constructed features for the procedure that creates artificial features with Grammatical Evolution.

YEAR	$N_f = 1$	$N_f = 2$	$N_f = 3$
2014	8.36%	8.04%	7.95%
2015	8.10%	7.51%	7.24%
2016	8.61%	8.60%	8.15%
2017	12.68%	12.66%	12.46%
2018	7.68%	7.72%	7.51%
2019	6.77%	6.62%	6.49%
2020	9.50%	9.61%	9.58%
2021	10.53%	9.55%	9.62%
<b>AVERAGE</b>	<b>9.03%</b>	<b>8.79%</b>	<b>8.63%</b>

For Table 2, a statistical analysis was conducted using the Wilcoxon Test (Figure 8) to compare classification error rates among configurations with different numbers of constructed features ( $N_f = 1$ ,  $N_f = 2$ , and  $N_f = 3$ ). The results of the test provide valuable insights into the statistical significance of the differences in the performance of these configurations. The overall result of the Wilcoxon Test, with  $p < 0.5$ , indicates that statistically significant differences exist in at least one of the pairwise comparisons between the configurations. Specifically, the comparison between  $N_f = 1$  and  $N_f = 2$  yields  $p = 0.15$ , which is not statistically significant. This suggests that adding a second constructed feature does not lead to a significant improvement in the model's performance. On the other hand, the comparison between  $N_f = 1$  and  $N_f = 3$  shows  $p = 0.016$ , a statistically significant value. This indicates that the inclusion of a third constructed feature substantially enhances the model's accuracy compared to using only one feature. The comparison between  $N_f = 2$  and  $N_f = 3$  also reveals a statistically significant difference, with  $p = 0.023$ . This result suggests that even the transition from  $N_f = 2$  to  $N_f = 3$  leads to an improvement in performance, although the difference is less pronounced than between  $N_f = 1$  and  $N_f = 3$ . Overall, the analysis demonstrates that increasing the number of constructed features from  $N_f = 1$  to  $N_f = 3$  results in a statistically significant improvement in the model's accuracy. The comparison between  $N_f = 1$  and  $N_f = 2$  is not statistically significant, possibly due to the limited impact of adding only one additional feature. In contrast, the difference

between  $N_f = 2$  and  $N_f = 3$  highlights that further increasing the number of features continues to enhance performance, albeit to a lesser degree.



**Figure 8.** Statistical comparison for the experiment involving different values of the critical parameter  $N_f$ .

#### 4. Conclusions

The study examines the application of feature construction techniques for predicting the duration of forest fires using data collected in Greece over a ten-year period. The methods utilized include Principal Component Analysis (PCA), Minimum Redundancy Maximum Relevance (MRMR), and Grammatical Evolution for constructing artificial features and generating neural networks. The analysis focused on meteorological parameters such as temperature, humidity, wind, and rainfall, which significantly influence the behavior of forest fires. The research concluded that the feature construction technique, using grammatical evolution, outperforms other methods in terms of stability and accuracy. The results indicated that this technique achieved the lowest error rate in predicting fire duration compared to other approaches such as PCA, MRMR, and traditional algorithms like Bayes and Adam. While PCA proved effective for dimensionality reduction, it often led to a loss of critical information. MRMR, though capable of identifying relevant features, did not exhibit consistent performance across all datasets. Traditional algorithms like Bayes showed significant variability, with their performance heavily influenced by the data characteristics. Statistical analysis using the Wilcoxon test demonstrated the clear superiority of feature construction over other methods. This advantage can be attributed to the technique's ability to adapt to the peculiarities of the data, avoiding the information loss observed with other approaches. Specifically, the method excelled in both accuracy and robustness. The study's findings underscore the potential of advanced machine learning techniques in addressing critical environmental challenges such as forest fires. Future research could focus on integrating data from diverse geographical regions or climatic conditions, developing automated real-time monitoring systems, and combining advanced algorithms for even more efficient analysis. Incorporating social and environmental factors into predictive models could also offer a multidimensional understanding of the causes and spread of fires. Overall, this study highlights the importance of scientific approaches and technology in tackling contemporary challenges posed by climate change and natural disasters.

**Author Contributions:** C.K., V.C., A.M. and I.G.T. conceived of the idea and the methodology, and C.K. and V.C. implemented the corresponding software. C.K. and A.M. conducted the experiments, employing objective functions as test cases, and provided the comparative experiments. V.C. performed the necessary statistical tests. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** This research has been financed by the European Union: Next Generation EU through the Program Greece 2.0 National Recovery and Resilience Plan, under the call RESEARCH-CREATE-INNOVATE, project name “iCREW: Intelligent small craft simulator for advanced crew training using Virtual Reality techniques” (project code: TAEDK-06195).

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Gowlett, J.A.J. The discovery of fire by humans: a long and convoluted process. *Philosophical Transaction B, Biological Sciences*, volume 371, Issue 1696. June 5, 2016.
2. Heinonen, Keri. The Fire of Prometheus: More Than Just a Gift to Humanity. *Greek Mythology*. November 19, 2024. Available from: <https://greek.mythologyworldwide.com/the-fire-of-prometheus-more-than-just-a-gift-to-humanity/> (accessed on November 29, 2024).
3. McCaffrey, S. (2004). Thinking of wildfire as a natural hazard. *Society and Natural Resources*, 17(6), 509-516.
4. Patrick, Van Hees. The burning challenge of fire safety. ISO, International Organization for Standardization. Available from: <https://www.iso.org/news/2014/11/Ref1906.html> (accessed on December 3, 2024).
5. UNEP. United Nations Environment Programme. Number of wildfires to rise by 50 per cent by 2100 and governments are not prepared, experts warn. 23 February 2022. Available from: <https://www.unep.org/news-and-stories/press-release/number-wildfires-rise-50-cent-2100-and-governments-are-not-prepared> (accessed on December 4, 2024).
6. NASA. Carbon Dioxide, Vital Signs. October 2024. Available from: <https://climate.nasa.gov/vital-signs/carbon-dioxide/?intent=121> (accessed on November 29, 2024).
7. Iliopoulos, N., Aliferis, I., & Chalaris, M. (2024). Effect of Climate Evolution on the Dynamics of the Wildfires in Greece. *Fire*, 7(5), 162.
8. Giorgi, F. (2006). Climate change hot-spots. *Geophysical research letters*, 33(8).
9. Satish, M., Prakash., Babu, S.M., Kumar, P.P., Devi, S., Reddy, K.P. Artificial Intelligence (AI) and the Prediction of Climate Change Impacts. 2023. IEEE 5th International Conference on Cybernetics, Cognition and Machine Learning Applications (ICCCMLA).
10. Walsh, Dylan. Tackling climate change with machine learning. MIT Management Sloan School. *Climate Change*. October 24, 2023. Available from: <https://mitsloan.mit.edu/ideas-made-to-matter/tackling-climate-change-machine-learning> (accessed on November 29, 2024).
11. ISO. Machine Learning (ML): All there is to know. International Organization for Standardization. Available from: <https://www.iso.org/artificial-intelligence/machine-learning> (accessed on November 30, 2024).
12. Watson, Ian. (2012). How Alan Turing Invented the Computer Age. *Scientific American*. Published: 26/04/2012. Available from: <https://blogs.scientificamerican.com/guest-blog/how-alan-turing-invented-the-computer-age/> (accessed on November 30, 2024).
13. Jain, P., Coogan, S. C., Subramanian, S. G., Crowley, M., Taylor, S., & Flannigan, M. D. (2020). A review of machine learning applications in wildfire science and management. *Environmental Reviews*, 28(4), 478-505.
14. Xiao, H. (2023). Estimating fire duration using regression methods. *arXiv preprint arXiv:2308.08936*.
15. Linardos, V., Drakaki, M., Tzionas, P., & Karnavas, Y. L. (2022). Machine learning in disaster management: recent developments in methods and applications. *Machine Learning and Knowledge Extraction*, 4(2).
16. Sevinc, V., Kucuk, O., & Goltas, M. (2020). A Bayesian network model for prediction and analysis of possible forest fire causes. *Forest Ecology and Management*, 457, 117723.
17. Chen, F., Jia, H., Du, E., Chen, Y., & Wang, L. (2024). Modeling of the cascading impacts of drought and forest fire based on a Bayesian network. *International Journal of Disaster Risk Reduction*, 111, 104716.
18. Kim, B., & Lee, J. (2021). A Bayesian network-based information fusion combined with DNNs for robust video fire detection. *Applied Sciences*, 11(16), 7624.
19. Nugroho, A. A., Iwan, I., Azizah, K. I. N., & Raswa, F. H. (2019). Peatland Forest Fire Prevention Using Wireless Sensor Network Based on Naïve Bayes Classifier. *KnE Social Sciences*, 20-34.

20. Zainul, M., & Minggu, E. (2022). Classification of Hotspots Causing Forest and Land Fires Using the Naive Bayes Algorithm. *Interdisciplinary Social Studies*, 1(5), 555-567. 676  
677
21. Karo, I. M. K., Amalia, S. N., & Septiana, D. Wildfires Classification Using Feature Selection with K-NN, Naïve Bayes, and ID3 Algorithms. *Journal of Software Engineering, Information and Communication Technology (SEICT)*, 3(1), 15-24. 678  
679
22. Vilar del Hoyo, L., Martín Isabel, M. P., & Martínez Vega, F. J. (2011). Logistic regression models for human-caused wildfire risk estimation: analysing the effect of the spatial accuracy in fire occurrence data. *European Journal of Forest Research*, 130, 983-996. 680  
681
23. de Bem, P. P., de Carvalho Júnior, O. A., Matricardi, E. A. T., Guimarães, R. F., & Gomes, R. A. T. (2018). Predicting wildfire vulnerability using logistic regression and artificial neural networks: a case study in Brazil's Federal District. *International journal of wildland fire*, 28(1), 35-45. 682  
683  
684
24. Nhongo, E. J. S., Fontana, D. C., Guasselli, L. A., & Bremm, C. (2019). Probabilistic modelling of wildfire occurrence based on logistic regression, Niassa Reserve, Mozambique. *Geomatics, Natural Hazards and Risk*, 10(1), 1772-1792. 685  
686
25. Peng, W., Wei, Y., Chen, G., Lu, G., Ye, Q., Ding, R., & Cheng, Z. (2023). Analysis of Wildfire Danger Level Using Logistic Regression Model in Sichuan Province, China. *Forests*, 14(12), 2352. 687  
688
26. Hossain, F. A., Zhang, Y., Yuan, C., & Su, C. Y. (2019, July). Wildfire flame and smoke detection using static image features and artificial neural network. In 2019 1st international conference on industrial artificial intelligence (iai) (pp. 1-6). IEEE. 689  
690
27. Lall, S., & Mathibela, B. (2016, December). The application of artificial neural networks for wildfire risk prediction. In 2016 International Conference on Robotics and Automation for Humanitarian Applications (RAHA) (pp. 1-6). IEEE. 691  
692
28. Sayad, Y. O., Mousannif, H., & Al Moatassime, H. (2019). Predictive modeling of wildfires: A new dataset and machine learning approach. *Fire safety journal*, 104, 130-146. 693  
694
29. Gao, K., Feng, Z., & Wang, S. (2022). Using multilayer perceptron to predict forest fires in jiangxi province, southeast china. *Discrete Dynamics in Nature and Society*, 2022(1), 6930812. 695  
696
30. Latifah, A. L., Shabrina, A., Wahyuni, I. N., & Sadikin, R. (2019, October). Evaluation of Random Forest model for forest fire prediction based on climatology over Borneo. In 2019 International Conference on Computer, Control, Informatics and its Applications (IC3INA) (pp. 4-8). IEEE. 697  
698  
699
31. Malik, A., Rao, M. R., Puppala, N., Koouri, P., Thota, V. A. K., Liu, Q., ... & Gao, J. (2021). Data-driven wildfire risk prediction in northern California. *Atmosphere*, 12(1), 109. 700  
701
32. Gao, C., Lin, H., & Hu, H. (2023). Forest-fire-risk prediction based on random forest and backpropagation neural network of Heihe area in Heilongjiang province, China. *Forests*, 14(2), 170. 702  
703
33. Andela, N., Morton, D. C., Giglio, L., Paugam, R., Chen, Y., Hantson, S., & Randerson, J. T. (2019). The Global Fire Atlas of individual fire size, duration, speed and direction. *Earth System Science Data*, 11(2), 529-552. 704  
705
34. Kc, U., Aryal, J., Hilton, J., & Garg, S. (2021). A surrogate model for rapidly assessing the size of a wildfire over time. *Fire*, 4(2), 20. 706
35. Liang, H., Zhang, M., & Wang, H. (2019). A neural network model for wildfire scale prediction using meteorological factors. *IEEE Access*, 7, 176746-176755. 707  
708
36. Xi, D. D., Dean, C. B., & Taylor, S. W. (2021). Modeling the duration and size of wildfires using joint mixture models. *Environmetrics*, 32(6), e2685. 709  
710
37. WFCA. Western Fire Chiefs Association. How Long Do Wildfires Last? October 2022. Available from: <https://wfca.com/wildfire-articles/how-long-do-wildfires-last/> (accessed on December 4, 2024). 711  
712
38. M.G. Smith, L. Bull, Genetic Programming with a Genetic Algorithm for Feature Construction and Selection, *Genet Program Evolvable Mach* 6, pp. 265–281, 2005. 713  
714
39. A. Maćkiewicz, W. Ratajczak, Principal components analysis (PCA). *Computers & Geosciences* 19, pp. 303-342, 1993. 715
40. J. Cadima, I.T. Jolliffe, Principal component analysis: a review and recent developments, National Library of Medicine. 2016. Available online: <https://pmc.ncbi.nlm.nih.gov/articles/PMC4792409/> (accessed on 16 November 2024). 716  
717
41. i2tutorials. What are the Pros and Cons of the PCA? October 1st, 2019. Available online: <https://www.i2tutorials.com/what-are-the-pros-and-cons-of-the-pca/> (accessed on 16 November 2024). 718  
719
42. S.C. Park, Physical Meaning of Principal Component Analysis for Lattice Systems with Translational Invariance. *arXiv preprint arXiv:2410.22682*, 2024. 720  
721
43. O. Sarma, M.A. Rather, S. Shahnaz, R.S. Barwal, Principal Component Analysis of Morphometric Traits in Kashmir Merino Sheep. *Journal of Advances in Biology & Biotechnology* 27, pp. 362-69, 2024. 722  
723
44. C. Gambardella, R. Parente, A. Ciambrone, M. Casbarra, A Principal Components Analysis – Based Method for the Detection of Cannabis Plants Using Representation data by Remote Sensing, Knowledge Extractions from data Using Machine Learning, volume 6 (10), 2021. 724  
725  
726
45. M. Slavkovic, D. Jevtic, Face Recognition Using Eigenface Approach, *Serbian Journal of Electrical Engineering* 9, pp. 121-130, 2012. 727  
728
46. C.A. Hargreaves, C.K. Mani, The Selection of Winning Stocks Using Principal Component Analysis, *American Journal of Marketing Research* 1, pp. 183 – 188, 2015. 729  
730
47. Z. Xu, F. Guo, H. Ma, X. Liu, L. Gao, On Optimizing Hyperspectral Inversion of Soil Copper Content by Kernel Principal Component Analysis. *Remote Sensing* 16, 2024. 731  
732
48. H. Zhang, R. Srinivasa, X. Yang, S. Ahrentzen, E.S. Coker, A. Alwisy, Factors influencing indoor air pollution in buildings using PCA – LMBP neural network: A case study of a university campus, *Building and environment* 225, 2022. 733  
734

49. M.I. Lourakis, A brief description of the Levenberg–Marquardt algorithm implemented by levmar, Foundation of Research and Technology **4**, pp. 1-6, 2005. 735  
736
50. B.A. Akinnuwesi, B.O. Macaulay, B.S. Aribisala, Breast cancer risk assessment and early diagnosis using Principal Component Analysis and support vector machine techniques, *Informatics in medicine unlocked* **21**, 100459, 2020. 737  
738
51. M. Awad, R. Khanna, M. Awad, R. Khanna, Support vector machines for classification. Efficient learning machines: Theories, concepts, and applications for engineers and system designers, pp. 39-66, 2015. 739  
740
52. R. Guan, Predicting forest fire with linear regression and random forest, *Highlights in Science, Engineering and Technology* **44**, pp. 1-7, 2023. 741  
742
53. N. Nikolov, P. Bothwell, J. Snook, Developing a gridded model for probabilistic forecasting of wildland-fire ignitions across the lower 48 States. USFS-CSU Joint Venture Agreement Phase 2 (2019-2021)-Final Report. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 33p, 2022. 743  
744
- 745
54. N. Nikolov, P. Bothwell, J. Snook, Probabilistic forecasting of lightning strikes over the Continental USA and Alaska: Model development and verification. *Scientific Journal, Fire* (7). Available from: <https://research.fs.usda.gov/treesearch/68447> (accessed 20 November 2024). 746  
747
- 748
55. C. Ding, H. Peng, Minimum redundancy feature selection from microarray gene expression data. *Journal of bioinformatics and computational biology* **3**, pp. 185-205, 2005. 749  
750
56. S. Ramirez – Gallego, I. Lastra, D. Martinez – Rego, V. Bolon – Canedo, J.M. Benitez, F. Herrera, A. Alonso – Betanzos, Fast-mRMR: Fast Minimum Redundancy Maximum Relevance Algorithm for High – Dimensional Big Data, *International Journal of Intelligent Systems* **32**, pp. 134 – 152, 2017. 751  
752
- 753
57. Zhao, Z., Anand, R., & Wang, M. (2019, October). Maximum relevance and minimum redundancy feature selection methods for a marketing machine learning platform. In 2019 IEEE international conference on data science and advanced analytics (DSAA) (pp. 442-452). IEEE. 754  
755
- 756
58. S.J. Rigatti, Random forest. *Journal of Insurance Medicine* **47**, pp. 31-39, 2017. 757
59. Wu, H., Yang, T., Li, H., & Zhou, Z. (2023). Air quality prediction model based on mRMR–RF feature selection and ISSA–LSTM. *Scientific Reports*, 13(1), 12825. 758  
759
60. Elbeltagi, A., Nagy, A., Szabo, A., Nxumalo, G.S., Bodí, E.B., Tamas, J. Hyperspectral indices data fusion-based machine learning enhanced by MRMR algorithm for estimating maize chlorophyll content. *Frontiers in Plant Science, Section Technical Advances in Plant Science*, volume 15, October 2024. 760  
761
- 762
61. Liu, J., Sun, H., Li, Y., Fang, W., & Niu, S. (2020). An improved power system transient stability prediction model based on mRMR feature selection and WTA ensemble learning. *Applied Sciences*, 10(7), 2255. 763  
764
62. Dietterich, T. G. (2000, June). Ensemble methods in machine learning. In International workshop on multiple classifier systems (pp. 1-15). Berlin, Heidelberg: Springer Berlin Heidelberg. 765  
766
63. Eristi, B. (2024). A New Approach based on Deep Features of Convolutional Neural Networks for Partial Discharge Detection in Power Systems. *IEEE Access*. 767  
768
64. Li, Y., Zhang, Y., Zhu, H., Yan, R., Liu, Y., Sun, L., & Zeng, Z. (2015). Recognition algorithm of acoustic emission signals based on conditional random field model in storage tank floor inspection using inner detector. *Shock and Vibration*, 2015(1), 173470. 769  
770
65. Karamouz, M., Zahmatkesh, Z., Nazif, S., & Razmi, A. (2014). An evaluation of climate change impacts on extreme sea level variability: Coastal area of New York City. *Water resources management*, 28, 3697-3714. 771  
772
66. M. O'Neill, C. Ryan, Grammatical evolution, *IEEE Trans. Evol. Comput.* **5**, pp. 349–358, 2001. 773
67. I.G. Tsoulos, D. Gavrilis, E. Glavas, Neural network construction and training using grammatical evolution, *Neurocomputing* **72**, pp. 269-277, 2008. 774  
775
68. G.V. Papamokos, I.G. Tsoulos, I.N. Demetropoulos, E. Glavas, Location of amide I mode of vibration in computed data utilizing constructed neural networks, *Expert Systems with Applications* **36**, pp. 12210-12213, 2009. 776  
777
69. I.G. Tsoulos, D. Gavrilis, E. Glavas, Solving differential equations with constructed neural networks, *Neurocomputing* **72**, pp. 2385-2391, 2009. 778  
779
70. I.G. Tsoulos, G. Mitsi, A. Stavrakoudis, S. Papapetropoulos, Application of Machine Learning in a Parkinson's Disease Digital Biomarker Dataset Using Neural Network Construction (NNC) Methodology Discriminates Patient Motor Status, *Frontiers in ICT* **6**, 10, 2019. 780  
781
- 782
71. V. Christou, I.G. Tsoulos, V. Loupas, A.T. Tzallas, C. Gogos, P.S. Karvelis, N. Antoniadis, E. Glavas, N. Giannakeas, Performance and early drop prediction for higher education students using machine learning, *Expert Systems with Applications* **225**, 120079, 2023. 783  
784
- 785
72. E.I. Toki, J. Pange, G. Tatsis, K. Plachouras, I.G. Tsoulos, Utilizing Constructed Neural Networks for Autism Screening, *Applied Sciences* **14**, 3053, 2024. 786  
787
73. J. W. Backus. The Syntax and Semantics of the Proposed International Algebraic Language of the Zurich ACM-GAMM Conference. Proceedings of the International Conference on Information Processing, UNESCO, 1959, pp.125-132. 788  
789
74. Dimitris Gavrilis, Ioannis G. Tsoulos, Evangelos Dermatas, Selecting and constructing features using grammatical evolution, *Pattern Recognition Letters* **29**, pp. 1358-1365, 2008. 790  
791

75. Dimitris Gavrilis, Ioannis G. Tsoulos, Evangelos Dermatas, Neural Recognition and Genetic Features Selection for Robust Detection of E-Mail Spam, Advances in Artificial Intelligence Volume 3955 of the series Lecture Notes in Computer Science pp 498-501, 2006. 792  
793  
794
76. George Georgoulas, Dimitris Gavrilis, Ioannis G. Tsoulos, Chrysostomos Stylios, João Bernardes, Peter P. Groumpas, Novel approach for fetal heart rate classification introducing grammatical evolution, Biomedical Signal Processing and Control **2**, pp. 69-79, 2007. 795  
796  
797
77. Otis Smart, Ioannis G. Tsoulos, Dimitris Gavrilis, George Georgoulas, Grammatical evolution for features of epileptic oscillations in clinical intracranial electroencephalograms, Expert Systems with Applications **38**, pp. 9991-9999, 2011. 798  
799
78. A. T. Tzallas, I. Tsoulos, M. G. Tsipouras, N. Giannakeas, I. Androulidakis and E. Zaitseva, Classification of EEG signals using feature creation produced by grammatical evolution, In: 24th Telecommunications Forum (TELFOR), pp. 1-4, 2016. 800  
801  
802
79. J. Park and I. W. Sandberg, Universal Approximation Using Radial-Basis-Function Networks, Neural Computation **3**, pp. 246-257, 1991. 803  
804
80. H. Yu, T. Xie, S. Paszczynski, B. M. Wilamowski, Advantages of Radial Basis Function Networks for Dynamic System Design, in IEEE Transactions on Industrial Electronics **58**, pp. 5438-5450, 2011. 805  
806
81. C. Bishop, Neural Networks for Pattern Recognition, Oxford University Press, 1995. 807  
808
82. G. Cybenko, Approximation by superpositions of a sigmoidal function, Mathematics of Control Signals and Systems **2**, pp. 303-314, 1989. 809  
810
83. M.J.D Powell, A Tolerant Algorithm for Linearly Constrained Optimization Calculations, Mathematical Programming **45**, pp. 547-566, 1989. 811  
812
84. M. Hall, F. Frank, G. Holmes, B. Pfahringer, P. Reutemann, I.H. Witten, The WEKA data mining software: an update. ACM SIGKDD explorations newsletter **11**, pp. 10-18, 2009. 813  
814
85. S.B. Aher, L.M.R.J. Lobo, Data mining in educational system using weka. In International conference on emerging technology trends, Foundation of Computer Science **3**, pp. 20-25, 2011. 815  
816
86. S. Hussain, N.A. Dahan, F.M. Ba-Alwib, N. Ribata, Educational data mining and analysis of students' academic performance using WEKA. Indonesian Journal of Electrical Engineering and Computer Science **9**, pp. 447-459, 2018. 817  
818
87. A.K. Sigurdardottir, H. Jonsdottir, R. Benediktsson, Outcomes of educational interventions in type 2 diabetes: WEKA data-mining analysis. Patient education and counseling **67**, pp. 21-31, 2007. 819  
820
88. M.N. Amin, A. Habib, Comparison of different classification techniques using WEKA for hematological data. American Journal of Engineering Research **4**, pp. 55-61, 2015. 821  
822
89. G.I. Webb, E. Keogh, R. Miikkulainen, Naïve Bayes, Encyclopedia of machine learning **15**, pp. 713-714, 2010. 823  
824
90. D. P. Kingma, J. L. Ba, ADAM: a method for stochastic optimization, in: Proceedings of the 3rd International Conference on Learning Representations (ICLR 2015), pp. 1-15, 2015. 825  
826
91. Ryan R. Curtin, James R. Cline, N. P. Slagle, William B. March, Parikshit Ram, Nishant A. Mehta, Alexander G. Gray, MLPACK: A Scalable C++ Machine Learning Library, Journal of Machine Learning Research **14**, pp. 801-805, 2013. 827  
828
92. I.G. Tsoulos, A. Tzallas, D. Tsalikakis, NNC: A tool based on Grammatical Evolution for data classification and differential equation solving, SoftwareX **10**, 100297, 2019. 829  
830
93. I.G. Tsoulos, QFC: A Parallel Software Tool for Feature Construction, Based on Grammatical Evolution. Algorithms **15**, 295, 2022. 831  
832