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Article

Tree-Based Classifier Ensembles for PE Malware Analysis: A Performance Revisit

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Abstract: Given their escalating number and variety, combating malware is becoming increasingly strenuous. Machine learning techniques are often used in the literature to automatically discover the models and patterns behind such challenges and create solutions that can maintain the rapid pace at which malware evolves. This article compares various tree-based ensemble learning methods that have been proposed in the analysis of PE malware. A tree-based ensemble is an unconventional learning paradigm that constructs and combines a collection of base learners (e.g., decision trees), as opposed to the conventional learning paradigm, which aims to construct individual learners from training data. Several tree-based ensemble techniques, such as random forest, XGBoost, CatBoost, GBM, and LightGBM, are taken into consideration and are appraised using different performance measures, such as accuracy, MCC, precision, recall, AUC, and F1. In addition, the experiment includes many public datasets, such as BODMAS, Kaggle, and CIC-MalMem-2022, to demonstrate the generalizability of the classifiers in a variety of contexts. Based on the test findings, all tree-based ensembles performed well, and performance differences between algorithms are not statistically significant, particularly when their respective hyperparameters are appropriately configured. The proposed tree-based ensemble techniques also outperformed other, similar PE malware detectors that have been published in recent years.

Keywords: portable executable malware; tree-based ensemble; performance comparison; statistical significance test

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1. Introduction

Malware (e.g., malicious software) is commonly recognized as one of the most potent cyber threats and hazards to modern computer systems [1,2]. It is an overarching word that refers to any code that potentially has a destructive, harmful effect [3]. On the basis of their behavior and execution processes, malicious softwares are categorized as worms, viruses, Trojan horses, rootkits, backdoors, spyware, logic bombs, adware, and ransomware. Computer systems are hacked for a variety of reasons, including the destruction of computer resources, financial gain, the theft of private and confidential information and the use of computing resources, as well as the inaccessibility of system services, to name a few [4].

Malware is recognized using signature-based or behavior-based methods. The signature-based malware detection techniques are quick and effective, but obfuscated malware can quickly circumvent them. In contrast, behavior-based methods are more resistant to obfuscation. Nonetheless, behavior-based methods are relatively time-intensive. Therefore, in addition to the signature-based and behavior-based malware detection techniques, numerous fusion techniques exist that contain the benefits of both [5,6]. The goal of these fusion strategies is to address the shortcomings of signature and behavior-based approaches.

While we work to defend ourselves from malware, cybercriminals continue to create increasingly complex techniques to obtain and steal data and resources. Conventional methods (i.e., rule-based, graph-based, and entropy-based) for analyzing and detecting malware focus on matching known malicious signatures to alleged malicious programs. Such static solutions require a known harmful signature, rendering them unsatisfactory against new (e.g., zero-day) attacks, and depend on end users to maintain system updates. Attackers are aware that these methods may also be vulnerable to obfuscation, such as code obfuscation to avoid detection against known signatures [7]. Hence, it is necessary to update and build malware detection mechanisms that are capable of withstanding significant attacks [8].

Machine learning offers the potential to construct malware detectors that are capable of combating newer versions of malware, and different supervised and unsupervised-algorithm-based machine learning methods have been reported in the literature [9–11]. More specifically, ensemble learning approaches have been utilized and achieved excellent results in malware detection [12–17]. In most cases, ensemble learning algorithms yield superior results as compared to individual classification algorithms, i.e., support vector machine, decision tree, naive Bayes, and neural networks. However, although classifier ensembles demonstrate a significant performance, the majority of these ensembles are deployed in a restricted manner without adequate hyperparameter tuning. Moreover, the performance of classifier ensembles is validated using a single dataset; consequently, no generalizable results are produced.

The tree-based ensemble technique is an ensemble learning paradigm in which a collection of base learners (e.g., decision trees or CART) are constructed and combined from the training data [18]. For instance, random forest [19] is comprised of a large number of individual decision trees that operate as an ensemble. It uses feature randomness to generate an uncorrelated forest of decision trees. In a similar fashion, the gradient boosting decision tree algorithms combine a collection of individual decision trees to form an ensemble. However, unlike random forest, the decision trees in gradient boosting are constructed serially (e.g., additively). Gradient boosting decision tree algorithms have recently been proposed and have demonstrated remarkable results in many domains, such as protein–protein interaction prediction [20], neutronic calculation [21], human activity recognition [22], etc. However, their performance in classifying and detecting malware remains questionable. This motivated us to employ ensembles of tree-based algorithms to classify PE malware. This paper makes the following contributions to the current literature.

(a) Fine-tuned tree-based classifier ensembles, i.e., random forest [19], XGBoost [23], CatBoost [24], GBM [25], and LightGBM [26], to detect PE malware are employed.
(b) The performance differences between classifier ensembles over the most recent datasets, i.e., BODMAS [27], Kaggle, and CIC-MalMem-2022 [28] are benchmarked using statistical significance tests. This study is among the first to utilize the most recent malware BODMAS and CIC-MalMem-2022 datasets. On the BODMAS and CIC-Malmem-2022 datasets, our proposed approaches outperform other baselines with a 99.96% and 100% accuracy rate, respectively.
(c) An in-depth exploratory analysis of each malware dataset is presented to better understand the characteristics of each malware dataset. The analysis includes a feature correlation analysis and t-SNE visualization of pairs of samples' similarities.

The remainder of the paper is structured as follows. An overview of PE malware detection based on classifier ensembles is provided in Section 2. Next, we present the background of tree-based classifier ensembles and datasets in Section 3. Section 4 discusses the experimental results, and in the end, Section 5 concludes the paper.

2. Related Work

Ucci et al. [7], Maniriho et al. [10] provide the machine learning taxonomy for malware analysis, while [11] present an overview of malware analysis in CPS and IoT. Malware analysis can be accomplished via either static or dynamic analysis, or a mix of the two, depending on how the information extraction procedure is carried out. Approaches based on static analysis evaluate the content of samples without necessitating their execution, whereas dynamic analysis examines the behavior of samples by executing them. This study analyzes a static analysis of PE files, since it can yield a plethora of useful information, e.g., the compiler and symbols used.

Meanwhile, machine learning techniques were largely employed in malware detection [29,30]. Malware samples were examined and the extracted features are used to train the classification algorithm. An overview of the machine learning techniques used for the classification of malware is provided in the following. We particularly explore malware detectors that employ at least one ensemble learning technique. Mills et al. [17], Vadrevu et al. [31], Uppal et al. [32], Kwon et al. [33] utilized random forest for malware detection based on PE file characteristics and networks. Furthermore, Mao et al. [34], Wüchner et al. [35], Ahmadi et al. [36] developed a random forest classifier to detect malware using various features, such as system calls, file system, and Windows registry. Amer and Zelinka [13] proposed an ensemble learning strategy to address the shortcomings of the existing commercial signature-based techniques. The proposed technique was able to focus on the most salient features of malware PE files by lowering the dimensionality of the data. Dener et al. [37] and Azmee et al. [38] compared the use of various machine learning algorithms to detect PE malware and showed that XGBoost and logistic regression were the best-performing methods.

Liu et al. [39] employed data visualization and adversarial training on ML-based detectors to effectively detect the various types of malware and their variants in order to address the current issues in malware detection, such as the consideration of attacks from adversarial examples and the massive growth in malware variants. In [40], a deep feature extraction technique for malware analysis was addressed in light of the current progress in deep learning. Deep features were obtained from a CNN and were fed to an SVM classifier for malware classification. Moreover, a CNN ensemble for malware classification was proposed in [15,16]. The proposed architecture was constructed in a stacked fashion, with a machine learning algorithm providing the final classification. A meta-classifier was selected after various machine learning algorithms were analyzed and evaluated. Most recently, [41] proposed a CNN-based feature extraction and a channel-attention module to reduce the information loss in the process of feature image generation of malware samples. Specific deep learning architectures, such as a deep belief network and transformer-based classifier, were also considered when classifying Android [42,43] and PE malware [44], respectively. Table 1 presents a summary of the existing malware detectors described in the literature.

Table 1. Summarization of the existing PE malware detectors.

Study	**Algorithm(s)**	**Data Set**	**Validation Technique**	**Best Result**
Mills et al. [17]	RF	Private	7-CV	-
Vadrevu et al. [31]	RF	Private	CV and Hold-out	TPR: 90%, FPR: 0.1%
Uppal et al. [32]	NB, DT, RF, and SVM	Private	10-CV	Accuracy: 98.5%
Kwon et al. [33]	RF	Private	10-CV	TPR: 98.0%, FPR: 2.00%, F1: 98.0%, AUC: 99.8%
Mao et al. [34]	RF	Private	Repeated hold-out	TPR: 99.88%, FPR: 0.1%
Wüchner et al. [35]	RF	Malicia	10-CV	DR: 98.01%, FPR: 0.48%
Ahmadi et al. [36]	XGBoost	Kaggle	5-CV	Accuracy: 98.62%
Amer and Zelinka [13]	RF and extra trees	Kaggle	Hold-out	Accuracy: 99.8%, FPR: 0.2%
Liu et al. [39]	CNN and autoencoder	MS BIG and Ember	10-CV	Accuracy: 96.25%

Table 1. *Cont.*

Study	Algorithm(s)	Data Set	Validation Technique	Best Result
Asam et al. [40]	CNN and SVM	MalImg	Hold-out	Accuracy: 98.61%, precision: 96.27%, recall: 96.30%, F1: 96.32%
Azeez et al. [15]	1D CNN and Extra trees	Kaggle	10-CV	Accuracy: 100%, precision: 100%, recall: 100%, F1: 100%
Damaševičius et al. [16]	Stacked CNN	ClaMP	10-CV	Accuracy: 99.9%, precision: 99.9%, recall: 99.8%, F1: 99.9%
Hou et al. [42]	DBN	Comodo cloud	10-CV	Accuracy; 96.66%
Hou et al. [43]	DBN and SAEs	Comodo cloud	10-CV	Accuracy: 96.66%
Azmee et al. [38]	XGBoost	Kaggle	10-CV	Accuracy: 98.6%, AUC: 0.99, TPR: 99.0%, FPR: 3.7%
Jingwei et al. [41]	CNN	MS BIG and BODMAS	10-CV	(MS BIG) accuracy: 99.40%, (BODMAS) accuracy: 99.26%
Lu et al. [44]	Transformer	BODMAS and MS BIG	Hold-out	(MS BIG) accuracy: 98.17%, F1: 98.14%, (BODMAS) accuracy:96.96%, F1: 96.96%
Dener et al. [37]	Logistic regression	CIC-MalMem-2022	Repeated hold-out	Accuracy: 99.97%

3. Materials and Methods

This study evaluates the performance of ensembles of tree-based classifiers in detecting PE malware. Figure 1 depicts the stages involved in our comparative analysis. Several tree-based ensemble approaches are trained on three distinct PE malware training datasets in order to generate classification models. The performance of classification models is then determined by validating them on a testing dataset. Finally, a two-step statistical significance test is then utilized to evaluate the performance benchmarks. In the following section, we provide a brief summary of the malware datasets and tree-based classifier ensembles utilized in this study.

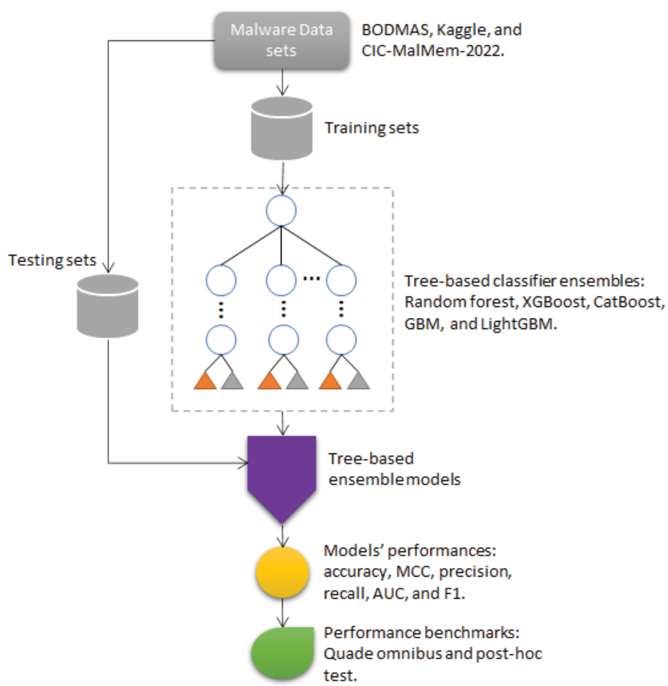


Figure 1. Performance comparison methodology of tree-based ensembles for PE malware detection.

3.1. Datasets

One of the most problematic aspects of using machine learning to solve malware detection problems is producing a realistic feature set from a large variety of unidentified portable executable samples. In essence, the dataset used to train machine learning models determines their level of sophistication. Hence, developing a solid, labeled dataset that represents all analyzed samples is more helpful for malware detection. In light of this, we utilize more recent public datasets that depict the characteristics and attack behaviors of contemporary malware:

(a) BODMAS [27]
The dataset contains 57,293 malicious and 77,142 benign samples (134,435 in total). The malware samples were arbitrarily picked each month from the internal malware database of a security company. The data were collected between 29 August 2019 and 30 September 2020. The benign samples were gathered between 1 January 2007 and 30 September 2020. In order to reflect benign PE binary distribution in real-world traffic, the database of the security company is also processed for benign samples. In addition, SHA-256 hash, the actual PE binary, and a pre-extracted feature vector were given for each malicious sample, whereas only SHA-256 hash and the pre-extracted feature vector were provided for each benign sample. BODMAS is comprised of 2381 input feature vectors and 1 class label feature, of which 0 is labeled as benign and 1 is labeled as malicious.

(b) Kaggle (https://tinyurl.com/22z7u898, access on 25 August 2022)
The dataset was developed using a Python library called $pefile$ (https://tinyurl.com/w75zewvr, accessed on 25 August 2022), which is a multi-platform module used to parse and work with PE files. Kaggle dataset contains 14,599 malicious and 5012 benign samples (19,611 in total). The dataset is comprised of 78 input features, denoting PE header files and one class label attribute.

(c) CIC-MalMem-2022 [28]
Unlike the two above-mentioned datasets, CIC-MalMem-2022 is an obfuscated malware dataset that is intended to evaluate memory-based obfuscated malware detection algorithms. The dataset was designed to mimic a realistic scenario as accurately as possible using reowned malware. Obfuscated malware comprises malicious software that conceals itself to escape detection and eradication. The dataset consists of an equal ratio of malicious and benign memory dumps (58,596 samples in total). In addition, CIC-MalMem-2022 is made up of 56 features that serve as inputs for machine learning algorithms.

3.2. Tree-Based Ensemble Learning

The tree-based ensemble is a non-ordinary learning paradigm that constructs and combines a set of base learners (e.g., decision trees or CART) as opposed to the commonplace learning paradigm that attempts to construct individual learners from training data. Normally, an ensemble is formed in two processes, i.e., by first producing the base learners and then integrating them. For a decent ensemble, it is commonly considered that the base learners must be as accurate and diversified as possible [18]. This study considers four tree-based ensemble learning algorithms. It is worth mentioning that tuning the hyperparamters for each algorithm is carried out using *random search* approach [45].

(a) Random forest [19]
As its name implies, a random forest is a tree-based ensemble in which each tree is dependent on a set of random variables. The original formulation of random forest algorithm provided by Breiman [19] is as follows. A random forest employs trees $h_j(\mathcal{X}, \Omega)$ as its base learners. For training data $\mathscr{D} = \{(\mathbf{x}_1, y_1), ..., (\mathbf{x}_\alpha, y_\alpha)\}$, where $\mathbf{x}_i = (\mathbf{x}_{i,1}, ..., \mathbf{x}_{i,p})^T$ represents the p predictors and y_i represents the response, and a specific manifestation ω_j of Ω_j, the fitted tree is given as $\hat{h}_j(\mathbf{x}, \omega_j, \mathscr{D})$. More precisely, the steps involved in the random forest algorithm are described in Algorithm 1.

Algorithm 1: A common procedure of random forest algorithm for classification task.

Training:
Require: Original training set $\mathscr{D} = \{(\mathbf{x}_1, y_1), (\mathbf{x}_2, y_2), ..., (\mathbf{x}_\alpha, y_\alpha)\}$, with $\mathbf{x}_i = (\mathbf{x}_{i,1}, ..., \mathbf{x}_{i,p})^T$
1. **for** $j = 1$ to J
2. Perform a bootstrap sample $\mathscr{D}_j$ of size α from $\mathscr{D}$.
3. Using binary recursive partitioning, fit a tree on $\mathscr{D}_j$.
4. **end for**

Testing:
Require: An instance to be classified $\mathbf{x}$.
1. $\hat{f}(\mathbf{x}) = \arg\max_y \sum_{j=1}^{J} I(\hat{h}_j(\mathbf{x}) = y)$

where $\hat{h}_j(\mathbf{x})$ denotes the response variable at $\mathbf{x}$ using the j-th tree.

We use a fast random forest implementation called *ranger* [46], available in *R*, which is suitable for high-dimensional data such as ours. The list of random forest's hyperparameters for each malware dataset is provided in Table 2. We set the search space for each hyperparameter tuning is as follows. Number of trees = {50, 100, 250, 500, 750, 1000}, split rule = {'gini','extratrees'}, minimum node size = {1, 2, ..., 10}, *mtry* = number of features × {0.05, 0.15, 0.25, 0.333, 0.4}, sample fraction = {0.5, 0.63, 0.8}, and *replace* = {TRUE, FALSE}.

Table 2. The final learning parameters of random forest used for each dataset after performing a *random search*.

Hyperparameter	**BODMAS**	**Kaggle**	**CIC-MalMem-2022**
Number of trees	100	1000	500
Split rule	'gini'	'gini'	'extratrees'
Minimum node size	4	8	6
mtry	119	30	18
Sample fraction	0.63	0.80	0.63
replace	FALSE	FALSE	TRUE

(b) Gradient Boosting Decision Trees

In this paper, we also considered various tree-based boosting ensemble approaches for malware detection, such as XGBoost [23], CatBoost [24], GBM [25], and LightGBM [26]. As a rule, GBDT ensembles are a linear additive model, where a tree-based classifier (e.g., CART) was utilized as their base model. Let $\mathscr{D} = \{(\mathbf{x}_i, y_i)|i \in \{1, ..., \alpha\}, \mathbf{x}_i \in \mathbb{R}^\eta, y_i \in \mathbb{R}\}$ denote the malware dataset comprising η features and α samples. Considering a collection of j trees, the prediction output $y(\hat{\mathbf{x}})^j$ for an input $\mathbf{x}$ is obtained by calculating the predictions from each tree $y(\hat{\mathbf{x}})^j$, as shown in the following formula.

$$y(\hat{\mathbf{x}})^j = \sum_{i=1}^{j} f_i(\mathbf{x}) \quad (1)$$

where f_i represents the output of the i-th regression tree of the $j-$tree ensemble. GBDTs minimize a regularized objective function Obj^t in order to create the $(j+1)$-th tree, as follows.

$$\min\{Obj(f)^t\} = \min\{\Omega(f)^t + \Theta(f)^t\} \quad (2)$$

where $\Omega(f)^t$ represents loss function and $\Theta(f)^t$ is a regularization function to control over-fitting. The loss function $\Omega(f)^t$ measures the difference between the prediction $\hat{y}_i$ and the target y_i. On the other hand, the regularization function is defined as $\Theta(f)^t = \gamma T + \frac{1}{2}\lambda \parallel w \parallel^2$, where T and w indicate the number of leaves and leaf weights in the tree, respectively.

(i) XGBoost [23]

XGBoost is a scalable end-to-end tree-boosting strategy that generates a large number of sequentially trained trees. Each succeeding tree corrects the errors made by the preceding one, resulting in an efficient classification model. Through sparsity-aware metrics and multi-threading approaches, XGBoost not only addresses the algorithm's overfitting problem, but also boosts the speed of most real-world computational tasks. This study utilizes two different XGBoost implementations, such as native implementation in *R* [47] and *H2O* [48]. We set the search space of native XGBoost's hyperparameters are as follows. Maximum depth = {2, 3, ..., 24}, eta = {0, 0.1, 0.2, ..., 1.0}, subsample = {0.5, 0.6, 0.7, 0.8}, and column sample by tree = {0.5, 0.6, 0.7, 0.8, 0.9}. Moreover, we set the search space of XGBoost's hyperparameters implemented in *H2O* are as follows. Maximum depth = {1, 3, 5, ..., 29}, sample rate = {0.2, 0.3, ..., 1}, column sample rate = {0.2, 0.21, 0.22, ..., 1}, column sample rate per tree = {0.2, 0.21, 0.22, ...,1}, and minimum rows = {0, 1, ..., $\log_2 \times$ number of rows-1}. The final learning parameters for both XGBoost implementations are presented in Table 3.

Table 3. The final learning parameters of XGBoost used for each dataset after performing a *random search*.

Hyperparameter	BODMAS	Kaggle	CIC-MalMem-2022
Native			
Maximum depth	11	19	19
eta	0.2	0.3	0.1
Subsample	0.6	0.8	0.6
Column sample by tree	0.7	0.5	0.6
H2O			
Maximum depth	24	23	26
Sample rate	0.52	0.94	0.99
Column sample rate	0.42	0.62	0.6
Column sample rate per tree	0.6	0.25	0.5
Minimum rows	2	2	2

(ii) CatBoost [24]

CatBoost is built with symmetric decision trees. It is acknowledged as a classification algorithm that is capable of producing an excellent performance and ten times the prediction speed of methods that do not employ symmetric decision trees. CatBoost, unlike other GBDT algorithms, is able to accommodate gradient bias and prediction shift to increase the accuracy of predictions and generalization ability of large datasets. In addition, CatBoost is comprised of two essential algorithms: ordered boosting, which estimates leaf values during tree structure selection to avoid overfitting, and a unique technique for handling categorical data throughout the training process. An implementation of CatBoost in *R* is employed in this paper, whereas the search space of each hyperparameter is considered as follows. Depth = {1, 2, ..., 10}, learning rate = {0.03, 0.001, 0.01, 0.1, 0.2, 0.3}, l2 leaf regularization = {3, 1, 5, 10, 100}, border count = {32, 5, 10, 20, 50, 100, 200}, and boosting type = {"Ordered", "Plain"}. The final learning parameters of CatBoost for each malware dataset are given in Table 4.

Table 4. The final learning parameters of CatBoost used for each dataset after performing a *random search*.

Hyperparameter	BODMAS	Kaggle	CIC-MalMem-2022
Depth	10	4	2
Learning rate	0.2	0.2	0.2
L2 leaf regularization	5	3	5
Border count	100	100	50
Boosting type	"Plain"	"Plain"	"Ordered"

(iii) Gradient boosting machine [25]
GBM is the first implementation of GBDT to utilize a forward learning technique. Trees are generated in a sequential manner, with future trees being dependent on the results of the preceding trees. Formally, GBM is achieved by iteratively constructing a collection of functions $f^0, f^1, ..., f^t$, given a loss function $\Omega(y_i, f^t)$. We can optimize our estimates of y_i by discovering another function $f^{t+1} = f^t + h^{t+1}(\mathbf{x})$, such that h^{t+1} reduces the estimated value of the loss function. In this study, we adopt GBM implementation in H2O, whereas the hyperparameters' search space is specified as follows. Maximum depth = {1, 3, 5, ..., 29}, sample rate = {0.2, 0.3, ..., 1}, column sample rate per tree = {0.2, 0.21, 0.22, ..., 1}, column sample rate change per level = {0.9, 0.91, ..., 1.1}, number of bins = $2^{\{4,5,...,10\}}$, and minimum rows = {0, 1, ..., $\log_2 \times$ number of rows-1}. Table 5 shows a list of all the final GBM hyperparameters that were used on each malware dataset.

Table 5. The final learning parameters of GBM used for each dataset after performing *random search*.

Hyperparameter	BODMAS	Kaggle	CIC-MalMem-2022
Maximum depth	24	25	27
Sample rate	0.52	0.44	0.72
Column sample rate per tree	0.42	0.64	0.61
Column sample rate change per level	1.02	1.04	0.92
Number of bins	64	512	1024
Minimum rows	2	2	8

(iv) LightGBM [26]
LightGBM is an inexpensive gradient boosting tree implementations that employs histogram and leaf-wise techniques to increase both processing power and prediction precision. The histogram method is used to combine features that are incompatible with each another. Before generating a n-width histogram, the core idea is to discretize continuous features into n integers. Based on the discretized values of the histogram, the training data are scanned to locate the decision tree. The histogram method considerably reduces the runtime complexity. In addition, in LightGBM, the leaf with the greatest splitting gain was found and then divided using a leaf-by-leaf strategy. Leaf-wise optimization may result in overfitting and a deeper decision tree. To ensure great efficiency and prevent overfitting, LightGBM includes a maximum depth constraint to leaf-wise. In this study, we employed a LightGBM implementation in R with the following hyperparameter search space; Maximum bin = {100, 255}, maximum depth = {1, 2, ..., 15}, number of leaves = $2^{(\{1,2,...,15\}}$, minimum data in leaf = {100, 200, ..., 1000}, learning rate = {0.01, 0.3, 0.01}, lambda l1 = {0, 10, 20, ..., 100}, lambda l2 = {0, 10, 20, ..., 100}, feature fraction = {0.5, 0.9}, bagging fraction = {0.5, 0.9}, path smooth = $\{1 \times 10^{-8}, 1 \times 10^{-3}\}$, and minimum gain to split = {0, 1, 2, ..., 15}. Table 6 contains the list of all final LightGBM hyperparameters used for each malware dataset.

Table 6. The final learning parameters of LightGBM used for each dataset after performing *random search*.

Hyperparameter	BODMAS	Kaggle	CIC-MalMem-2022
Maximum bin	100	100	255
Maximum depth	10	9	3
Number of leaves	8192	8	512
Minimum data in leaf	1000	800	700
Learning rate	0.29	0.27	0.07
Lambda l1	40	0	0
Lambda l2	90	20	90
Feature fraction	0.5	0.9	0.9
Bagging fraction	0.5	0.5	0.5
Path smooth	0.001	1×10^{-8}	0.001
Minimum gain to split	2	15	11

4. Result and Discussion

This section analyzes and discusses the results of the tree-based classifier ensembles applied to malware classification. The results of exploratory analysis are presented first, followed by a performance comparison between the tree-based ensemble models.

4.1. Exploratory Analysis

We first provide a correlation analysis between multiple variables in each malware dataset. Figure 2 shows the correlation coefficient score matrix measured by Pearson correlation. Correlation analysis is useful to understand the relationship between variables in a dataset, since the Good input features of a dataset should have a high correlation with target features, but should be uncorrelated with each other. Figure 2 confirms that both BODMAS and Kaggle datasets have fewer uncorrelated features than CIC-MalMem-2022. Hence, to mitigate the curse of dimesionality, it is strongly recommended to employ feature selection before employing a machine learning method on CIC-MalMem-2022. Highly correlated features have a negligible effect on the output prediction but raise the computational cost.

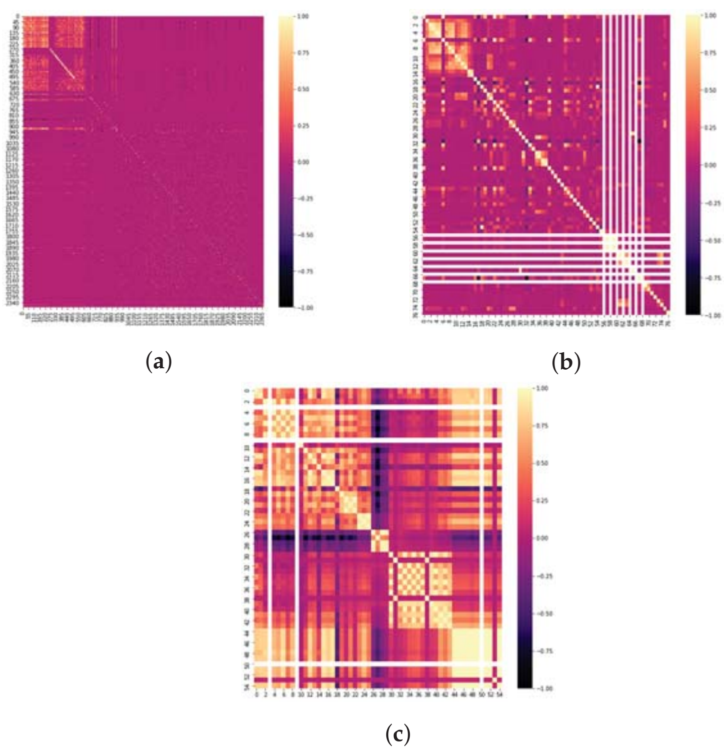
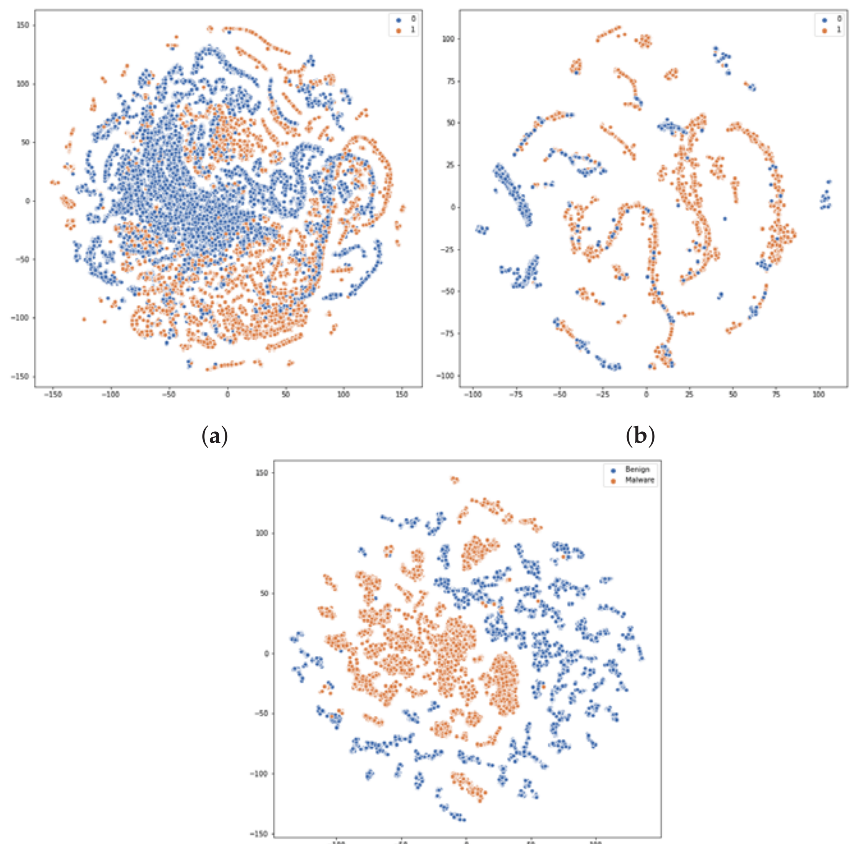


Figure 2. Feature correlation analysis of each malware dataset: (**a**) BODMAS, (**b**) Kaggle, and (**c**) CIC-MalMem-2022.

In addition, we ran a t-SNE algorithm [49] with a learning rate = 5000 and perplexity = 100. The t-SNE is an approach that converts a set of high-dimensional points to two dimensions in such a way that, ideally, close neighbors remain close and far points remain far. Figure 3 provides a spatial representation of the dataset in two dimensions. The t-SNE provides a pliable border between the local and global data structures. It also estimates the size of each datapoint's local neighborhood based on the local density of the data by requiring each conditional probability distribution to have the same perplexity (e.g., Gaussian kernel). Furthermore, Figure 3 demonstrates that both BODMAS and Kaggle datasets are highly imbalanced as compared with CIC-MalMem-2022.



(**a**) (**b**)

(**c**)

Figure 3. Two-dimensional visualization of instance pairs using t-SNE technique of each malware dataset: (**a**) BODMAS, (**b**) Kaggle, and (**c**) CIC-MalMem-2022.

4.2. Comparison Analysis

In the experiment, we employed a k cross-validation technique ($k = 10$), where the final performance outcome for each tree-ensemble model is the mean of the ten folds. The performance of each model was measured based on six performance metrics, such as accuracy, MCC, precision, recall, AUC, and F1. These metrics are chosen to provide more accurate estimates of the behavior of the classifier ensembles under the experiment. Especially, Chicco et al. [50] have shown that MCC is more informative than accuracy and F1, which yield reliable estimates when used to balanced datasets, but misleading outcomes when applied to imbalanced data sets. For a binary classification problem, the outcome of a tree-based classifier ensemble is typically derived from a contigency matrix, $\mathcal{T} = \begin{pmatrix} TP & FN \\ FP & TN \end{pmatrix}$, where TP is true positive, FN is false negative, FP is false positive, and TN is true negative. Let $\xi_+ = TP + FN$ and $\xi_- = TN + FP$ be the number of samples labeled as malware and non-malware, respectively. Hence, the performance metrics used in this study can be calculated as follows.

$$\text{Accuracy} = \frac{TP + TN}{\xi_+ + \xi_-} \tag{3}$$

$$\text{MCC} = \frac{TP \times TN - FP \times FN}{((TP + FP) \times \xi_- \times (TN + FN) \times \xi_+)^{1/2}} \tag{4}$$

$$\text{Precision} = \frac{TP}{TP + FP} \tag{5}$$

$$\text{Recall} = \frac{TP}{\xi_+} \tag{6}$$

$$\text{AUC} = \int_0^1 \text{Recall} \times \frac{FP}{\xi_-} d\frac{FP}{\xi_-} = \int_0^1 \text{Recall} \times \left(\frac{FP}{\xi_-}\right)^{-1}(x))dx \tag{7}$$

$$\text{F1} = \frac{2TP}{2TP + FP + FN} \tag{8}$$

Figure 4 presents the performance score of each algorithm on each dataset. Overall, considering MCC as a performance indicator, LightGBM is the worst-performing algorithm, while XGBoost (native) is the best-performing on BODMAS and Kaggle datasets, followed by GBM (H2O). Interestingly, random forest has also performed well on the remaining dataset. Using accuracy as a performance metric, it is also apparent that there are modest performance disparities amongst algorithms (e.g., all algorithms achieve 100% accuracy). Consequently, our results support the findings stated by [50]. In Table 7, we provide the performance average of each algorithm over various datasets and demonstrate that XGBoost (native) is superior to any competitors on the board in terms of accuracy, MCC, and precision metrics. On the other hand, when recall, AUC, and F1 metrics are utilized, GBM (H2O) shows a superior performance.

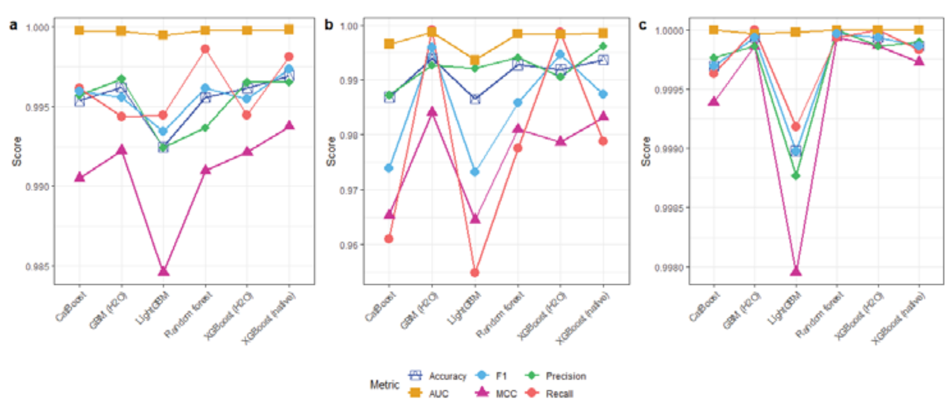


Figure 4. Performance comparison of various tree-based ensemble models on different datasets, i.e., (**a**) BODMAS, (**b**) Kaggle, and (**c**) CIC-MalMem-2022.

Table 7. Performance average of each ensemble technique over various malware datasets.

Ensemble Algorithms	Accuracy	MCC	Precision	Recall	AUC	F1
CatBoost	0.9940	0.9851	0.9943	0.9856	0.9988	0.9899
XGBoost (native)	0.9968	0.9922	0.9975	0.9923	0.9994	0.9949
LightGBM	0.9927	0.9823	0.9945	0.9828	0.9977	0.9885
Random forest	0.9961	0.9906	0.9959	0.9921	0.9994	0.9940
GBM (H2O)	0.9967	0.9920	0.9964	0.9978	0.9995	0.9971
XGBoost (H2O)	0.9960	0.9902	0.9956	0.9977	0.9994	0.9967

This section includes a two-step statistical significance test using Quade omnibus test and Quade post-hoc test [51] to better comprehend the performance difference between tree-based ensemble models. Using a significant threshold $\alpha = 0.05$ and MCC as a performance indicator, the Quade omnibus test demonstrates that at least one classifier performs differently than others (p-value = 0.01725). Since we found significance in the previous test, we then applied the Quade post-hoc test to determine the pairwise performance difference between classifiers. Here, we considered XGBoost (native) as a control classifier for comparison with the remaining algorithms. Table 8 depicts the p-value of the pairwise comparison. It is clear that the performance differences between XGBoost and the other algorithms are not statistically significant (p-value > 0.05).

Table 8. The p-value of Quade post-hoc, in which XGBoost (native) is used as a control algorithm.

CatBoost	XGBoost (Native)	LightGBM	Random Forest	GBM (H2O)	GBM (H2O)
0.250153	-	0.125201	0.7014781	0.6092802	0.8983268

To demonstrate the efficacy of tree-based ensemble models for malware detection, we compared our performance findings to those of previous studies for each dataset. Table 9 denotes the performance comparisons in terms of several performance measures, such as accuracy, precision, recall, and F1. Please note that the comparison is conducted as objectively as possible, given that the prior experiment may have been conducted under different settings, such as validation techniques and the number of training and testing samples. Nevertheless, this study shows that the top-performing tree-based ensemble examined for each dataset outperforms prior research, with a comparable result. More precisely, GBM (H2O), XGBoost (native), and random forest are the best performers on the Kaggle, BODMAS, and CIC-MalMem-2022 datasets, respectively, which also outperform other state-of-the-art malware detection techniques available in the recent literature.

Table 9. Performance comparisons over existing studies. The best performance value on each dataset is shown in bold.

Study	Accuracy (%)	Precision (%)	Recall (%)	F1 (%)
Kaggle				
Hou et al. [42]	93.68	93.96	93.36	93.68
Hou et al. [43]	96.66	96.55	96.76	96.66
Azmee et al. [38]	98.60	96.30	99.00	-
This study (GBM (H2O))	**99.39**	**99.27**	**99.92**	**99.59**
BODMAS				
Jingwei et al. [41]	99.29	98.07	98.26	94.23
Lu et al. [44]	96.96	-	-	96.96
This study (XGBoost (native))	**99.96**	**99.65**	**99.81**	**99.73**
CIC-MalMem-2022				
Dener et al. [37]	99.97	99.98	99.97	99.97
This study (Random forest)	**100.00**	**100.00**	99.99	**100.00**

5. Conclusions

This article examined tree-based ensemble learning algorithms that analyze PE malware. Several tree-based ensemble techniques, including random forest, XGBoost, CatBoost, GBM, and LightGBM, were assessed based on a number of performance criteria, such as accuracy, MCC, precision, recall, AUC, and F1. In addition, we incorporated cutting-edge malware datasets to comprehend the most recent attack trends. This work contributed to the prior research in several ways, including by providing a statistical comparison of fine-tuned tree-based ensemble models utilizing several malware datasets. Furthermore, this article can be expanded in a number of ways, including by looking at the explainability of tree-based ensemble models and signature-based malware classification. Furthermore, a deep neural network model for tabular data, such as TabNet [52], has been underexplored in this application domain, providing a new direction for future research. Finally, it is anticipated that tree-based PE malware detection will be deployed in various real-world settings, such as in host, network, and cloud-based malware detection components.

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List of Acronyms

AUC	Area Under ROC Curve.
CART	Classification and Regression Tree.
CNN	Convolutional Neural Network.
CPS	Cyber-Physical Systems.
CV	Cross Validation.
DBN	Deep Belief Network.
DR	Detection Rate.
DT	Decision Tree.
FPR	False Positive Rate.
GBDT	Gradient Boosting Decision Tree.
GBM	Gradient Boosting Machine.
IoT	Internet of Things.
MCC	Matthews Correlation Coefficient.
NB	Naive Bayes.
PE	Portable Executable.
RF	Random Forest.
SAEs	Stacked AutoEncoders.
SVM	Support Vector Machine.
t-SNE	t-Stochastic Neighbor Embedding.
TPR	True Positive Rate.

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Special Issues, Collections and Topics in MDPI journals
Special Issue in ***Algorithms*: Biological Networks (/journal/algorithms/special_issues/biological_networks)**
Special Issue in ***Algorithms*: Biological Networks II (/journal/algorithms/special_issues/Biological_Networks_II)**

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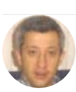
Special Issues, Collections and Topics in MDPI journals
Special Issue in ***Algorithms*: Stochastic Optimization: Algorithms and Applications (/journal/algorithms/special_issues/stochastic_programming)**



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Special Issues, Collections and Topics in MDPI journals
Special Issue in ***Algorithms*: Security Applications of Machine Learning (/journal/algorithms/special_issues/machine_learning_security)**
Special Issue in ***Algorithms*: AI for Cybersecurity: Robust models for Authentication, Threat and Anomaly Detection (/journal/algorithms/special_issues/AI_Cybersecurity_Model)**

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Interests: machine learning; evolutionary computation; deep learning; pattern recognition; neuro-evolution

Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Computational Intelligence and Nature-Inspired Algorithms for Real-World Data Analytics and Pattern Recognition (/journal/algorithms/special_issues/Computational_Intelligence_and)**

Special Issue in ***Algorithms*: Computational Intelligence and Nature-Inspired Algorithms for Real-World Data Analytics and Pattern Recognition II (/journal/algorithms/special_issues/Pattern_Recognition_II)**

Special Issue in ***Applied Sciences*: Deep Learning and Neuro-Evolution Methods in Biomedicine and Bioinformatics (/journal/applsci/special_issues/Deep_Learning_Bioinformatics)**

Special Issue in ***Applied Sciences*: Generative Models in Artificial Intelligence and Their Applications (/journal/applsci/special_issues/Generative_Models_Applications)**

Special Issue in ***Entropy*: Special Issue Dedicated to the 15th International Special Track on Biomedical and Bioinformatics Challenges for Computer Science (/journal/entropy/special_issues/BBC2022)**

Special Issue in ***Applied Sciences*: Generative Models in Artificial Intelligence and Their Applications II (/journal/applsci/special_issues/Generative_Models_Applications_II)**

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Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Journal of Sensor and Actuator Networks*: Techno-Human Collective Systems for Smart Cities Innovation (/journal/jsan/special_issues/THCSSCI)**

Special Issue in ***Sensors*: Advances in Sensors for Sustainable Smart Cities and Smart Buildings (/journal/sensors/special_issues/ASSSCB)**

Special Issue in ***Applied Sciences*: Gamification, Playfulness, and Ludicity in Intelligent Environments (/journal/applsci/special_issues/intelligent_environments)**

Special Issue in ***Sensors*: Recent Advances Technologies for Intelligent Sensing in Augmented Reality Environments (/journal/sensors/special_issues/AR_envion)**

Special Issue in ***Future Internet*: The Application of the Mobile and Pervasive Computing in the Smart City (/journal/futureinternet/special_issues/the_Smart_City)**

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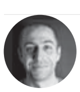

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Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Novel Meta-heuristic Approaches and Their Applications to Preemptive Operational Planning and Logistics in Disaster Management**

(/journal/algorithms/special_issues/disaster-management)

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Special Issue in ***Algorithms*: Clustering Algorithms (/journal/algorithms/special_issues/clustering_algorithms)**

Special Issue in ***Algorithms*: Data Analytics and Optimization for Hybrid Communication Systems (/journal/algorithms/special_issues/data_analytics)**

Special Issue in ***Algorithms*: Selected Papers from the 3rd International Conference on the Harmony Search Algorithm (ICHSA 2017) (/journal/algorithms/special_issues/harmony_search_algorithm)**

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Interests: simulation-based design optimization in ship hydrodynamics; fluid-structure interaction and multidisciplinary design optimization; uncertainty quantification and reliability-based robust design optimization; design space dimensionality reduction in shape optimization; dynamic metamodeling and machine learning methods; global derivative-free bio-inspired optimization algorithms

Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Methods and Applications of Uncertainty Quantification in Engineering and Science (/journal/algorithms/special_issues/uncertainty_quant)**

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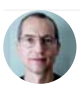
Interests: design and analysis of algorithms; combinatorial optimization; scheduling (esp. in parallel computer systems); computer performance evaluation; operations research; web engineering



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Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Dictionary Learning Algorithms and Applications (/journal/algorithms/special_issues/dictionary_learning)**

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* Former Editor-in-Chief

Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Selected Papers from LATA 2010 (/journal/algorithms/special_issues/lata-2010)**

Special Issue in ***Algorithms*: Selected papers from "Theorietage der Gesellschaft für Informatik" in Speyer; Invited Talks (/journal/algorithms/special_issues/gesellschaft_f%C3%BCr_informatik)**

Special Issue in ***Algorithms*: Reconfiguration Problems (/journal/algorithms/special_issues/Reconfiguration_Problems)**

Special Issue in ***Algorithms*: Selected Algorithmic Papers From CSR 2020 (/journal/algorithms/special_issues/CSR_2020)**

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Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Algorithm Engineering: Towards Practically Efficient Solutions to Combinatorial Problems (/journal/algorithms/special_issues /algorithm_engineering)**

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Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Symmetry*: Advances in Computer Graphics, Geometric Modeling, and Virtual and Augmented Reality (/journal/symmetry/special_issues /Advances_Computer_Graphics_Geometric_Modeling_Virtual_Augmented_Reality)**

Special Issue in ***Applied Sciences*: Applied Artificial Intelligence (AI) (/journal/applsci/special_issues/Applied_Artificial_Intelligence_AI)**

Special Issue in ***Mathematics*: Computer Graphics, Image Processing and Artificial Intelligence (/journal/mathematics/special_issues/CGIAI)**

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Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Entropy*: Artificial Intelligence and Complexity in Art, Music, Games and Design (/journal/entropy/special_issues/ai_complexity)**

Special Issue in ***Entropy*: Artificial Intelligence and Complexity in Art, Music, Games and Design II (/journal/entropy/special_issues/ai_complexity_II)** (/toggle_desktop_layout_cookie)

Special Issue in ***Algorithms*: Algorithms for Real-World Complex Engineering Optimization Problems (/journal/algorithms/special_issues/algorithms_engineering_optimization)**

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Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Algorithms for complex network and its applications (/journal/algorithms/special_issues/complex_network)**

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Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Simulation-Optimization in Logistics, Transportation, and SCM (/journal/algorithms/special_issues/Simulation_Optimization)**

Special Issue in ***Energies*: Advanced Technologies in Smart Cities (/journal/energies/special_issues/advanced_smart_cities)**

Special Issue in ***Algorithms*: Applications of Data Analytics, Simulation-Optimization, and Machine Learning in Services: From Sustainable Transportation and Supply Chains to Smart Cities, Health Care and Finance (/journal/algorithms/special_issues/WSC21)**

Special Issue in ***Data*: Joint Issue: Applications of Data Analytics, Simulation-Optimization, and Machine Learning in Services: from Sustainable Transportation and Supply Chains to Smart Cities, Health Care and Finance (/journal/data/special_issues/jointWSC21)**

Topics: **Numerical Methods and Computer Simulations in Energy Analysis (/topics/numerical_methods)**

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Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Algorithmic Game Theory (/journal/algorithms/special_issues/game-theory)**

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Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Parallel Algorithms for Combinatorial Optimization Problems (/journal/algorithms/special_issues/parallel_algorithms)**

Special Issue in ***Algorithms*: Modeling Computing and Data Handling for Marine Transportation (/journal/algorithms/special_issues/Modeling_Computing)**

Topical Collection in ***Algorithms*: Parallel and Distributed Computing: Algorithms and Applications (/journal/algorithms/special_issues/parallel_distributed_computing)**

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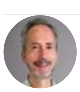

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Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Sensors*: Communication, Coordination and Sensing of Networked Drones (/journal/sensors/special_issues/Networked_Drones)**

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Special Issues, Collections and Topics in MDPI journals
Special Issue in ***Electronics*: Data Processing and Wearable Systems for Effective Human Monitoring (/journal/electronics/special_issues/dpws)**
Special Issue in ***Animals*: Biotechnology in Animals' Management, Health and Welfare (/journal/animals/special_issues/biotech_animal)**
Special Issue in ***Bioengineering*: Advances in Multivariate Physiological Signal Analysis (/journal/bioengineering/special_issues/physiological_signal)**
Special Issue in ***Electronics*: 10th Anniversary of Electronics: Hot Topics in Bioelectronics (/journal/electronics/special_issues/anniversary_bioelectronics)**
Special Issue in ***Bioengineering*: Monitoring and Analysis of Human Biosignals (/journal/bioengineering/special_issues/monitoring_analysis_human_biosignals)**
Special Issue in ***Electronics*: Feature Papers in Bioelectronics - Edition of 2022-2023 (/journal/electronics/special_issues/9H197189UA)**

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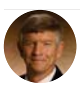
Special Issues, Collections and Topics in MDPI journals
Special Issue in ***Algorithms*: Algorithmic Themes in Bioinformatics (/journal/algorithms/special_issues/Algorithmic_bioinformatics)**



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Special Issue in ***Algorithms*: Sensor Network (/journal/algorithms/special_issues/sensor-network)**

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Special Issue in ***Algorithms*: Fuzzy Sets and Fuzzy Logic. A Commemorative Special Issue in Honor of 100th Anniversary of the Birth of Professor Lotfi A. Zadeh, Creator of Fuzzy Sets and Fuzzy Logic (/journal/algorithms/special_issues/FUZZY_SETSLOGIC)**

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Special Issue in ***Algorithms*: Discrete Algorithms and Discrete Problems in Machine Intelligence (/journal/algorithms/special_issues/Discrete_Machine_Intelligence)**
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Special Issue in ***Algorithms*: The Second Symposium on Machine Intelligence and Data Analytics (/journal/algorithms/special_issues/MIDA)**
Special Issue in ***Mathematics*: Advances in Machine Learning, Optimization, and Control Applications (/journal/mathematics/special_issues/machine_learning_optimization_control_applications)**
Special Issue in ***Algorithms*: Algorithms in Complex Networks (/journal/algorithms/special_issues/algorithms_complex_networks)**

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Special Issues, Collections and Topics in MDPI journals
Special Issue in ***Algorithms*: Special Issue on Matching under Preferences (/journal/algorithms/special_issues/selected_papers_2012)**

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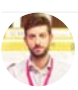

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Special Issues, Collections and Topics in MDPI journals
Special Issue in ***Applied Sciences*: Cloud Computing for Big Data Analysis (/journal/applsci/special_issues/Cloud_Computin_Big_Data_Analysis)**
Special Issue in ***Algorithms*: Scalable Programming Models and Algorithms for Big Data (/journal/algorithms/special_issues/Scalable_Programming_Big_Data)**
Special Issue in ***Electronics*: Advances in Machine Learning, IoT and Big Data for Sustainable Communities (/journal/electronics/special_issues/IE_2022)**
Special Issue in ***Big Data and Cognitive Computing*: Review Papers in Big Data, Cloud-Based Data Analysis and Learning Systems (/journal/BDCC/special_issues/Review_Big_Data)**
Special Issue in ***Future Internet*: Big Data Analytics in Green Supply Chain and Social Media Influences (/journal/futureinternet/special_issues/163853G02V)**

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Special Issues, Collections and Topics in MDPI journals
Special Issue in ***Algorithms*: Algorithms for Systems of Autonomous and Mobile Computational Entities (/journal/algorithms/special_issues/Autonomous_Mobile_Computational_Entities)**

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Special Issues, Collections and Topics in MDPI journals
Special Issue in ***Mathematics*: Evolutionary Computation for Deep Learning and Machine Learning (/journal/mathematics/special_issues/evolutionary_computation_deep_learning_machine_learning)**

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Special Issue in ***Electronics*: Efficient Algorithms and Architectures for DSP Applications (/journal/electronics/special_issues/DSP_Applications)**
Special Issue in ***Symmetry*: New Approaches for System Identification Problems (/journal/symmetry/special_issues/New_Approaches_System_Identification_Problems)**

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Special Issue in ***Algorithms*: Distributed Algorithms and Applications (/journal/algorithms/special_issues/Distributed_Algorithms)**

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Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Parallel and Distributed Algorithms for Demanding Data Analysis and Applications (/journal/algorithms/special_issues/Parallel_Distributed_Algorithms)**

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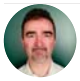
Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Algorithmics in Dynamic Environments (/journal/algorithms/special_issues/Algorithmics_Dynamic_Environments)**

Topical Collection in ***Algorithms*: Feature Paper in Algorithms and Complexity Theory (/journal/algorithms/special_issues/approximation_algorithms_complexity_theory)**



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Special Issues, Collections and Topics in MDPI journals

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Special Issue in ***Algorithms*: Extreme Algorithmics: Analysis of Huge, Noisy, and Dynamic Networked Data (/journal/algorithms/special_issues/Extreme_Algorithmics)**

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Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Bisimulation and Simulation Algorithms (/journal/algorithms/special_issues/Bisimulation_Simulation_Algorithms)**

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Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Feature Papers in Algorithms for Multidisciplinary Applications (/journal/algorithms/special_issues/FP_Algorithms_Multidisciplinary_Applications)**

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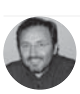

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Special Issues, Collections and Topics in MDPI journals
Special Issue in ***Algorithms*: Algorithmic Themes in Bioinformatics (/journal/algorithms/special_issues/Algorithmic_bioinformatics)**
Special Issue in ***Algorithms*: Bisimulation and Simulation Algorithms (/journal/algorithms/special_issues/Bisimulation_Simulation_Algorithms)**
Special Issue in ***Algorithms*: Algorithms and Data-Structures for Compressed Computation (/journal/algorithms/special_issues/Compressed_Computation)**

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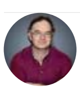
Special Issues, Collections and Topics in MDPI journals
Special Issue in ***Algorithms*: New Frontiers in Parameterized Complexity and Algorithms (/journal/algorithms/special_issues/Parameterized_Complexity)**



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Special Issues, Collections and Topics in MDPI journals

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Special Issue in ***Electronics*: AI Enabled Communication on IoT Edge Computing (/journal/electronics/special_issues/ai_Iot_computing)**

Special Issue in ***Sustainability*: Edge Artificial Intelligence in Future Sustainable Computing Systems (/journal/sustainability/special_issues/Sustainable_Edge_Artificial_Intelligence)**

Special Issue in ***Sustainability*: IoT and Computational Intelligence Applications in Digital and Sustainable Transitions (/journal/sustainability/special_issues/1H0L275A4V)**

Special Issue in ***Algorithms*: AI-Based Algorithms in IoT-Edge Computing (/journal/algorithms/special_issues/6ZC2YWL45C)**

Topical Collection in ***Algorithms*: Featured Reviews of Algorithms (/journal/algorithms/special_issues/featured_review_algorithms)**

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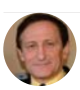
Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Algorithms for Wireless Sensor Networks (/journal/algorithms/special_issues/wireless_sensor_networks)**

Special Issue in ***Sustainability*: Optimization in Logistics and Mobility Using Metaheuristics (/journal/sustainability/special_issues/Optimization_Logistics_Mobility_Metaheuristics)**

Special Issue in ***Algorithms*: Reconfigurable Production Systems (/journal/algorithms/special_issues/reconfig_systems)**



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Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Optimization Techniques, Algorithms, Applications for Cloud and Edge/Fog Computing Environments (/journal/algorithms/special_issues/Optimization_Algorithms_EFC)**

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Special Issues, Collections and Topics in MDPI journals

Special Issue in ***Algorithms*: Quantum Optimization Theory, Algorithms, and Applications (/journal/algorithms/special_issues/Quantum_Optimization_Algorithms)**
Special Issue in ***Algorithms*: Quantum Optimization and Machine Learning (/journal/algorithms/special_issues/quantum_optimization_ML)**
Special Issue in ***Algorithms*: Commemorative Special Issue: Adversarial and Federated Machine Learning: State of the Art and New Perspectives (/journal/algorithms/special_issues/Adversarial_Federated_Machine_Learning)**

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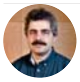

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Special Issue in ***Algorithms*: Optimization Algorithms for Graphs and Complex Networks (/journal/algorithms/special_issues/optimization_graph_complex_network)**

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Special Issues, Collections and Topics in MDPI journals
Special Issue in ***Algorithms*: Optimization and Coordination Algorithms for Energy Management Systems (/journal/algorithms/special_issues/Algorithm_Energy_Management)**

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Special Issues, Collections and Topics in MDPI journals
Special Issue in ***Algorithms*: Machine Learning for Medical Image Analysis (/journal/algorithms/special_issues/Medical_Image_Analysis)**

Special Issue in ***Electronics*: Recent Applications of Object Detection, Tracking, and Abnormal Detection Based on AI (/journal/electronics/special_issues/Object_Detection_Tracking)**

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Special Issues, Collections and Topics in MDPI journals
Special Issue in ***Algorithms*: Natural Language Processing in the Era of Deep Learning (/journal/algorithms/special_issues/Natural_Language_Processing_Deep_Learning)**

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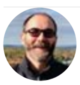
Special Issues, Collections and Topics in MDPI journals
Special Issue in ***Algorithms*: Algorithms for Shortest Paths in Dynamic and Evolving Networks (/journal/algorithms/special_issues/Algorithms_Shortest_Paths_Networks)**



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Special Issue in ***Energies*: Smart Design, Smart Manufacturing and Industry 4.0 (/journal/energies/special_issues/smart_manufacturing)**

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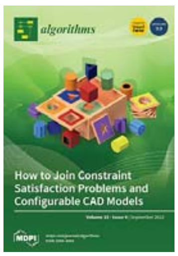

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Cover Story (**view full-size image (/files/uploaded/covers/algorithms/big_cover-algorithms-v15-i9.png)**): In configuration design, the task is to compose a system out of a set of predefined, modular building blocks. Product configuration systems implement reasoning techniques to model and explore the resulting solution spaces. Among others, the formulation of constraint satisfaction problems (CSP) is state of the art and the background in many proprietary configuration engine software packages. Configuration design tasks can also be implemented in computer-aided design (CAD) systems as these contain different techniques for knowledge-based product modeling, but the literature reports only little about modeling examples or training materials. This article is aimed at bridging this gap and presents a step-by-step implementation guide for CSP-based CAD configurators on the example of Autodesk Inventor. **View this paper (https://www.mdpi.com/1999-4893/15/9/318)**

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Non-Interactive Decision Trees and Applications with Multi-Bit TFHE (/1999-4893/15/9/333)

by **Jestine Paul (https://sciprofiles.com/profile/1316676)**, **Benjamin Hong Meng Tan (https://sciprofiles.com/profile/author/MysxT3hjUVp4UVRGNUo3bHpQMG1KZWU4a0JwY0Nxb3ZJZE1zVEVvV0xuUT0=)**, **Bharadwaj Veeravalli (https://sciprofiles.com/profile/643835)** and **Khin Mi Mi Aung (https://sciprofiles.com/profile/1062352)**

Algorithms **2022**, *15*(9), 333; **https://doi.org/10.3390/a15090333 (https://doi.org/10.3390/a15090333)** - 18 Sep 2022

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Abstract Machine learning classification algorithms, such as decision trees and random forests, are commonly used in many applications. Clients who want to classify their data send them to a server that performs their inference using a trained model. The client must trust the server **[...] Read more.**

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Open Access Article **(/1999-4893/15/9/332/pdf?version=1663659182)**

Tree-Based Classifier Ensembles for PE Malware Analysis: A Performance Revisit (/1999-4893/15/9/332)

by **Maya Hilda Lestari Louk (https://sciprofiles.com/profile/1948671)** and **Bayu Adhi Tama (https://sciprofiles.com/profile/828102)**

Algorithms **2022**, *15*(9), 332; **https://doi.org/10.3390/a15090332 (https://doi.org/10.3390/a15090332)** - 17 Sep 2022

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Abstract Given their increasing number and variety, combating malware is becoming increasingly strenuous. Machine learning techniques are often used in the literature to automatically discover the models and patterns behind such challenges and create solutions that can maintain the rapid pace at which malware **[...] Read more.**

(This article belongs to the Special Issue **AI for Cybersecurity: Robust models for Authentication, Threat and Anomaly Detection (/journal/algorithms/special_issues/AI_Cybersecurity_Model)**)

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Irregular Workpiece Template-Matching Algorithm Using Contour Phase (/1999-4893/15/9/331)

by **Shaohui Su (https://sciprofiles.com/profile/2232761)**, **Jiadong Wang (https://sciprofiles.com/profile/2084412)** and **Dongyang Zhang (https://sciprofiles.com/profile/2364737)**

Algorithms **2022**, *15*(9), 331; **https://doi.org/10.3390/a15090331 (https://doi.org/10.3390/a15090331)** - 16 Sep 2022

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Abstract The current template-matching algorithm can match the target workpiece but cannot give the position and orientation of the irregular workpiece. Aiming at this problem, this paper proposes a template-matching algorithm for irregular workpieces based on the contour phase difference. By this, one can **[...] Read more.**

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by **Mattia Conte (https://sciprofiles.com/profile/2413789)**, **Andrea M. Chiariello (https://sciprofiles.com/profile/1386689)**, **Alex Abraham (https://sciprofiles.com/profile/author/S3FLZ2FmZFpJVzlwbnIrckNFMzU3Mm1seG9ha3Iwamt5aExUbk90WHV5VT0=)**, **Simona Bianco (https://sciprofiles.com/profile/1396428)**, **Andrea Esposito (https://sciprofiles.com/profile/author/a0Q1dFV1ZEd2dFQ5QjA0RGduR1E4eHhTcmt0WWFHWmxYakEzN25nRVFBND0=)**, **Mario Nicodemi (https://sciprofiles.com/profile/author/RVRkdXBWRC9OTkkvalJHN0ZVcTczOGRxcFR0c0JRRG1OYVpUdk1sOTlyUT0=)**, **Tommaso Matteuzzi (https://sciprofiles.com/profile/author/dUN2ZUxtbU1QcDY5eHNHUXhOeW1ZdExjUkVHREpvRW41SFcrQndjUTdkZz0=)** and **Francesca Vercellone (https://sciprofiles.com/profile/author/RnV4SFo0TExOakJhYUVmZ0haOVhCRGZtSXhqSC9EYUYyd3dzTlBJa0U2TT0=)**

Algorithms **2022**, *15*(9), 330; **https://doi.org/10.3390/a15090330 (https://doi.org/10.3390/a15090330)** - 16 Sep 2022

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Abstract Recent super-resolution imaging technologies enable tracing chromatin conformation with nanometer-scale precision at the single-cell level. They revealed, for example, that human chromosomes fold into a complex three-dimensional structure within the cell nucleus that is essential to establish biological activities, such as the regulation **[...] Read more.**

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Classification of Program Texts Represented as Markov Chains with Biology-Inspired Algorithms-Enhanced Extreme Learning Machines (/1999-4893/15/9/329)

by **Liliya A. Demidova (https://sciprofiles.com/profile/1176066)** and **Artyom V. Gorchakov (https://sciprofiles.com/profile/1016599)**

Algorithms **2022**, *15*(9), 329; **https://doi.org/10.3390/a15090329 (https://doi.org/10.3390/a15090329)** - 15 Sep 2022

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Abstract The massive nature of modern university programming courses increases the burden on academic workers. The Digital Teaching Assistant (DTA) system addresses this issue by automating unique programming exercise generation and checking, and provides means for analyzing programs received from students by the end **[...] Read more.**

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A Model Architecture for Public Transport Networks Using a Combination of a Recurrent Neural Network Encoder Library and a Attention Mechanism (/1999-4893/15/9/328)

by Thilo Reich (https://sciprofiles.com/profile/2385011),
David Hulbert (https://sciprofiles.com/profile/author/dXJ3bDZGWWJUZm94QW4wNk9va1Z0KzVkeWd0U2ZEQmJPKy9yQ01XWVdSczo=) and
Marcin Budka (https://sciprofiles.com/profile/6456)
Algorithms **2022**, *15*(9), 328; https://doi.org/10.3390/a15090328 (https://doi.org/10.3390/a15090328) - 14 Sep 2022
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Abstract This study presents a working concept of a model architecture allowing to leverage the state of an entire transport network to make estimated arrival time (ETA) and next-step location predictions. To this end, a combination of an attention mechanism with a dynamically changing [...] Read more.
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Infrared Image Deblurring Based on Lp-Pseudo-Norm and High-Order Overlapping Group Sparsity Regularization (/1999-4893/15/9/327)

by Zhen Ye (https://sciprofiles.com/profile/author/MGR6bkI2aGlJNHJHTlRwb2tRT2NieHBnZDMvb2pnUThETXdUYzNRWEJ4MD0=),
Xiaoming Ou (https://sciprofiles.com/profile/author/UFVxZk1ISzdMRS9GaWRLRzJ6TnVjZz09),
Juhua Huang (https://sciprofiles.com/profile/author/UG5adDU3bGM1R1h4NENyUkZKZGFHU0E4dXAxbnVKbjRpS2VRY1JkOHdKTT0=) and
Yingpin Chen (https://sciprofiles.com/profile/author/WWIyQ3pxOW1yWWxNN0hCRmUwTmk1VG5uSitab2NoNmVIWDJFeHYvMGlSND0=)
Algorithms **2022**, *15*(9), 327; https://doi.org/10.3390/a15090327 (https://doi.org/10.3390/a15090327) - 14 Sep 2022
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Abstract A traditional total variation (TV) model for infrared image deblurring amid salt-and-pepper noise produces a severe staircase effect. A TV model with low-order overlapping group sparsity (LOGS) suppresses this effect; however, it considers only the prior information of the low-order gradient of the [...] Read more.

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Autonomous Intersection Management by Using Reinforcement Learning (/1999-4893/15/9/326)

by P. Karthikeyan (https://sciprofiles.com/profile/2431408),
Wei-Lun Chen (https://sciprofiles.com/profile/author/amhqcTI0U3dyOXRsdUFUV2Y4T1g4S3l4TzBZSWtuOW9JenZrM21ueWthQT0=) and
Pao-Ann Hsiung (https://sciprofiles.com/profile/447871)
Algorithms **2022**, *15*(9), 326; https://doi.org/10.3390/a15090326 (https://doi.org/10.3390/a15090326) - 13 Sep 2022
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Abstract Developing a safer and more effective intersection-control system is essential given the trends of rising populations and vehicle numbers. Additionally, as vehicle communication and self-driving technologies evolve, we may create a more intelligent control system to reduce traffic accidents. We recommend deep reinforcement [...] Read more.
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Fed-DeepONet: Stochastic Gradient-Based Federated Training of Deep Operator Networks (/1999-4893/15/9/325)

by **Christian Moya (https://sciprofiles.com/profile/author/N2tleUhpbGFsd2ZjV3VuMldYZ1NHbUdEaVZnT3hWdnVMOEQ3Yk81TFVsST0=)** and **Guang Lin (https://sciprofiles.com/profile/152288)**

Algorithms **2022**, *15*(9), 325; **https://doi.org/10.3390/a15090325 (https://doi.org/10.3390/a15090325)** - 12 Sep 2022

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Abstract The Deep Operator Network (DeepONet) framework is a different class of neural network architecture that one trains to learn nonlinear operators, i.e., mappings between infinite-dimensional spaces. Traditionally, DeepONets are trained using a centralized strategy that requires transferring the training data to a centralized **[...] Read more.**

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Accounting for Round-Off Errors When Using Gradient Minimization Methods (/1999-4893/15/9/324)

by **Dmitry Lukyanenko (https://sciprofiles.com/profile/769807)**, **Valentin Shinkarev (https://sciprofiles.com/profile/2385028)** and **Anatoly Yagola (https://sciprofiles.com/profile/486994)**

Algorithms **2022**, *15*(9), 324; **https://doi.org/10.3390/a15090324 (https://doi.org/10.3390/a15090324)** - 09 Sep 2022

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Abstract This paper discusses a method for taking into account rounding errors when constructing a stopping criterion for the iterative process in gradient minimization methods. The main aim of this work was to develop methods for improving the quality of the solutions for real **[...] Read more.**

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Special Issue: Stochastic Algorithms and Their Applications (/1999-4893/15/9/323)

by **Stéphanie Allassonnière (https://sciprofiles.com/profile/2431124)**

Algorithms **2022**, *15*(9), 323; **https://doi.org/10.3390/a15090323 (https://doi.org/10.3390/a15090323)** - 09 Sep 2022

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Abstract Stochastic algorithms are at the core of machine learning and artificial intelligence [...] **Full article (/1999-4893/15/9/323)**

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Projection onto the Set of Rank-Constrained Structured Matrices for Reduced-Order Controller Design (/1999-4893/15/9/322)

by **Masaaki Nagahara (https://sciprofiles.com/profile/2357324)**, **Yu Iwai (https://sciprofiles.com/profile/author/YTFobmJnajFSekFjdHpwaHpWK2hkK1lGK0UrWnZ0MUt1RG1xOGNkc3BFWT0=)** and **Noboru Sebe (https://sciprofiles.com/profile/2357457)**

Algorithms **2022**, *15*(9), 322; **https://doi.org/10.3390/a15090322 (https://doi.org/10.3390/a15090322)** - 09 Sep 2022

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Abstract In this paper, we propose an efficient numerical computation method of reduced-order controller design for linear time-invariant systems. The design problem is

described by linear matrix inequalities (LMIs) with a rank constraint on a structured matrix, due to which the problem is non-convex. [...] Read more.
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A Practical Staff Scheduling Strategy Considering Various Types of Employment in the Construction Industry (/1999-4893/15/9/321)

by Chan Hee Park (https://sciprofiles.com/profile/2393427) and Young Dae Ko (https://sciprofiles.com/profile/240583)

Algorithms **2022**, *15*(9), 321; https://doi.org/10.3390/a15090321 (https://doi.org/10.3390/a15090321) - 09 Sep 2022

Abstract The Korean government implemented a 52-h workweek policy for employees' welfare. Consequently, companies face workforce availability reduction with the same number of employees. That is, labor-dependent companies suffer from workforce shortage. To handle the workforce shortage, they increase irregular employees who are paid [...] Read more.
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Adaptive Piecewise Poly-Sinc Methods for Ordinary Differential Equations (/1999-4893/15/9/320)

by Omar Khalil (https://sciprofiles.com/profile/2367984),
Hany El-Sharkawy (https://sciprofiles.com/profile/author/cGN3UFY1ODk1NGQ3ME9EMzQ1clZuaHhhZ0ZDVTN2NkExbDhzalp2UGZUND0=),
Maha Youssef (https://sciprofiles.com/profile/author/T3lXbUJ0QjNML3laSmFpUnlyY0lzSEUvY1E5VTNuelFoVC95bUdiT3dSa3I2ZWlJQk9oQ2IvTnExNXZWSHBtN
and
Gerd Baumann (https://sciprofiles.com/profile/96338)

Algorithms **2022**, *15*(9), 320; https://doi.org/10.3390/a15090320 (https://doi.org/10.3390/a15090320) - 08 Sep 2022

Abstract We propose a new method of adaptive piecewise approximation based on Sinc points for ordinary differential equations. The adaptive method is a piecewise collocation method which utilizes Poly-Sinc interpolation to reach a preset level of accuracy for the approximation. Our work extends the [...] Read more.
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Federated Optimization of ℓ_0-norm Regularized Sparse Learning (/1999-4893/15/9/319)

by Qianqian Tong (https://sciprofiles.com/profile/2295038), Guannan Liang (https://sciprofiles.com/profile/986722),
Jiahao Ding (https://sciprofiles.com/profile/2386013),
Tan Zhu (https://sciprofiles.com/profile/author/SVE2QXFBYWNhUlhGaXArMU9tZ0x2WTl1YkI4elRQWitMSFFGK2tSSGV3bz0=),
Miao Pan (https://sciprofiles.com/profile/947386) and Jinbo Bi (https://sciprofiles.com/profile/2311431)

Algorithms **2022**, *15*(9), 319; https://doi.org/10.3390/a15090319 (https://doi.org/10.3390/a15090319) - 06 Sep 2022

Abstract Regularized sparse learning with the ℓ_0-norm is important in many areas, including statistical learning and signal processing. Iterative hard thresholding (IHT) methods are the state-of-the-art for nonconvex-constrained sparse learning due to their capability of recovering true support and scalability with large [...] Read more.
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Joining Constraint Satisfaction Problems and Configurable CAD Product Models: A Step-by-Step Implementation Guide (/1999-4893/15/9/318)

by Paul Christoph Gembarski (https://sciprofiles.com/profile/105649)

Algorithms **2022**, *15*(9), 318; https://doi.org/10.3390/a15090318 (https://doi.org/10.3390/a15090318) - 06 Sep 2022

Abstract In configuration design, the task is to compose a system out of a set of predefined, modu-lar building blocks assembled by defined interfaces. Product configuration systems, both with or without integration of geometric models, implement reasoning techniques to model and explore the resulting [...] Read more.

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Improved Slime Mold Algorithm with Dynamic Quantum Rotation Gate and Opposition-Based Learning for Global Optimization and Engineering Design Problems (/1999-4893/15/9/317)

by Yunyang Zhang (https://sciprofiles.com/profile/2327883), Shiyu Du (https://sciprofiles.com/profile/1436900) and Quan Zhang (https://sciprofiles.com/profile/2192547)

Algorithms **2022**, *15*(9), 317; https://doi.org/10.3390/a15090317 (https://doi.org/10.3390/a15090317) - 04 Sep 2022

Abstract The slime mold algorithm (SMA) is a swarm-based metaheuristic algorithm inspired by the natural oscillatory patterns of slime molds. Compared with other algorithms, the SMA is competitive but still suffers from unbalanced development and exploration and the tendency to fall into local optima. [...] Read more.

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Sustainable Risk Identification Using Formal Ontologies (/1999-4893/15/9/316)

by Avi Shaked (https://sciprofiles.com/profile/author/VUt2WTUrVVhDTy9nbTFNUW5ld0J6YlFxUS9iZ0M4YzhQL3gxeXEzVE9vdz0=) and Oded Margalit (https://sciprofiles.com/profile/2397279)

Algorithms **2022**, *15*(9), 316; https://doi.org/10.3390/a15090316 (https://doi.org/10.3390/a15090316) - 02 Sep 2022

Abstract The cyber threat landscape is highly dynamic, posing a significant risk to the operations of systems and organisations. An organisation should, therefore, continuously monitor for new threats and properly contextualise them to identify and manage the resulting risks. Risk identification is typically performed [...] Read more.

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High Per Parameter: A Large-Scale Study of Hyperparameter Tuning for Machine Learning Algorithms (/1999-4893/15/9/315)

by Moshe Sipper (https://sciprofiles.com/profile/1976893)

Algorithms **2022**, *15*(9), 315; **https://doi.org/10.3390/a15090315 (https://doi.org/10.3390/a15090315)** - 02 Sep 2022

Abstract Hyperparameters in machine learning (ML) have received a fair amount of attention, and hyperparameter tuning has come to be regarded as an important step in the ML pipeline. However, just how useful is said tuning? While smaller-scale experiments have been previously conducted, herein **[...] Read more.**

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CVE2ATT&CK: BERT-Based Mapping of CVEs to MITRE ATT&CK Techniques (/1999-4893/15/9/314)

by **Octavian Grigorescu (https://sciprofiles.com/profile/2395010)**,
Andreea Nica (https://sciprofiles.com/profile/author/NzVEMXI0ak5qUmhiNVVVYUluSnYvM0VrZGtKbmlsQWFzTWx5ZFErTWxSWjQ2b0Y2ZDMxRmpGb211Ykw3M
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Mihai Dascalu (https://sciprofiles.com/profile/1947343) and
Razvan Rughinis (https://sciprofiles.com/profile/author/UVFOY3h1RThyVHhUVWVWand1L2o3c0FSNTZRVndTRmplV050aENqK3FJTT0=)
Algorithms **2022**, *15*(9), 314; **https://doi.org/10.3390/a15090314 (https://doi.org/10.3390/a15090314)** - 31 Aug 2022

Abstract Since cyber-attacks are ever-increasing in number, intensity, and variety, a strong need for a global, standardized cyber-security knowledge database has emerged as a means to prevent and fight cybercrime. Attempts already exist in this regard. The Common Vulnerabilities and Exposures (CVE) list documents **[...] Read more.**
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Open Access Review **(/1999-4893/15/9/313/pdf?version=1663821975)**

Artificial Intelligence for Cell Segmentation, Event Detection, and Tracking for Label-Free Microscopy Imaging (/1999-4893/15/9/313)

by **Lucia Maddalena (https://sciprofiles.com/profile/422781)**, **Laura Antonelli (https://sciprofiles.com/profile/537267)**,
Alexandra Albu (https://sciprofiles.com/profile/author/Z21tVnlBVm9EUTlyVS9JWlduaE9uRGFITXVNTXFyRmRFWk4wakR1TCtwRXIxdkI3VUs5bVlTWlNLV25Bc0d
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Aroj Hada (https://sciprofiles.com/profile/2403590) and **Mario Rosario Guarracino (https://sciprofiles.com/profile/430442)**
Algorithms **2022**, *15*(9), 313; **https://doi.org/10.3390/a15090313 (https://doi.org/10.3390/a15090313)** - 31 Aug 2022

Abstract Background: Time-lapse microscopy imaging is a key approach for an increasing number of biological and biomedical studies to observe the dynamic behavior of cells over time which helps quantify important data, such as the number of cells and their sizes, shapes, and dynamic **[...] Read more.**
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Open Access Article **(/1999-4893/15/9/312/pdf?version=1661856081)**

Images Segmentation Based on Cutting the Graph into Communities (/1999-4893/15/9/312)

by **Sergey V. Belim (https://sciprofiles.com/profile/1832379)** and **Svetlana Yu. Belim (https://sciprofiles.com/profile/2328947)**
Algorithms **2022**, *15*(9), 312; **https://doi.org/10.3390/a15090312 (https://doi.org/10.3390/a15090312)** - 30 Aug 2022

Abstract This article considers the problem of image segmentation based on its representation as an undirected weighted graph. Image segmentation is equivalent to partitioning a graph into communities. The image segment corresponds to each community. The growing area algorithm search communities on the graph. **[...] Read more.**
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Accelerating the Sinkhorn Algorithm for Sparse Multi-Marginal Optimal Transport via Fast Fourier Transforms (/1999-4893/15/9/311)

by Fatima Antarou Ba (https://sciprofiles.com/profile/2373452) and Michael Quellmalz (https://sciprofiles.com/profile/2404963)
Algorithms **2022**, *15*(9), 311; https://doi.org/10.3390/a15090311 (https://doi.org/10.3390/a15090311) - 30 Aug 2022
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Abstract We consider the numerical solution of the discrete multi-marginal optimal transport (MOT) by means of the Sinkhorn algorithm. In general, the Sinkhorn algorithm suffers from the curse of dimensionality with respect to the number of marginals. If the MOT cost function decouples according [...] Read more.
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Open Access Article (/1999-4893/15/9/310/pdf?version=1663761188)

Implicit A-Stable Peer Triplets for ODE Constrained Optimal Control Problems (/1999-4893/15/9/310)

by Jens Lang (https://sciprofiles.com/profile/2031775) and Bernhard A. Schmitt (https://sciprofiles.com/profile/2055732)
Algorithms **2022**, *15*(9), 310; https://doi.org/10.3390/a15090310 (https://doi.org/10.3390/a15090310) - 29 Aug 2022
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Abstract This paper is concerned with the construction and convergence analysis of novel implicit Peer triplets of two-step nature with four stages for nonlinear ODE constrained optimal control problems. We combine the property of superconvergence of some standard Peer method for inner grid points [...] Read more.
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Open Access Systematic Review (/1999-4893/15/9/309/pdf?version=1661780673)

Integrated Industrial Reference Architecture for Smart Healthcare in Internet of Things: A Systematic Investigation (/1999-4893/15/9/309)

by Aswani Devi Aguru (https://sciprofiles.com/profile/2396069), Erukala Suresh Babu (https://sciprofiles.com/profile/668009), Soumya Ranjan Nayak (https://sciprofiles.com/profile/1536998), Abhisek Sethy (https://sciprofiles.com/profile/author/azR4OVFzai9FcGpUNEo5S3VaK2cvR2U5RWF2bVo5ZC9aaTBVd3F0SVkwMD0=) and Amit Verma (https://sciprofiles.com/profile/author/dTlScGNuUkhBbDBleWJzdE5Zb1htRTZoRVRTT3NqUGNmOHRnQ1Y3eFNjYz0=)
Algorithms **2022**, *15*(9), 309; https://doi.org/10.3390/a15090309 (https://doi.org/10.3390/a15090309) - 29 Aug 2022
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Abstract Internet of Things (IoT) is one of the efflorescing technologies of recent years with splendid real-time applications in the fields of healthcare, agriculture, transportation, industry, and environmental monitoring. In addition to the dominant applications and services of IoT, many challenges exist. As there [...] Read more.
(This article belongs to the Special Issue Deep Learning for Internet of Things (/journal/algorithms/special_issues/Deep_Computation))

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Open Access Feature Paper Article (/1999-4893/15/9/308/pdf?version=1661748839)

Early Prediction of Chronic Kidney Disease: A Comprehensive Performance Analysis of Deep Learning Models (/1999-4893/15/9/308)

by Chaity Mondol (https://sciprofiles.com/profile/author/akllQ2VKUzVMbnJvMFVjTDV6a3JwbnJTc0xSdEUxNnVWWXltczNLWEtNRT0=), F. M. Javed Mehedi Shamrat (https://sciprofiles.com/profile/1757506), Md. Robiul Hasan (https://sciprofiles.com/profile/2408243), Saidul Alam (https://sciprofiles.com/profile/author/Q05UVzUwalFPOUlqRm5DWnRrVVV1RktkWW8vaHZaRGp0MkxJbGlZT3dGOD0=), Pronab Ghosh (https://sciprofiles.com/profile/2020558), Zarrin Tasnim (https://sciprofiles.com/profile/author/aUJBdW9uMzF4TDcwcEkzUVNPUDRsTEdhSWdlaW8ySlZBOHRZVjJtdjNmdz0=), Kawsar Ahmed (https://sciprofiles.com/profile/2269713), Francis M. Bui (https://sciprofiles.com/profile/801161) and Sobhy M. Ibrahim (https://sciprofiles.com/profile/27403)

Algorithms **2022**, *15*(9), 308; https://doi.org/10.3390/a15090308 (https://doi.org/10.3390/a15090308) - 29 Aug 2022

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Abstract Chronic kidney disease (CKD) is one of the most life-threatening disorders. To improve survivability, early discovery and good management are encouraged. In this paper, CKD was diagnosed using multiple optimized neural networks against traditional neural networks on the UCI machine learning dataset, to [...] Read more.

(This article belongs to the Special Issue Artificial Intelligence Algorithms for Medicine (/journal/algorithms/special_issues/artificial_intellighence_algorithms_medicine))

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Traffic Demand Estimations Considering Route Trajectory Reconstruction in Congested Networks (/1999-4893/15/9/307)

by Wenyun Tang (https://sciprofiles.com/profile/1706500), Jiahui Chen (https://sciprofiles.com/profile/author/a2w4ajVJVlhiWUtrcnRpUUczblZOMldJMCtzQitEN1hGSzJXVlh2QVJ5RT0=), Chao Sun (https://sciprofiles.com/profile/2383323), Hanbing Wang (https://sciprofiles.com/profile/author/Z3JJbHZjMFFZSWZYN1hWK3RNa205WXhCczhGRzkyS2VwdC9FUW9hcUZkTT0=) and Gen Li (https://sciprofiles.com/profile/341183)

Algorithms **2022**, *15*(9), 307; https://doi.org/10.3390/a15090307 (https://doi.org/10.3390/a15090307) - 28 Aug 2022

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Abstract Traffic parameter characteristics in congested road networks are explored based on traffic flow theory, and observed variables are transformed to a uniform format. The Gaussian mixture model is used to reconstruct route trajectories based on data regarding travel routes containing only the origin [...] Read more.

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Open Access Article (/1999-4893/15/9/306/pdf?version=1661675226)

MIMO Radar Imaging Method with Non-Orthogonal Waveforms Based on Deep Learning (/1999-4893/15/9/306)

by Hongbing Li (https://sciprofiles.com/profile/592090) and Qunfei Zhang (https://sciprofiles.com/profile/2320915)

Algorithms **2022**, *15*(9), 306; https://doi.org/10.3390/a15090306 (https://doi.org/10.3390/a15090306) - 28 Aug 2022

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Abstract Transmitting orthogonal waveforms are the basis for giving full play to the advantages of MIMO radar imaging technology, but the commonly used waveforms with the same frequency cannot meet the orthogonality requirement, resulting in serious coupling noise in traditional imaging methods and affecting [...] Read more.

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Open Access Article (/1999-4893/15/9/305/pdf?version=1663754056)

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[A Systematic Approach for Developing a Robust Artwork Recognition Framework Using Smartphone Cameras (/1999-4893/15/9/305)]

by Zenonas Theodosiou (https://sciprofiles.com/profile/2318587), Marios Thoma (https://sciprofiles.com/profile/2402529), (/toggle_desktop_layout_cookie) Harris Partaourides (https://sciprofiles.com/profile/author/MGRuTXhuQnh2UHRzc1I4TXNmdVgwRkh1cWVNUTlYbUhWQ1lJSmtNbDFzVT0=) and Andreas Lanitis (https://sciprofiles.com/profile/2397125)

Algorithms **2022**, *15*(9), 305; https://doi.org/10.3390/a15090305 (https://doi.org/10.3390/a15090305) - 27 Aug 2022

Abstract The provision of information encourages people to visit cultural sites more often. Exploiting the great potential of using smartphone cameras and egocentric vision, we describe the development of a robust artwork recognition algorithm to assist users when visiting an art space. The algorithm [...] Read more.

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Open Access Article (/1999-4893/15/9/304/pdf?version=1663828263)

[Computational Analysis of PDE-Based Shape Analysis Models by Exploring the Damped Wave Equation (/1999-4893/15/9/304)]

by Alexander Köhler (https://sciprofiles.com/profile/2360715) and Michael Breuß (https://sciprofiles.com/profile/412504)

Algorithms **2022**, *15*(9), 304; https://doi.org/10.3390/a15090304 (https://doi.org/10.3390/a15090304) - 27 Aug 2022

Abstract The computation of correspondences between shapes is a principal task in shape analysis. In this work, we consider correspondences constructed by a numerical solution of partial differential equations (PDEs). The underlying model of interest is thereby the classic wave equation, since this may [...] Read more.

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[Dealing with Gender Bias Issues in Data-Algorithmic Processes: A Social-Statistical Perspective (/1999-4893/15/9/303)]

by Juliana Castaneda (https://sciprofiles.com/profile/1601208), Assumpta Jover (https://sciprofiles.com/profile/author/WmNwR1l1RHduZ0M2UTNhRkdQZ3ZQVDhseUlrZ1BJWXM0NlZpNGdFRG1FRT0=), Laura Calvet (https://sciprofiles.com/profile/785530), Sergi Yanes (https://sciprofiles.com/profile/author/dlpjUkdUYXd3YjdMcXRDTGhFbWhGdz09), Angel A. Juan (https://sciprofiles.com/profile/189152) and Milagros Sainz (https://sciprofiles.com/profile/author/TExFQko2dXhvNkJtYWJwNTNBdzJtdz09)

Algorithms **2022**, *15*(9), 303; https://doi.org/10.3390/a15090303 (https://doi.org/10.3390/a15090303) - 27 Aug 2022

Abstract Are algorithms sexist? This is a question that has been frequently appearing in the mass media, and the debate has typically been far from a scientific analysis. This paper aims at answering the question using a hybrid social and technical perspective. First a [...] Read more.

(This article belongs to the Special Issue Interpretability, Accountability and Robustness in Machine Learning (/journal/algorithms/special_issues/Interpretability_Accountability_Robustness))

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Boosting the Performance of CDCL-Based SAT Solvers by Exploiting Backbones and Backdoors (/1999-4893/15/9/302)

by Tasniem Al-Yahya (https://sciprofiles.com/profile/2204706), Mohamed El Bachir Abdelkrim Menai (https://sciprofiles.com/profile/459731) and Hassan Mathkour (https://sciprofiles.com/profile/830596)

Algorithms **2022**, *15*(9), 302; https://doi.org/10.3390/a15090302 (https://doi.org/10.3390/a15090302) - 26 Aug 2022

Abstract Boolean structural measures were introduced to explain the high performance of conflict-driven clause-learning (CDCL) SAT solvers on industrial SAT instances. Those considered in this study include measures related to backbones and backdoors: backbone size, backbone frequency, and backdoor size. A key area of [...] Read more.

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Application of the Tomtit Flock Metaheuristic Optimization Algorithm to the Optimal Discrete Time Deterministic Dynamical Control Problem (/1999-4893/15/9/301)

by Andrei V. Panteleev (https://sciprofiles.com/profile/1836102) and Anna A. Kolessa (https://sciprofiles.com/profile/2145073)

Algorithms **2022**, *15*(9), 301; https://doi.org/10.3390/a15090301 (https://doi.org/10.3390/a15090301) - 26 Aug 2022

Abstract A new bio-inspired method for optimizing the objective function on a parallelepiped set of admissible solutions is proposed. It uses a model of the behavior of tomtits during the search for food. This algorithm combines some techniques for finding the extremum of the [...] Read more.

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Correlation Analysis of Factors Affecting Firm Performance and Employees Wellbeing: Application of Advanced Machine Learning Analysis (/1999-4893/15/9/300)

by Jozsef Pap (https://sciprofiles.com/profile/author/eWlVMTlUYXg2ZlhqTDFpM0huTDduTE5IdDZQR3Y2MFJnTWMxUGkwaW0rcz0=), Csaba Mako (https://sciprofiles.com/profile/author/TFZvT0hiaVBRQXJMSW1aZ0FoajdscE5zZ2ZNUXFMaXdMK0RpQVlrSTVFOD0=), Miklos Illessy (https://sciprofiles.com/profile/1635695), Zef Dedaj (https://sciprofiles.com/profile/author/S2diNDBuNFRnYmwwNHo2RnRSZzdOUHUvV3pYdCt3ci9ZSDlrcmFYQ1FJVT0=), Sina Ardabili (https://sciprofiles.com/profile/1061050), Bernat Torok (https://sciprofiles.com/profile/1698341) and Amir Mosavi (https://sciprofiles.com/profile/2241799)

Algorithms **2022**, *15*(9), 300; https://doi.org/10.3390/a15090300 (https://doi.org/10.3390/a15090300) - 26 Aug 2022

Abstract Given the importance of identifying key performance points in organizations, this research intends to determine the most critical intra- and extra-organizational elements in assessing the performance of firms using the European Company Survey (ECS) 2019 framework. The ECS 2019 survey data were used [...] Read more.

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Artificial Intelligence Algorithms for Treatment of Diabetes (/1999-4893/15/9/299)

by Mudassir M. Rashid (https://sciprofiles.com/profile/885173), Mohammad Reza Askari (https://sciprofiles.com/profile/2176510), Canyu Chen (https://sciprofiles.com/profile/author/Wk1IWHRJZzYyZUd3alVSOWFjOU9zM2krTm0yS0dXakJacFpNZ2ZvbmM5Yz0=), Yueqing Liang (https://sciprofiles.com/profile/author/QmZJYUY2KzlaTWQzSzBTNWVlcFpPU2U3UHAwelo4R2htZk53WUU4QS8yUT0=), Kai Shu (https://sciprofiles.com/profile/author/cnN5aXY1R2pNV2tMeHl5YmxHalFTdz09) and Ali Cinar (https://sciprofiles.com/profile/215242)

Algorithms **2022**, *15*(9), 299; https://doi.org/10.3390/a15090299 (https://doi.org/10.3390/a15090299) - 26 Aug 2022

Abstract Artificial intelligence (AI) algorithms can provide actionable insights for clinical decision-making and managing chronic diseases. The treatment and management of complex chronic diseases, such as diabetes, stands to benefit from novel AI algorithms analyzing the frequent real-time streaming data and the occasional medical [...] Read more.

(This article belongs to the Special Issue Artificial Intelligence Algorithms for Medicine (/journal/algorithms/special_issues/artificial_intelligence_algorithms_medicine))

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Optimal Design Parameters for Hybrid DC Circuit Breakers Using a Multi-Objective Genetic Algorithm (/1999-4893/15/9/298)

by Van-Vinh Nguyen (https://sciprofiles.com/profile/437654), Nhat-Tung Nguyen (https://sciprofiles.com/profile/2372451), Quang-Thuan Nguyen (https://sciprofiles.com/profile/author/UTNqeXVEWHpKcW1yVThoNlc3OHdvdVoxcnFkQTJLMXFHK1ZJUHY1eWNrMD0=), Van-Hai Bui (https://sciprofiles.com/profile/882347) and Wencong Su (https://sciprofiles.com/profile/102301)

Algorithms **2022**, *15*(9), 298; https://doi.org/10.3390/a15090298 (https://doi.org/10.3390/a15090298) - 25 Aug 2022

Abstract The primary function of hybrid direct current circuit breakers (HCBs) is to quickly interrupt fault currents to protect high-voltage direct current (HVDC) systems. To enhance the reliability and stability of HVDC systems, optimal design of HCBs is required to minimize the peak fault [...] Read more.

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SepFree NMF: A Toolbox for Analyzing the Kinetics of Sequential Spectroscopic Data (/1999-4893/15/9/297)

by Renata Sechi (https://sciprofiles.com/profile/2322956), Konstantin Fackeldey (https://sciprofiles.com/profile/1615948), Surahit Chewle (https://sciprofiles.com/profile/1363206) and Marcus Weber (https://sciprofiles.com/profile/371742)

Algorithms **2022**, *15*(9), 297; https://doi.org/10.3390/a15090297 (https://doi.org/10.3390/a15090297) - 24 Aug 2022

Abstract This work addresses the problem of determining the number of components from sequential spectroscopic data analyzed by non-negative matrix factorization without separability assumption (SepFree NMF). These data are stored in a matrix *M* of dimension “measured times” versus “measured wavenumbers” and can be [...] Read more.

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Algorithms **2022**, *15*(9), 296; **https://doi.org/10.3390/a15090296 (https://doi.org/10.3390/a15090296)** - 23 Aug 2022

Abstract Identifying the most important nodes according to specific centrality indices is an important issue in network analysis. Node metrics based on the computation of functions of the adjacency matrix of a network were defined by Estrada and his collaborators in various papers. This **[...] Read more.**

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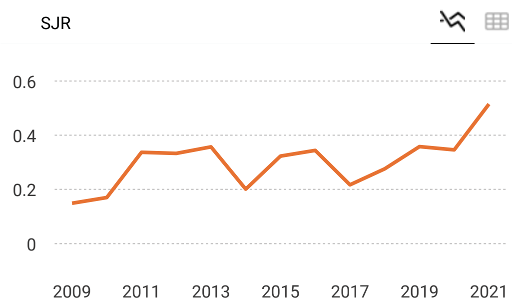

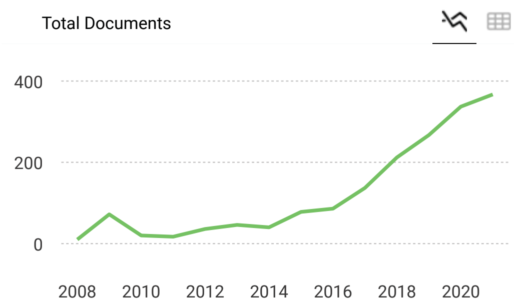

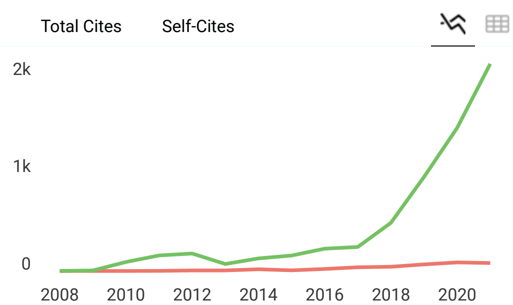

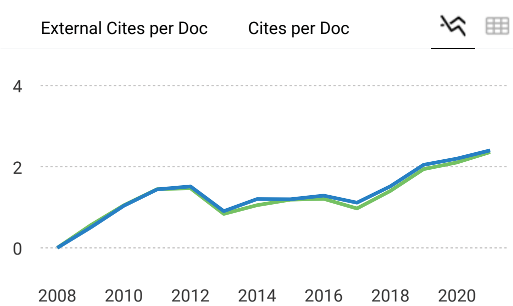

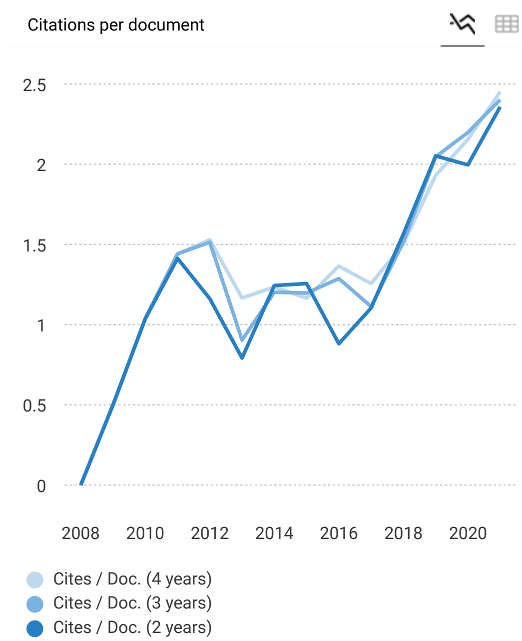

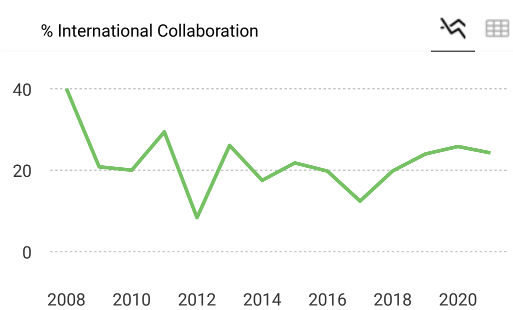

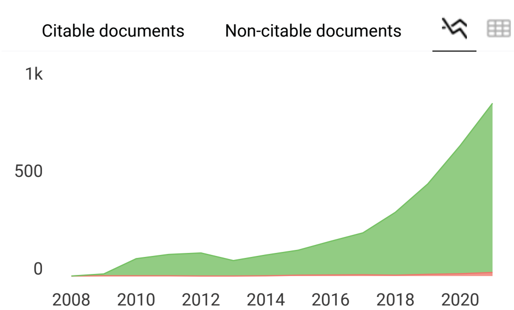

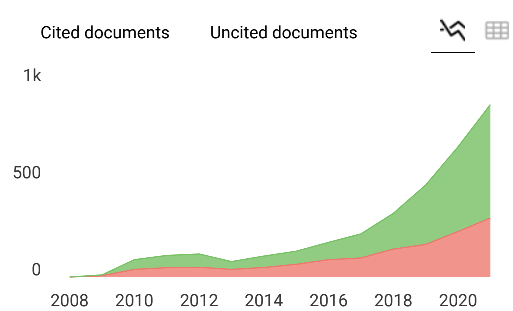

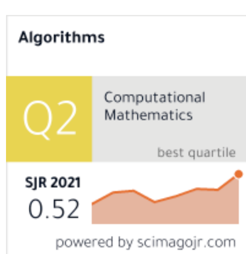

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