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Editorial

Dear Esteemed Readers,

It is our great pleasure to present to you a new issue of *JITA – Journal of Information Technology and Applications*, marking a significant milestone: 15 years of successful publishing. Over the years, we have remained committed to maintaining high standards in the quality of papers we publish—contributions that have inspired researchers and advanced both scientific understanding and real-world applications.We take particular pride in the fact that some of our contributors began their publishing journeys with us as Master's students. Today, many of them are leading researchers at reputable institutions, and they continue to publish in *JITA*. We sincerely hope this tradition continues. Our vision is that *JITA* will remain a valuable resource for early-career researchers and a respected platform for sharing innovative work in the domain of ICT applications.

In this issue, we bring you a selection of compelling research papers:

- The first article advances the field of fingerprint recognition by applying artificial intelligence techniques, including natural language processing (NLP) and machine learning, to improve classification accuracy.
- The second paper presents a system for analyzing chaotic patterns in financial markets. By combining classical chaos theory metrics with artificial immune systems, the authors propose an adaptive algorithm for identifying anomalous behavior.
- The third contribution explores how antenna design affects the performance of LoRa communication systems. Through experimental and simulation-based analysis, the authors compare three antenna models— a commercial omnidirectional antenna, a manually constructed Yagi antenna, and a simulation-optimized Yagi antenna—all designed for 868 MHz operation.
- Another article addresses the increasing need for standardized knowledge sources in the context of e-learning and ICT in education. The paper explores frameworks and practices for the effective implementation of information technologies in learning environments.
- With energy efficiency in software systems emerging as a pressing topic, one of our featured studies investigates key factors affecting energy-efficient software design—an area still underrepresented in current research.
- As traditional human-centric approaches to information systems design evolve, AI is playing a growing role in automating key tasks. A review article in this issue discusses how innovations such as low-code platforms, federated learning, and explainable AI are shaping the future of system design.
- The application of IoT in the food industry is examined in another paper, focusing on technologies such as RFID, WiFi-based data collection, and cloud integration, highlighting the industrial shift toward smart and interconnected systems.
- Finally, we close this issue with a timely paper on propaganda in social media. The rise of fake news and misinformation in the digital age poses serious societal challenges. This article underscores the need for greater awareness and engagement from all sectors of society to mitigate these risks.

We hope you find this issue both informative and inspiring. Our goal is to contribute meaningfully to the advancement of ICT and its applications in daily life. Therefore, we warmly invite you to submit your original research to *JITA*, share new ideas, and explore opportunities for collaboration.
Let *JITA* be your first choice for disseminating your scholarly work.

Editor-in-Chief
Dalibor P. Drljača, PhD
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Raw and Noisy Fingerprint Image Classification with Natural Language Processing Techniques and Ensemble Machine Learning Methods

Milan Panić[1], Nemanja Maček[2], Branimir Trenkić[3], Daniel Menićanin[4]

[1]*Pan-European University "APEIRON", Faculty of Information Technology, Banja Luka, Bosnia and Herzegovina, milan.v.panic@apeiron-edu.eu, https://orcid.org/0009-0006-9270-7354*

[2]*University Business Academy in Novi Sad, Faculty of Social Sciences, Belgrade, Republic of Serbia, macek.nemanja@gmail.com, https://orcid.org/0000-0002-3465-7524*

[3]*Academy of Technical and Art Applied Studies, School of Electrical and Computer Engineering, Belgrade, Republic of Serbia, trenkic.branimir@gmail.com, https://orcid.org/0009-0006-8795-3040*

[4]*Pan-European University "APEIRON", Faculty of Information Technology, Banja Luka, Bosnia and Herzegovina, danijel.menicanin@gmail.com, https://orcid.org/0009-0001-6311-4043*

Original scientific paper

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Abstract: This paper presents a raw and noisy fingerprint image recognition system based on natural language processing feature extraction methods and ensemble machine learning methods. The main goal of the proposed model is to reach state-of-the-art classification accuracy, even with the noisy images, eliminate false acceptance rates, and cancel the possibility of recreating a fake fingerprint image from a generated template. To achieve this, we omit preprocessing phase such as application of gradient vectors and multiple filter banks that are typically employed in traditional fingerprint recognition systems. Instead, we employ machine learning methods that classify biometric templates as numeric features. The biometric templates are generated by converting raw fingerprint image into a one-dimensional set of fixed-length codes, which then undergoes stylometric extraction of features further being used for classification. The experimental evaluation shows that the system performs as intended. In addition, the computational and storage costs are significantly decreased with respect to traditional systems, which makes it suitable for use in practical applications.

Keywords: biometrics, ensemble learning, fingerprint, machine learning, natural language processing, stylometry

Introduction

Fingerprint recognition represents a biometric technology based on unique fingerprint characteristics aimed at identifying and verifying an individual's identity. Given that human fingerprints have been discovered on a large number of archaeological artifacts [1, 2], it has been considered one of the most popular technique for human recognition as well as identification for over a century.

Each person has unique fingerprints, even twins do. This makes fingerprints extremely reliable for individual identification. Fingerprints can be relatively easily collected using various devices, making the collection process quick and non-invasive. Fingerprint recognition technology enables rapid identification and verification of an individual's identity. In forensics, fingerprints are often used as key evidence. They can be found at crime scenes, on items used in criminal activities, or on evidence found at the crime scene. Using fingerprint recognition technology, forensic experts can compare fingerprints to databases to identify suspects or confirm the identities of victims. Fingerprints are less susceptible to theft or misuse compared to traditional identification methods such as passwords or cards. Therefore, in many banks, government and military institutions, access to sensitive information is based on the application of fingerprint recognition technology to improve security.

The method of identification and authentication is based on the analysis of unique fingerprint characteristics. To create a unique biometric profile of a person, details found on the surface of the skin of the fingers, such as ridges and valleys, are used. Using optical, capacitive, or ultrasonic scanning techniques, characteristics are collected from the surface of the finger skin (ridges and valleys). After the collection process, the fingerprint image undergoes preprocessing, which involves noise removal, normalization, and segmentation, to improve its quality.

Extracting characteristic points from the preprocessed or enhanced image is a key step. Each fingerprint contains a large number of characteristic points called minutiae. Depending on the type, minutiae indicate branching and changes at the ends of ridges. Characteristic points of the fingerprint are stored in a database as a biometric profile. The accuracy of the minutiae extraction process directly affects the accuracy of fingerprint matching notably disrupting the identification process, where the template is compared with all fingerprint template in the database to find a best match.

The paper describes a new approach to fingerprint recognition that avoids the use of traditional filter banks and wavelet transformations. The described approach is based on converting a fingerprint image into a textual format using the Base64 encoding algorithm as presented in [3]. The use of a textual format eliminates the detection of the region of interest (ROI) segment of the image and the application of gradient vectors for identifying changes in pixel intensity in the edge or contour detection process of the fingerprint. Extraction of numerical characteristics is realized by applying a stylometric (natural language processing, NLP) extraction methods. By using appropriate ensemble machine learning techniques, classification of the extracted numerical characteristics is conducted. The described process excludes the preprocessing phase, which involves extracting numerical characteristics from raw data. The main contribution of the solution described in the paper relates to increasing the accuracy of fingerprint recognition by eliminating the False Acceptance Rate (FAR) and minimizing False Rejection Rate (FRR). Exclusion of the preprocessing phase, which involves applying appropriate image enhancement algorithms, significantly reduces the time in the fingerprint recognition and verification process. Additionally, the proposed approach enables the realization of a system on a low cost hardware.

In brief, the main contributions of this paper are listed as follows:

- no preprocessing phase whatsoever, i.e. no region of interest detection or gradient vector application, resulting in lower computational cost (please note that additional filters are neither applied);
- no tradeoff between FAR and FRR or seeking equal error rate, as FAR is zero;
- FRR ranging from 0,01% to 0,001%;
- applicability to raw and noisy images and
- providing a system that makes biometric template (a NLP feature vector) resilient to attackers that use artificial neural networks and genetic algorithms for malicious reverse processing (regenerating sample from template).

Methods and materials

Before we present methods used here, we need to clarify for a reader why fingerprint recognition systems may be computationally expensive. And has tradeoffs. But, first, one shall provide an insight in how they work, and what mathematics is behind the engine that slows them up, provides impostors a grant to a system as well as unwanted false rejections for genuine users.

The fingerprint recognition system typically goes through several key stages to provide accurate identification or verification: acquisition, image preprocessing, feature extraction and classification. Based on the classification results, the system makes a decision regarding the user's identity typically using some kind of a threshold. In identification, one or more potential identities may be returned, while in verification, the decision is based on the degree of feature match.

The fingerprint recognition system is used for both verification and identification purposes. In verification, a registered fingerprint is compared with an identified user to determine if two prints are from the same finger (1-1 matching). In identification, an input fingerprint is compared with all registered fingerprints in the database to determine if it matches any (1-N matching). In this context, systems have been developed relying on two key phases: enrollment and identification. The enrollment phase involves registering an individual's identity, or fingerprint, in the database for future use. On the other hand, the identification phase aims to extract an individual's identity from the database based on the user's claim of identity.

Although fingerprint acquisition, preprocessing, and feature extraction are common steps for both enrollment and identification, fingerprint matching represents an additional mandatory step in the identification phase. This step enables the identification of a person based on their fingerprint from a previously collected database. It is important to emphasize that processing time and identification accuracy are key factors in improving the performance of these systems.

Traditional fingerprint recognition

Fingerprint recognition systems operate as follows: first, an enhancement algorithm is applied to increase the clarity of ridges and valleys. These algorithms use visual characteristics such as continuity and orientation of ridges to improve image quality. Subsequently, the enhanced fingerprint image undergoes segmentation, separating the background from the fingerprint areas containing essential information. Segmentation is achieved by observing local intensity variations in the original grayscale image. In the minutiae identification process, the segmented image is first binarized, converting grayscale to a black-and-white image. Then, the image is thinned to reduce ridge thickness to a single pixel and isolate pixels corresponding to minutiae.

Gabor wavelets and filters are signal processing techniques commonly used in image analysis and shape recognition. Gabor wavelets are complex sinusoidal signals that are spatially and frequency limited. They can be oriented in specific directions and scaled to certain sizes, making them useful for detecting different orientations and frequencies in images. When applied to an image, Gabor filters produce an output that emphasizes regions similar to the local characteristics of the wavelet shape the filter is designed to detect. This enables the identification of textures, edges, and other details in the image. In the context of fingerprint recognition, Gabor filters are used to extract key fingerprint features such as ridges and valleys, facilitating further analysis and fingerprint identification. However, the use of Gabor wavelets and filters can be computationally demanding. It is important to note that systems based on Gabor technique implementation face challenges such as a high false acceptance rate, template size, and reliability, further complicating the fingerprint identification process.

Extraction of minutiae is a crucial step in fingerprint recognition systems, where distinctive features of the fingerprint are identified and extracted for further analysis. Minutiae are specific points where ridge lines in the fingerprint pattern end or bifurcate. These points serve as unique identifiers for fingerprint matching and are essential parts of the fingerprint recognition process. Minutiae extraction typically involves several steps: preprocessing, segmentation, orientation field estimation, image enhancement, and minutiae detail extraction. After capturing the fingerprint image using a fingerprint scanner or sensor, minutiae details are extracted from the biometric fingerprint before generating a pattern in which unwanted effects and components are removed.

Just to illustrate the needs of mathematics behind traditional fingerprint recognition system, we present some of it below. Preprocessing of the sample involves analyzing the image histogram, i.e., the distribution of pixel intensities (histogram equalization), to enhance the local contrast of the image. The process of removing blurring and additional noise from the fingerprint image, without altering the structures of the biometric sample, is based on the implementation of a Wiener filter. The Wiener filter [4] in the frequency domain can be represented by the equation:

$$W(u,v) = \frac{H^*(u,v)}{|H(u,v)|^2 + \frac{P_n(u,v)}{P_s}(u,v)}\,, \tag{1}$$

where $H(u,v)$ is the Fourier transform of the point spread function $h(x,y)$, $H^*(u,v)$ is the complex conjugate of this function, $P_n(u,v)$ is the spectral power density of the noise, and $P_s(u,v)$ is the spectral power density of the under-graded image,

$$W(u,v) = \frac{P_s(u,v)}{P_s(u,v) + \sigma_n^2}\,, \tag{2}$$

where σ_n^2 is the noise variance.

Segmentation involves extracting significant parts from the rest of the image, i.e., ridge structures from the background and other artifacts. The process is based on dividing the resulting output of the Wiener filter into blocks of the same size that do not overlap. Let N denote the block size, and $\mu(I)$ represent the mean pixel value of the block. Block I is considered a foreground block if its noise variance is greater than the threshold τ_s:

$$\sigma^2(I) = \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}\big(I(i,j) - \mu(I)\big)^2 > \tau_s \, , \tag{3}$$

Estimation of the orientation field, i.e., the local orientations of ridge and valley structures, is also performed on a block-by-block basis. One way of estimating it is based on gradient vectors that show the greatest intensity deviation perpendicular to the ridge lines [5]. The orientation θ of each block is given by the equation:

$$\theta = \frac{1}{2}tan^{-1}\left[\frac{\sum_{i=1}^{N}\sum_{j=1}^{N}2g_x(i,j)g_y(i,j)}{\sum_{i=1}^{N}\sum_{j=1}^{N}(g_x{}^2(i,j)-g_y{}^2(i,j))}\right] + \frac{\pi}{2} \, , \tag{4}$$

where g_x and g_y denote the gradient vectors of a block centered at pixel (i, j) in the horizontal and vertical directions, respectively. To enhance the image, a Gaussian low-pass filter is used, followed by a 2-D Gabor filter [6] defined by:

$$G(x, y, \theta, f_0) = e^{-\frac{1}{2}\left(\frac{x_\theta{}^2}{\sigma_x{}^2}+\frac{y_\theta{}^2}{\sigma_y{}^2}\right)}\cos(2\pi f_0 x_0) \, , \tag{5}$$

$$x_0 = xsin\theta + ycos\theta \, , \tag{6}$$

$$y_0 = -xcos\theta + ysin\theta \, , \tag{7}$$

where f_0 denotes the ridge frequency, θ the orientation of the filter, σ_x and σ_y the standard deviations of the Gaussian envelope along the x and y axes, $[x_\theta, y_\theta]$ the coordinates $[x, y]$ after rotating the coordinate axes by $0.5\pi-\theta$ clockwise. Considering that point feature extraction algorithms work with images in binary format, the output of filtering is binarized. The grayscale level of each pixel is compared with a global threshold, resulting in an image with two levels of interest: ridges and valleys. Narrowing the width of ridge lines is achieved by applying a thinning algorithm described in [7]. According to the Hilditch's definition, the number of transitions represents the measure of transitions from white to black pixels while passing through points in a certain order. The result of the algorithm is an image composed of ridge lines one pixel wide, with clearly visible ridge endings and bifurcation points (valley endings). For each pixel in the resulting image, according to the Rutovitz's definition, the number of transitions is calculated as the number of transitions from white to black and vice versa as points are passed in sequence. Pixel is identified as a ridge end point if number of transitions equals two, and as a bifurcation point if number of transition equals six. Reader may cf. [8, 9] for more details.

Related work

There is a wealth of research describing techniques for fingerprint recognition. Contemporary studies increasingly involve the application of various machine learning techniques to improve accuracy, performance, and system stability. In this chapter, we analyze relevant research exploring fingerprint recognition methods using machine learning techniques for feature extraction, fingerprint image enhancement, classification, and matching.

In the work by Xie and Qi [10], a backpropagation neural network method is proposed for grayscale fingerprint image quality assessment. Their methodology involves segmenting fingerprint images into blocks, which requires additional computational resources.

Zhu et al. [11] use a neural network to estimate the quality of fingerprint images, focusing on the orientation of fingerprint ridges. Precise ridge orientation is estimated using trained neural networks.

Labati et al. [12] proposed using neural networks to measure image quality in wireless fingerprint scanning. They identified a new set of features and developed a neural network for extracting complex characteristics for future fingerprint matching.

Liu et al. [13] propose using backpropagation neural network method for detecting singular points on grayscale fingerprint images divided into blocks of size 35 times 35 pixels.

Bartunek et al. [14] used a backpropagation neural network for extracting minutiae from fingerprint images. Minutiae detection was performed using a sliding window of size 5 times 5 pixels to access the entire fingerprint image.

Yang et al. [15] used fuzzy logic-based neural networks for extracting minutiae from grayscale images, with a high degree of rotation and grayscale invariance.

In the research described in [16], Kumar and Vikram described the application of multidimensional artificial neural networks (MDANN) for fingerprint matching using minutiae points. This algorithm achieved a maximum recognition rate of 97.37%.

Liu et al. [17] used the SVM method with a five-dimensional feature vector to determine the quality of fingerprint images. Fingerprints were classified into high, medium, and low-quality images with an accuracy of 96.03%.

Li et al. [18] proposed using the SVM technique for fingerprint classification into 5 classes using a combination of singular points and image orientation. Using only orientation coefficients achieved an accuracy of 87.4%, while using only singular points achieved an accuracy of 88.3%.

In the study described in [19], the authors presented the development of a fingerprint classification model based on the SVM algorithm. The algorithm was tested on the FVC2000 and FVC2002 datasets, achieving a fingerprint classification accuracy of 92.5%.

Kahraman et al. [20] proposed a methodology for extracting characteristic minutiae from fingerprint images using a multilayer artificial neural network based on orientation maps. This algorithm was evaluated on the UPEK and FVC2000 datasets, achieving significant results. Specifically, an accuracy of 95.57% was achieved for UPEK, while an accuracy of 91.38% was achieved for FVC2000.

Zeng et al. [21] proposed an algorithm for recognizing partial fingerprints based on deep learning. The Deep Neural Network (DNN) was trained and evaluated using the NIST-DB4 dataset, achieving an accuracy of 93%.

In the research conducted by Saponara et al. [22], an autoencoder architecture based on Convolutional Neural Network (CNN) for reconstructing fingerprint images is proposed. The proposed architecture was evaluated on four different fingerprint image datasets, achieving accuracies of 98.1%, 97%, 95.9%, and 95.02%, respectively, for each of the four datasets.

In the work by Elsadai et al. [23], a method for fingerprint recognition based on machine learning techniques and stylometric features is proposed. For the evaluation of machine learning algorithms, the CASIA-FingerprintV5 database was used. The application of random sampling before and during the cross-validation process was analyzed. The CatBoost algorithm for classification, along with the over-sampling method SMOTE during cross-validation, achieved accuracies of 99.95% and 99.98% for the All_features and GRRF datasets, respectively.

In the work by Sun et al. [24], the authors propose an APFI model based on deep learning focused on feature extraction from partial fingerprint images. Experimental results on their dataset and the NIST SD4 dataset show that the proposed method achieves an accuracy of 98.9% for the complete image, 98.6% when the effective fingerprint area is 75%, 94.9% when the effective fingerprint area is 50%, 88.9% when the effective fingerprint area is 75%, and 94.9% when the effective fingerprint area is 25%.

Further, we will let a reader screen a summary table in the discussion section with a brief comparison of fellow researchers aforementioned.

Natural language processing based feature extraction

Traditional fingerprint recognition systems utilize minutiae extraction methods that employ Gabor wavelet transformations or filters, segmentation, binarization, thinning, and generation of binary fingerprint templates for individual recognition. This process, besides being based on a complex mathematical apparatus, requires more time and better computational performance to optimize parameters to balance the FAR and FRR values in the matching phase. In this work, we propose a framework (Fig. 1) that is based on encoding raw data representing fingerprint images and converting them into raw textual data without modifying statistical characteristics.

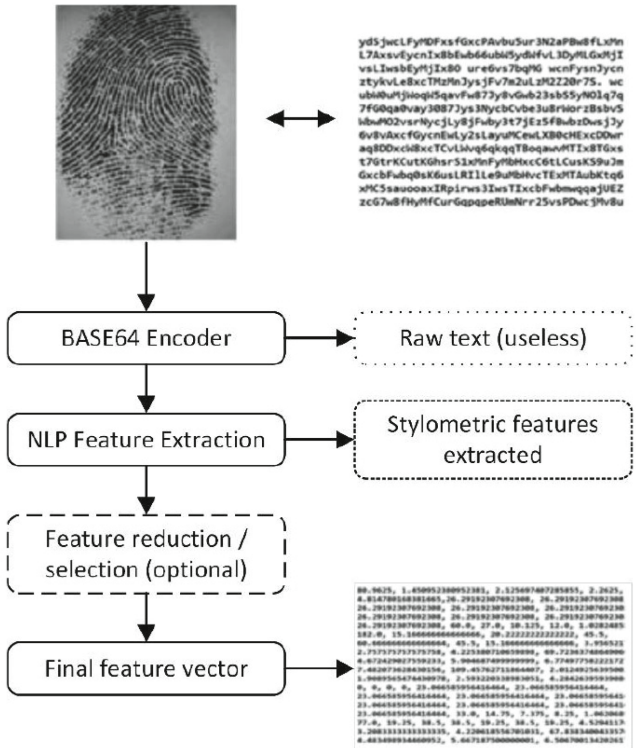

Figure 1. *Fingerprint data acquisition framework.*

Source: *author's contribution. Fingerprint image is adopted from [25].*

The Base64 encoding algorithm was implemented to encode original fingerprint images into raw textual form without modifying their statistical characteristics. From the raw textual data, significant features listed below were extracted:

- the average sentence length in a text;
- the percentage of capital letters in relation to the number of lower-case letters;
- the percentage of lower-case letters in relation to the total number of characters in a text;
- the percentage of punctuation signs in relation to the total number of blank spaces in a text;
- the percentage of the numeric characters in relation to the total number of letter characters in a text;
- the average word length per sentence in a text;
- the frequency of the most frequent stop word in a text;
- the frequency of the most frequent starting word of a sentence in a text;
- the frequency of the most frequent starting letter of a starting word;
- the frequency of the most frequent starting letter of a stop word;
- the number of words occurring only once in a text;
- the number of words occurring twice in a text;
- the number of words of a given length in a text;
- the number of words whose lengths are within a given range and
- the number of vowels in a text.

This list includes language-independent features selected from the stylometry tagging model proposed in [26]. Additionally, we employ:

- the Deflate algorithm - text compression in the best compression mode and
- the Kolmogorov complexity of text fragments of a given length.

The transformation of a fingerprint image into a source of information via a finite alphabet induced by Base64 encoding has a significant impact on the accuracy of the proposed biometric system. Spatial correlations are easier to detect in text generated using Base64 than from a fingerprint image. This argument particularly applies to properties based on global information measures, such as Kolmogorov complexity and structural stylometric properties. These measures, calculated for the textual representation of a fingerprint image, actually include structural spatial interdependencies within the given image, indirectly encoded in the corresponding text. On the other hand, Base64 encoding preserves enough information related to local spatial properties, encoded in stylometric properties. Since text is considered a biometric source, it generates biometric characteristics in our proposed method. The obtained information enables verification or authentication of authorship based on extracted characteristics. Generated feature templates based on input text obtained from raw data will ensure achieving higher accuracy.

The intuition behind using stylometric features is that the spatial structure of fingerprint images, when encoded into text, introduces statistical regularities similar to those found in natural language. These regularities can be captured using language-independent features, providing a novel representation for classification.

Elsemble learner classification

In the proposed approach described in the paper, data preprocessing is reduced to the extraction of feature vectors, which are then forwarded to the classifier when the fingerprint is loaded into the system for testing. No noise reduction, normalization, oversampling, or filter application procedures were conducted on the raw data. This approach significantly improves the performance of the proposed fingerprint recognition system framework.

For the selection of significant feature vectors, dimensionality reduction, and generation of classifier models, several machine learning methods were used, such as:

- Multiboost [27] from the Weka system [28] named *MultiboostAB*,
- Random Forest [29] from the R package *randomForest* (the original Breiman and Cutler's Fortran code ported to R) and
- Gradient boosting (CatBoost) [30] from the Python package *catboost*.

Results

The procedure was implemented on data obtained from the CasiaV5 fingerprint image database [25] developed by the Chinese Academy of Science, Institute of Automation (Fig 2). The database has been offe43red free of charge for the biometric research community. The fingerprint samples were captured using the URU4000 sensor during one session. CASIA-FingerprintV5 database consists of 20,000 fingerprint images of 500 individuals, including graduate students, waiters, workers, etc.

Figure 2. *Fingerprint data acquisition.*

Source: *Chinese Academy of Science, Institute of Automation [25]. Used with permission.*

The analyzed dataset was divided into training and test sets using the 10-fold cross-validation method. The performance of the generated classifier models was evaluated using the measures accuracy, precision, recall, F-measure, and the area under the curve (AUC). In addition, two important biometric measures are taken into account: the FAR and FRR. In the binary classification considered in our approach, they are equivalent to the False Positive Rate (FPR) and False Negative Rate (FNR), respectively.

The proposed approach can be briefly described by the following procedure: each of the two fingerprint images is represented by a feature vector. The array representing the first image is denoted as A, and the array representing the second image is denoted as B. Feature vectors A and B are classified as Y (the observed fingerprints belong to the same person) or N (the observed fingerprints belong to different individuals).

Results are presented in Table 1. Reader may find these comparable to aforementioned studies.

Discussion

This section of the paper will briefly deal with the following issues: finding the optimal hyper-parameters of the classification models, generalizability of the solution and the need for oversampling, introduction of filter bank preprocessing and the applicability and security issues.

Regarding the optimal hyper-parameters, authors may conclude that different parameters apply to other datasets. To put it simple, parameters will vary with different image acquisition device in real life scenario – be it with or without oversampling. Here, for example, forests are built with 150 trees, while CatBoost employs 500.

Regarding generalizability, the proposed method is tested by considering the average classification accuracy of the repeated cross-validation procedure (ten-fold cross-validation repeated ten times, every time with a different seed of a random number generator). Depending on the dataset properties, an over-

Table 1. *Experimental evaluation of CASIA samples with three ensemble learning algorithms.*

	Accuracy	Precision	Recall	F-measure	AUC
Multiboost	0.9946 ± 0.006	0.97 ± 0.03	0.99 ± 0.01	0.98 ± 0.01	0.98 ± 0.01
Random Forest	0.9982 ± 0.002	1.00 ± 0.00	0.99 ± 0.01	0.99 ± 0.01	1.00 ± 0.00
CatBoost	0.9967 ± 0.003	0.97 ± 0.01	1.00 ± 0.00	1.00 ± 0.00	0.99 ± 0.00

estimation of the performance is possible as a consequence of the applied approach for cross-validation after the over-sampling [31].

Although ROI estimation and gradient vectors could provide an additional image tuning in the preprocessing phase, the idea behind this research was to provide a proof that this method is applicable to raw images and is prone to errors originating from noise. Reader may consult [23] to compare results of the similar research that includes noise reduction and normalization with the results presented here.

To make the proposed approach suitable for an efficient algorithmic verification in embedded devices and IoT technologies, efforts are made to reduce the size of the fingerprint biometric template. The results of the feature extraction show that it is possible to reduce the size of an biometric template to 128 and 256 bits, which represent a significant reduction with respect to the biometric templates generated by the traditional methods.

Regarding applicability, this reduction of the computational costs and template size enables implementation of the proposed approach in devices with small memory capacity, it does not have a negative impact on the security of the biometric templates. In the proposed approach, a biometric template is stored as a set of numeric feature values in a database. In contrast to the traditional approaches, these templates cannot be used to reconstruct the original fingerprint images by using genetic algorithms or artificial neural networks, which cancels the possibility of performing a successful attack on the biometric system by using synthetic fingerprint images.

Last, but not least, we provide a comparison table with the other researchers (Table 2).

Conclusion

The disadvantages of the traditional fingerprint recognition systems include the existence of the FAR, which is unacceptable in most of authentication scenarios, the existence of a threshold in the authentication phase, the need to find a balance between the FAR and FRR, the fine-tuning of filter parameters, and large template sizes which are not suitable for some applications.

To overcome these disadvantages, we employ feature extraction approach based on an encoder that generates a set of stylometric features from a raw fingerprint image. As expected, the transformation of an image into an information source over a finite alphabet has a significant positive impact on the recognition accuracy, as spatial correlations are more easily detected, and thus more easily utilized, in a Base64-generated text than in an fingerprint image.

As for further work, we will provide the research on impact of traditional preprocessing phases on the confusion matrix as well as impact of oversampling techniques, such as oversampling before and during cross-validation.

Table 2. *Comparison to other researchers.*

Ref.	Methods	Pros.	Cons.
Xie and Qi [10]	ANN, grayscale fingerprint segmentation	N/A	Image segmentation leads to additional computational resources
Zhu et al. [11]	ANN, minutiae	N/A	Precise ridge orientation overhead
Labati et al. [12]	ANN, minutiae	New set of features	Complexity
Bartunek et al. [14]	ANN, minutiae	N/A	Sliding window application, low accuracy
Yang et al. [15]	Fuzzy logic, ANN	High degree of rotation and grayscale invariance	Low accuracy
Kumar and Vikram [16]	Multidimensional ANN	N/A	Low accuracy
Liu et al. [17]	SVM	Low dimensionality	Low accuracy
Li et al. [18]	SVM	N/A	Extremely low accuracy
Kahraman et al. [20]	Orientation maps ANN	N/A	Low accuracy
Zeng et al. [21]	Deep neural nets	N/A	N/A
Saponara et al. [22]	Autoencoder based on Convolutional Neural Network	High accuracy	N/A
Elsadai et al. [23]	Stylometry, preprocessing, machine learning	Very high accuracy	Preprocessing and oversampling
Panić et al. [this contribution]	Stylometry, ensemble machine learning	Very high accuracy	N/A

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Conflict of Interests
Authors declare that there is no conflict of interest regarding the publication of this article.

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About the authors

Milan Panić was born in Gradiška in 1999. He earned the title of Bachelor of Computer Science and Informatics Engineer in the field of computer security and information protection in July 2023 at the Pan-European University "Apeiron" Banja Luka as a top student with an average of 9.48 out of 10. Since 2021, he has been employed at the Pan-European University Apeiron in Banja Luka as a system administrator, and since 2024 as an assistant in the courses of computer forensics and mobile forensic. He holds a certificate from ISC2 (CC), which confirms his understanding of key principles in the field of cybersecurity, including network security, data protection and risk management.

Nemanja D. Maček is a senior lecturer at the School of Electrical and Computer Engineering and the full professor at the Faculty of Social Sciences. He also works, as a contractor, for the SECIT Security Consulting and as a senior AI researcher and scientific advisor for several companies. Nemanja graduated from University of Novi Sad in 2006 and received Advanced Security Systems PhD from Singidunum University in 2013. The research of Prof. Maček involves machine learning, pattern recognition and natural language processing applied to information security, as well as biometric systems, cryptology and designing novel security mechanisms. He is a passionate cat lover and a very lousy musician.

Branimir Trekić, Full Professor in Computer Sciences, was born in Ćuprija, Serbia, in 1961. Dr. Trenkić joined the Faculty of Computer Sciences in Belgrade as associate professor in 2011. In 2013 he became a full professor at the Faculty of Computer Sciences and in 2016 he joined the School of Electrical and Computer Engineering of Applied Studies. Throughout his career, he has authored numerous impactful publications in peer-reviewed journals, contributing valuable insights to the scientific community, projects etc. Area of work: performance analysis of communication networks, high-performance systems (HPC), IoT, queueing strategies for communication networks, software development and testing.

Daniel Menićanin, a student at the Faculty of Information Technology specializing in Programming and Software Engineering at Paneuropean University Apeiron, is an innovator recognized for developing groundbreaking solutions. In recognition of his exceptional contributions to education, science, and the arts, Daniel received the Plaque of the City of Banja Luka. He was also awarded the prestigious Butterfly Innovation Award in the Youth category, presented by the Regional Cooperation Council. Currently, Daniel's research focuses on robotics, industrial machinery, and automation, further advancing his expertise in developing cutting-edge technological solutions.

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A Hybrid Model Based on Chaos Theory and Artificial Immune Systems for the Analysis and Classification of Stock Market Anomalies

Marko M. Živanović[1], Emilija Kisić[2]
[1]*Faculty of Information Technology, University Metropolitan, Belgrade, Serbia, marko.zivanovic@metropolitan.ac.rs, https://orcid.org/0009-0005-9264-3314*
[2]*Faculty of Information Technology, University Metropolitan, Belgrade, Serbia, emilija.kisic@metropolitan.ac.rs, https://orcid.org/0000-0003-3059-2353*

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Abstract: In this-paper, a system for analyzing chaotic patterns in financial markets has been developed by combining classical chaos metrics with artificial immune systems for anomaly detection. Implemented indicators include the Lyapunov exponent, correlation dimension, approximate entropy, Hurst exponent, and the distance from a reference Lorenz trajectory. These metrics enable the detection of changes in market stability and predictability over time. An adaptive algorithm inspired by artificial immune systems was developed for identifying anomalous behaviors, adjusting detectors based on detected deviations. The results are presented through a series of interactive visualizations, including 3D plots, time series, and anomaly density maps. In addition to standard analysis, the system supports false alarm detection through controlled parameter variations. This approach provides deeper insights into the complex dynamics of financial markets and can serve as a tool for forecasting periods of instability.

Keywords: anomaly detection, artificial immune systems, chaos metrics, financial markets, lorenz attractor, lyapunov exponent

Introduction

The intricate and nonlinear dynamics of financial markets have long challenged researchers seeking to model, predict, and understand their behavior [1]. In particular, the emergence of chaotic patterns [2], characterized by sensitivity to initial conditions and underlying structural complexity, necessitates the development of sophisticated analytical frameworks. Within this context, quantifying chaos using dynamical system metrics—such as the Lyapunov exponent, correlation dimension, approximate entropy, and the Hurst exponent—has proven instrumental in revealing hidden order within seemingly stochastic market behavior [3,4]. This study introduces an integrated computational framework for the detection and analysis of chaotic phenomena in financial time series. By employing a combination of classical chaos theory metrics and novel bio-inspired anomaly detection techniques—specifically, artificial immune system algorithms—this work offers a robust methodology for identifying critical transitions and stability fluctuations in financial markets. The innovative incorporation of Lorenz attractor trajectory comparisons further enhances the model's sensitivity to nonlinear deviations, providing an enriched perspective on temporal evolution and emergent anomalies [5]. The proposed system facilitates both qualitative and quantitative exploration through interactive, multidimensional visualizations, encompassing 3D scatter plots, temporal evolution graphs, and anomaly density heatmaps. Within this context, two distinct adaptive immune detection models are employed to simulate varying market surveillance scenarios—one of which incorporates stochastic false alarm mechanisms to emulate noisy and unpredictable detection environments. The second model operates without false alarm mechanisms, thereby reflecting a more idealized and deterministic surveillance framework for comparative analysis. By integrating traditional chaos theory with quantitative classification based on dynamical system indicators—such as the Lyapunov exponent and the Hurst exponent—the presented approach aims to enhance early warning systems and predictive analytics in financial engineering.

Methodology

In this work, an innovative methodology was developed for analyzing the chaotic characteristics of capital markets by combining mathematical models, chaos-based metrics (such as the Lyapunov and Hurst exponents), and adaptive immune system-inspired detection frameworks. The analysis was carried out through a series of functional components that enable quantitative measurement of nonlinear dynamics in stock price time series, as well as anomaly detection in market behavior. Stock price data were obtained using the Yahoo Finance service, ensuring the timeliness and relevance of the time series for the purposes of the analysis. Each method used is described in detail below. The Lorenz system is a classic mathematical model that describes chaotic behavior. It was created in 1963 when meteorologist Edward Lorenz tried to model atmospheric convection [6]. A particularly notable feature of this system is its extreme sensitivity to initial conditions, where even minimal changes can lead to vastly different outcomes—a hallmark of chaotic behavior.

The Lorenz system is defined by three coupled nonlinear differential equations:

$$\frac{dx}{dt} = \sigma(y - x) \tag{1}$$

$$\frac{dy}{dt} = x(\rho - z) - y \tag{2}$$

$$\frac{dz}{dt} = xy - \beta z \tag{3}$$

Where:
x – position in space (can be seen as the system's state),
y – second coordinate (e.g., rate of change),
z – third coordinate (could represent heat or altitude in atmospheric modeling) [7];

Parameters that control the system's behavior:
σ=10(Prandtl number – measures the ratio of viscosity to thermal diffusivity),
ρ=28(Rayleigh number – measures temperature difference),
β=83(geometric factor – depends on the system's shape);

When these parameters are set to these values, the Lorenz system exhibits pure chaotic behavior — the famous "Lorenz attractor"[8].

Numerical solutions were obtained using the variable-step integration method via the `solve_ivp` function, with initial conditions (x_0, y_0, z_0) = (1.0, 1.0, 1.0) and a time step of dt = 0.01. The resulting trajectory consists of state vectors (*x(t), y(t), z(t)*) at each discrete time point, allowing the creation of a representative pattern of chaotic behavior. After generating the Lorenz trajectory, a function was developed to quantify the similarity between the real-time series of market prices and the reference chaotic trajectory. The market price time window and the x-component of the Lorenz trajectory were independently normalized using standard Z-score normalization:

$$u_{norm} = \frac{u - \mu_u}{\sigma_u + 10^{-8}}, \tag{4}$$

where represents the mean, and the standard deviation of the observed series [9]. Normalization removes the influence of absolute scale, enabling a focus purely on fluctuation patterns.

The similarity between the normalized sequences was then measured using the Euclidean norm:

$$d(u, v) = \sqrt{\sum_{i=1}^{m} (u_i - v_i)^2}, \tag{5}$$

where m is the length of the shorter of the two compared sequences. This metric quantifies the global distance between the two signals, where lower distance values indicate a higher degree of similarity, i.e., a stronger chaotic resemblance between the market window and the Lorenz attractor [10]. In this way, a robust method was created for detecting latent chaotic dynamics within time series of market prices [11]. The choice of the Lorenz system as a reference model is justified by its ability to exhibit extremely sensitive and nonlinear behavior despite its deterministic nature, providing a valid benchmark for comparison with real-world market processes [12].

In this study, four key metrics were applied to quantify chaotic behavior in time series: Approximate Entropy, Hurst Exponent, Maximal Lyapunov Exponent, and Correlation Dimension. Each of these metrics provides a specific perspective on the internal complexity and predictability of temporal processes.

Approximate Entropy (ApEn) measures the regularity and unpredictability of fluctuations in a time series [13]. Formally, ApEn is defined as:

$$ApEn(m, r) = \phi(m) - \phi(m+1) \tag{6}$$

where:

$$\phi(m) = \frac{1}{N-m+1} \sum_{i=1}^{N-m+1} ln\, C_i^m(r) \tag{7}$$

Here, $C_i^m(r)$ represents the proportion of vectors of length mmm that are within a distance *r* from the reference vector *x(i)*. The threshold *r* is usually chosen as a percentage of the standard deviation of the time series.

The distance between two vectors is measured by the maximum absolute difference between their respective components [14].

$$d(x(i), x(j)) = \max_{k=1,2,\dots,m} |x(i+k-1) - x(j+k-1)| \tag{8}$$

Higher values of Approximate Entropy indicate lower predictability and greater chaos within the system.The Hurst Exponent is a measure of long-term memory in a time series [15]. Its interpretation is as follows:

- H=0.5: The process is a random walk (memoryless),
- H>0.5H: Positive autocorrelation (trending behavior),
- H<0.5H: Negative autocorrelation (mean-reverting behavior).

Hurst's relation is expressed through the rescaled range analysis:

$$E[R(n)/S(n)] \propto n^H \tag{9}$$

where *R(n)* is the range of cumulative deviations, *S(n)* is the standard deviation, and nnn is the length of the subseries.

The Maximal Lyapunov Exponent measures the rate of divergence between initially close trajectories in the phase space [16]. Formally:

$$\lambda max = \lim_{t\to\infty} \frac{1}{t} ln \frac{d(t)}{d(0)}, \tag{10}$$

where *d(0)* and *d(t)* are the initial and evolved distances between two nearby points, respectively.

The Correlation Dimension estimates the fractal complexity of a system [17]. It is defined through the correlation function *C(r)* as:

$$C(r) = \lim_{N\to\infty} \frac{2}{N(N-1)} \sum_{i<j} \Theta(r - \|x_i - x_j\| \tag{11}$$

where Θ is the Heaviside step function, and *r* is the distance threshold. In practice, the correlation dimension D_2 is approximated as:

$$D_2 \approx \frac{dlnC(r)}{dlnr} \tag{12}$$

For calculation, the distance matrix between reconstructed phase space vectors is generated, and the number of vector pairs with distances less than *r* is counted, providing an insight into the complexity of the dynamical system [18].

The Artificial Immune System (AIS) is inspired by the biological immune system and is utilized for anomaly detection in complex datasets. Two versions of the AIS algorithm were used here: without false alarms and with false alarms, both based on reactive cloning of detectors [19]. For a dataset $X = \{x1, x2, \dots, xN\}$ where each vector instance is defined as:

$$xi = (Lyapunovi, CorrDimi, ApproxEntropyi, Hursti, Lorenz\ Disti) \tag{13}$$

the features are first standardized:

$$z_i = \frac{x_i - \mu}{\sigma} \tag{14}$$

where and are the vectors of mean values and standard deviations of the individual features.

The formulation with false alarms is:

$$Anomaly = (\min_i di > \theta) \vee (rand() < pfalse) \tag{15}$$

where *rand ()* is a uniformly random value from the interval [0,1].

Results

In this study, we analyzed the chaotic dynamics of the stock prices of major technology companies (AAPL, MSFT, GOOGL, NVDA, INTC, AMD, and IBM) [20, 21] using a set of nonlinear time series metrics. The analysis covered the period from January

1, 2020, to April 3, 2025. For each company's closing price time series, a sliding window approach was used with a window size of

$$W = 200 \tag{16}$$

samples and a step size of S = 20. Within each window, the following metrics were calculated:

- Maximum Lyapunov Exponent (λmax), indicating sensitivity to initial conditions.
- Correlation Dimension (D_2), measuring the fractal complexity of the trajectory.
- Approximate Entropy (ApEn), evaluating the unpredictability of the system.
- Hurst Exponent (H), indicating long-term memory and trend persistence.
- Lorenz Distance (d_{Lorenz}), comparing the real data to the reference Lorenz attractor.

The calculated features were then passed through the Artificial Immune System (AIS) algorithm for anomaly detection. Two AIS versions were tested: Normal AIS without induced false alarms, AIS with False Alarms, which introduces 5% random anomalies to simulate realistic detection imperfections. Additionally, each time window was classified into one of several market states based on threshold conditions over the Lyapunov exponent and Hurst exponent. Classification of Market States Based on Lyapunov and Hurst Exponents (Table 1) [22].

Table 1. *Summary of Quantitative Data for Apple Inc.*

Lyapunov	Hurst	Market State
λ>0.3	H<0.3	Very Chaotic
0.1<λ≤0.30	H<0.4	Chaotic
λ<0.05	H>0.7	Highly Predictable
λ<0.1	0.5≤H≤0.70	Stable
0.05≤λ≤0.2	0.4≤H≤0.6	Semi-Stable
otherwise	otherwise	Highly Unstable

A series of visualizations was generated to illustrate the behavior and evolution of chaotic metrics across time for selected stock market symbols. These include time-series plots of individual metrics (Lyapunov exponent, correlation dimension, approximate entropy, Hurst exponent, and Lorenz distance), a 3D scatter plot of the Lyapunov–Correlation Dimension–Lorenz Distance space, as well as anomaly detection visualizations such as heatmaps and scatter diagrams. These visual analyses reveal transitions between different market states and highlight the artificial immune system's effectiveness in identifying anomalies, even when false alarms are introduced, such as during periods of heightened volatility (e.g., the 2020 pandemic shock).

The following images show the results for Apple (Figure1, Figure 2, Figure 3, Figure 4 and Figure 5)

Time	Lyapunov	CorrDim	proxEntro	Hurst	LorenzDist	Anomaly	AnomalySt	MarketStat	nomalyNur
2020-10-1	0,48216	-2,1976	0,34375	0,79571	457,082	FALSE	Normal	Highly Un	0
2020-11-1	0,55553	-2,3307	0,36797	0,78121	457,082	FALSE	Normal	Highly Un	0
2020-12-1	0,56424	-2,2752	0,3324	0,80563	457,082	FALSE	Normal	Highly Un	0
2021-01-1	0,56597	-2,318	0,35487	0,85975	457,082	FALSE	Normal	Highly Un	0
2021-02-1	0,55063	-2,4358	0,40324	0,80464	457,082	FALSE	Normal	Highly Un	0
2021-03-1	0,53603	-2,6871	0,55594	0,70303	457,082	FALSE	Normal	Highly Un	0
2021-04-1	0,42991	-2,9484	0,69205	0,6153	457,082	FALSE	Normal	Highly Un	0
2021-05-1	0,36805	-3,2935	0,79913	0,57356	457,082	FALSE	Normal	Highly Un	0
2021-06-0	0,27624	-3,706	0,88305	0,44629	457,082	FALSE	Normal	Highly Un	0
2021-07-0	0,21742	-3,4778	0,85138	0,50773	457,082	FALSE	Normal	Highly Un	0
2021-08-0	0,25271	-3,2195	0,75521	0,51714	457,082	FALSE	Normal	Highly Un	0
2021-09-0	0,20766	-3,0205	0,7026	0,53207	457,082	FALSE	Normal	Highly Un	0
2021-09-3	0,19298	-2,9285	0,69084	0,52385	457,082	FALSE	Normal	Semi-Stat	0
2021-10-2	0,16061	-2,8634	0,64578	0,57001	457,082	FALSE	Normal	Semi-Stat	0
2021-11-2	0,18411	-2,604	0,57023	0,58573	457,082	FALSE	Normal	Semi-Stat	0
2021-12-2	0,31997	-2,3124	0,42398	0,68238	457,082	FALSE	Normal	Highly Un	0
2022-01-2	0,35091	-2,2493	0,41762	0,7124	457,082	FALSE	Normal	Highly Un	0
2022-02-2	0,38919	-2,2483	0,43006	0,70994	457,082	FALSE	Normal	Highly Un	0
2022-03-2	0,45047	-2,576	0,56611	0,63136	457,082	FALSE	Normal	Highly Un	0
2022-04-2	0,34665	-2,769	0,67216	0,5023	457,082	FALSE	Normal	Highly Un	0
2022-05-1	0,43679	-3,0939	0,75499	0,48007	457,082	FALSE	Normal	Highly Un	0
2022-06-1	0,53381	-3,1683	0,72412	0,50075	457,082	FALSE	Normal	Highly Un	0
2022-07-1	0,56283	-3,1028	0,72007	0,52776	457,082	FALSE	Normal	Highly Un	0
2022-08-1	0,60588	-3,3821	0,77552	0,4859	457,082	FALSE	Normal	Highly Un	0
2022-09-1	0,60927	-3,397	0,79571	0,47893	457,082	FALSE	Normal	Highly Un	0
2022-10-1	0,61928	-3,4412	0,81961	0,49588	457,082	FALSE	Normal	Highly Un	0
2022-11-0	0,63459	-3,6147	0,84956	0,48084	457,082	FALSE	Normal	Highly Un	0
2022-12-0	0,6276	-3,6899	0,87353	0,46445	457,082	FALSE	Normal	Highly Un	0
2023-01-0	0,66281	-3,4697	0,83232	0,51093	457,082	FALSE	Normal	Highly Un	0
2023-02-0	0,60189	-3,6642	0,87401	0,47972	457,082	FALSE	Normal	Highly Un	0
2023-03-0	0,50928	-3,5225	0,86592	0,47583	457,082	FALSE	Normal	Highly Un	0
2023-04-0	0,50767	-3,4444	0,81832	0,52233	457,082	FALSE	Normal	Highly Un	0
2023-05-0	0,50934	-3,3249	0,77097	0,53153	457,082	FALSE	Normal	Highly Un	0
2023-06-0	0,54491	-3,1005	0,68284	0,57694	457,082	FALSE	Normal	Highly Un	0
2023-07-0	0,60887	-2,7762	0,55925	0,63977	457,082	FALSE	Normal	Highly Un	0
2023-08-0	0,65724	-2,5793	0,42076	0,66876	457,082	FALSE	Normal	Highly Un	0
2023-08-2	0,63185	-2,5405	0,3582	0,71933	457,082	FALSE	Normal	Highly Un	0
2023-09-2	0,61843	-2,4995	0,38044	0,7616	457,082	FALSE	Normal	Highly Un	0
2023-10-2	0,51438	-2,4965	0,40877	0,73271	457,082	FALSE	Normal	Highly Un	0
2023-11-2	0,41593	-2,7284	0,55107	0,65626	457,082	FALSE	Normal	Highly Un	0
2023-12-2	0,35891	-2,8138	0,57995	0,63599	457,082	FALSE	Normal	Highly Un	0
2024-01-2	0,25351	-3,095	0,70483	0,50851	457,082	TRUE	Anomalou	Highly Un	1
2024-02-2	0,1458	-3,2669	0,78332	0,43129	457,082	FALSE	Normal	Semi-Stat	0
2024-03-2	0,15715	-3,397	0,81478	0,38629	457,082	FALSE	Normal	Chaotic	0
2024-04-1	0,17632	-3,2669	0,79853	0,39379	457,082	FALSE	Normal	Chaotic	0
2024-05-1	0,22649	-3,3999	0,79234	0,3784	457,082	FALSE	Normal	Chaotic	0
2024-06-1	0,25063	-3,0786	0,72035	0,47607	457,082	FALSE	Normal	Highly Un	0
2024-07-1	0,41159	-2,441	0,51908	0,5555	457,082	FALSE	Normal	Highly Un	0
2024-08-1	0,50241	-2,3169	0,47883	0,6317	457,082	FALSE	Normal	Highly Un	0
2024-09-1	0,53607	-2,2944	0,43547	0,65063	457,082	FALSE	Normal	Highly Un	0
2024-10-0	0,54965	-2,2526	0,42121	0,60915	457,082	FALSE	Normal	Highly Un	0
2024-11-0	0,60395	-2,2143	0,39217	0,59774	457,082	FALSE	Normal	Highly Un	0
2024-12-0	0,61316	-2,0327	0,35441	0,68222	457,082	FALSE	Normal	Highly Un	0
2025-01-0	0,72899	-2,1011	0,37317	0,71007	457,082	FALSE	Normal	Highly Un	0
2025-02-0	0,76423	-2,3541	0,5049	0,75331	457,082	FALSE	Normal	Highly Un	0
2025-03-0	0,66032	-2,8704	0,69222	0,58978	457,082	FALSE	Normal	Highly Un	0
2025-04-0	0,59573	-3,4196	0,84517	0,41427	457,082	FALSE	Normal	Highly Un	0

Figure 1. *Summary of Quantitative Data for Apple Inc.*

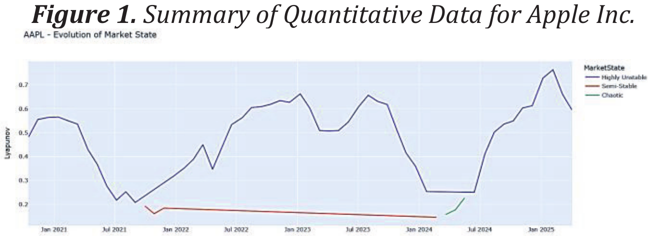


Figure 2. *APPL Evaluation of Market State*

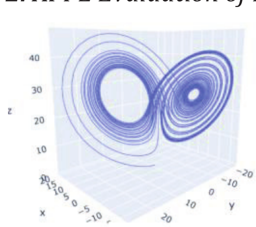


Figure 3. *Lorenz Attractor Reference*

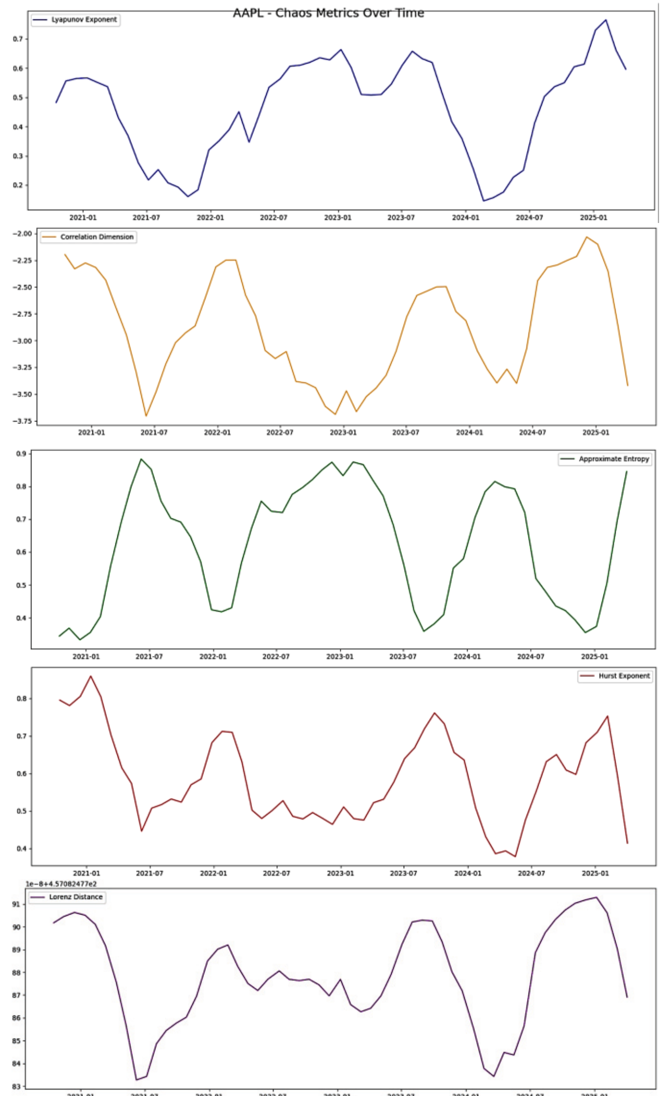


Figure 4. *Chaos Metrics Over Time*

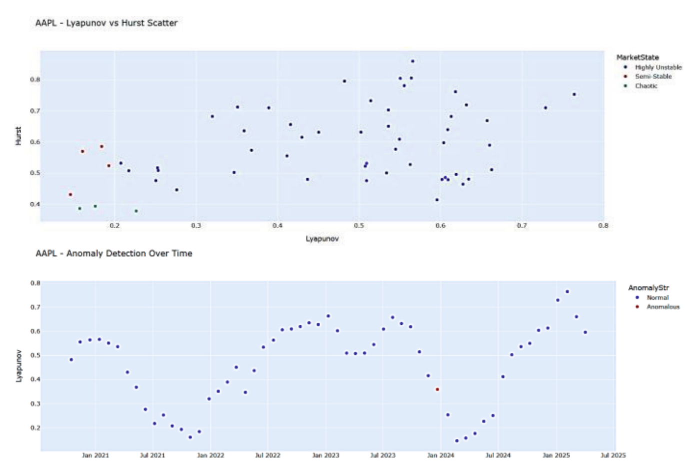


Figure 5. *Lyapunov vs Hurst Scatter and Anomaly Detection over Time for Apple Inc.*

The following images show the results for Microsoft. (Figure 6, Figure 7, Figure 8, Figure 9 and Figure 10).

	Time	Lyapunov	CorrDim	ApproxEntropy	Hurst	LorenzDist	Anomaly	AnomalyStr	MarketState	AnomalyNum
0	2020-10-16	0.984298	-2.682017	0.570056	0.585099	457.082478	False	Normal	Highly Unstable	0
1	2020-11-13	0.998497	-2.701199	0.611944	0.593761	457.082478	False	Normal	Highly Unstable	0
2	2020-12-14	0.920346	-2.515469	0.570249	0.648166	457.082478	False	Normal	Highly Unstable	0
3	2021-01-13	0.751093	-2.764224	0.675680	0.661012	457.082478	False	Normal	Highly Unstable	0
4	2021-02-11	0.689698	-2.934167	0.724048	0.598357	457.082478	False	Normal	Highly Unstable	0
5	2021-03-12	0.701985	-3.142494	0.804076	0.533935	457.082478	False	Normal	Highly Unstable	0
6	2021-04-12	0.650608	-3.194793	0.825943	0.484882	457.082478	False	Normal	Highly Unstable	0
7	2021-05-10	0.712619	-2.921089	0.729886	0.474338	457.082478	False	Normal	Highly Unstable	0
8	2021-06-08	0.733561	-2.964718	0.689436	0.517207	457.082478	True	Anomalous	Highly Unstable	1
9	2021-07-07	0.767630	-2.710929	0.530177	0.613295	457.082478	False	Normal	Highly Unstable	0
10	2021-08-04	0.799445	-2.491629	0.436138	0.671190	457.082478	False	Normal	Highly Unstable	0
11	2021-09-01	0.853220	-2.432409	0.338486	0.738178	457.082478	False	Normal	Highly Unstable	0
12	2021-09-30	0.901489	-2.485607	0.356349	0.736367	457.082478	False	Normal	Highly Unstable	0
13	2021-10-28	0.915244	-2.460702	0.366667	0.752828	457.082478	False	Normal	Highly Unstable	0
14	2021-11-26	0.951830	-2.327647	0.285807	0.740972	457.082478	False	Normal	Highly Unstable	0
15	2021-12-27	0.998164	-2.353089	0.302287	0.794351	457.082478	False	Normal	Highly Unstable	0
16	2022-01-25	0.988753	-2.450215	0.384786	0.730161	457.082478	False	Normal	Highly Unstable	0
17	2022-02-23	1.037871	-2.599981	0.502917	0.708916	457.082478	False	Normal	Highly Unstable	0
18	2022-03-23	0.981474	-2.900877	0.646844	0.619015	457.082478	False	Normal	Highly Unstable	0
19	2022-04-21	0.894979	-3.145974	0.848138	0.456487	457.082478	False	Normal	Highly Unstable	0
20	2022-05-19	1.019042	-3.141336	0.779832	0.482120	457.082478	False	Normal	Highly Unstable	0
21	2022-06-17	1.143725	-3.066691	0.701566	0.555545	457.082478	False	Normal	Highly Unstable	0
22	2022-07-19	1.195809	-3.074235	0.707257	0.544714	457.082478	False	Normal	Highly Unstable	0
23	2022-08-16	1.216830	-3.041253	0.719884	0.553879	457.082478	False	Normal	Highly Unstable	0
24	2022-09-14	1.225081	-3.286753	0.765167	0.505864	457.082478	False	Normal	Highly Unstable	0
25	2022-10-12	1.226230	-3.320770	0.755602	0.538620	457.082478	False	Normal	Highly Unstable	0
26	2022-11-09	1.234830	-3.442801	0.778267	0.516192	457.082478	False	Normal	Highly Unstable	0
27	2022-12-08	1.210647	-3.460152	0.769982	0.542845	457.082478	False	Normal	Highly Unstable	0
28	2023-01-09	1.162100	-3.354552	0.758508	0.555709	457.082478	False	Normal	Highly Unstable	0
29	2023-02-07	1.049384	-3.594479	0.843838	0.459868	457.082478	False	Normal	Highly Unstable	0
30	2023-03-08	0.993462	-3.650621	0.869896	0.472113	457.082478	False	Normal	Highly Unstable	0
31	2023-04-05	1.003873	-3.466536	0.859058	0.496799	457.082478	False	Normal	Highly Unstable	0
32	2023-05-04	1.074886	-3.141336	0.742662	0.514793	457.082478	True	Anomalous	Highly Unstable	1
33	2023-06-02	1.149076	-2.682748	0.625510	0.607650	457.082478	False	Normal	Highly Unstable	0
34	2023-07-03	1.202703	-2.321513	0.489533	0.699241	457.082478	False	Normal	Highly Unstable	0
35	2023-08-01	1.290793	-2.340547	0.422638	0.723780	457.082478	False	Normal	Highly Unstable	0
36	2023-08-29	1.250200	-2.336918	0.395311	0.746010	457.082478	False	Normal	Highly Unstable	0
37	2023-09-27	1.265569	-2.299340	0.386631	0.736183	457.082478	False	Normal	Highly Unstable	0
38	2023-10-25	1.204165	-2.250704	0.432721	0.750561	457.082478	False	Normal	Highly Unstable	0
39	2023-11-22	1.202694	-2.340027	0.452886	0.747497	457.082478	False	Normal	Highly Unstable	0
40	2023-12-21	1.175137	-2.416034	0.454924	0.765458	457.082478	False	Normal	Highly Unstable	0
41	2024-01-23	1.111447	-2.441560	0.470068	0.714646	457.082478	False	Normal	Highly Unstable	0
42	2024-02-21	1.124517	-2.311374	0.468566	0.630300	457.082478	False	Normal	Highly Unstable	0
43	2024-03-20	1.130141	-2.206139	0.437044	0.656068	457.082478	False	Normal	Highly Unstable	0
44	2024-04-18	1.173874	-2.182804	0.366677	0.682638	457.082478	False	Normal	Highly Unstable	0
45	2024-05-16	1.146041	-2.120889	0.348884	0.706774	457.082478	False	Normal	Highly Unstable	0
46	2024-06-14	1.148405	-2.200254	0.380316	0.712386	457.082478	True	Anomalous	Highly Unstable	1
47	2024-07-16	1.253697	-2.283518	0.382470	0.759977	457.082478	False	Normal	Highly Unstable	0
48	2024-08-13	1.234615	-2.610130	0.519382	0.753948	457.082478	False	Normal	Highly Unstable	0
49	2024-09-11	1.085106	-2.881065	0.676735	0.601865	457.082478	False	Normal	Highly Unstable	0
50	2024-10-09	1.087597	-3.270827	0.823788	0.561699	457.082478	False	Normal	Highly Unstable	0
51	2024-11-06	0.974305	-3.631554	0.902828	0.461063	457.082478	False	Normal	Highly Unstable	0
52	2024-12-05	0.949707	-3.612845	0.933565	0.468615	457.082478	False	Normal	Highly Unstable	0
53	2025-01-06	0.972903	-3.587226	0.878578	0.460124	457.082478	False	Normal	Highly Unstable	0
54	2025-02-05	1.010847	-3.609144	0.862471	0.439534	457.082478	False	Normal	Highly Unstable	0
55	2025-03-06	0.988234	-3.529315	0.849170	0.426025	457.082478	False	Normal	Highly Unstable	0
56	2025-04-03	1.111512	-3.280087	0.797710	0.476636	457.082478	False	Normal	Highly Unstable	0

Figure 6. *Summary of Quantitative Data for Microsoft Inc.*

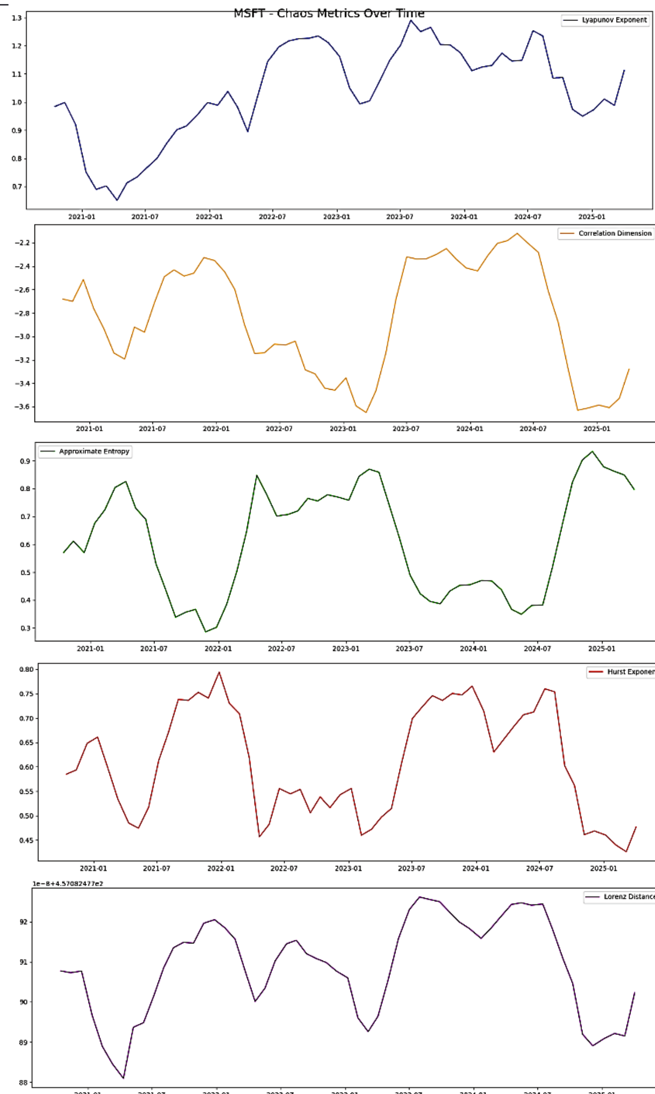


Figure 9. *Chaos Metrics Over Time*

Figure 7. *Evaluation of Market State*

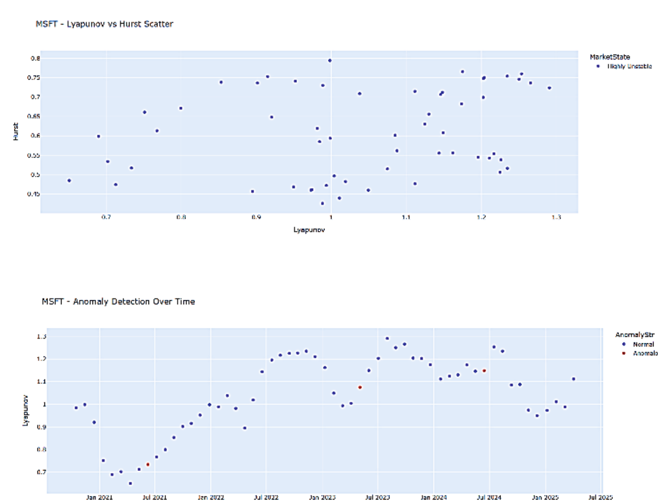


Figure 10. *Lyapunov vs Hurst Scatter and Anomaly Detection over Time for Microsoft Inc.*

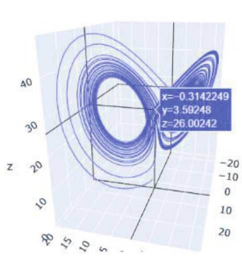


Figure 8. *Lorenz Attractor Reference*

The following images show the results for Google
(Figure 11, Figure 12, Figure 13, Figure 14 and Figure 15)

	Time	Lyapunov	CorrDim	ApproxEntropy	Hurst	LorenzDist	Anomaly	AnomalyStr	MarketState	AnomalyNum
0	2020-10-16	-0.182609	-2.651788	0.613614	0.596597	457.082478	True	Anomalous	Stable	1
1	2020-11-13	-0.059585	-2.704930	0.601382	0.603933	457.082478	False	Normal	Stable	0
2	2020-12-14	-0.000017	-2.569485	0.499421	0.669283	457.082478	False	Normal	Stable	0
3	2021-01-13	-0.134693	-2.463047	0.461234	0.763910	457.082478	False	Normal	Highly Predictable	0
4	2021-02-11	-0.142109	-2.365791	0.458772	0.723040	457.082478	False	Normal	Highly Predictable	0
5	2021-03-12	-0.139782	-2.173972	0.407186	0.689217	457.082478	False	Normal	Stable	0
6	2021-04-12	-0.066037	-2.132210	0.393831	0.730600	457.082478	False	Normal	Highly Predictable	0
7	2021-05-10	0.035418	-2.110107	0.326000	0.750482	457.082478	False	Normal	Highly Predictable	0
8	2021-06-08	0.082162	-2.147935	0.309625	0.798282	457.082478	False	Normal	Highly Unstable	0
9	2021-07-07	0.056863	-2.085258	0.251369	0.854776	457.082478	False	Normal	Highly Unstable	0
10	2021-08-04	0.110805	-2.104349	0.269326	0.856547	457.082478	False	Normal	Highly Unstable	0
11	2021-09-01	0.116805	-2.115483	0.229827	0.839183	457.082478	False	Normal	Highly Unstable	0
12	2021-09-30	0.167918	-2.207957	0.242523	0.858604	457.082478	False	Normal	Highly Unstable	0
13	2021-10-28	0.214939	-2.232360	0.299093	0.845996	457.082478	False	Normal	Highly Unstable	0
14	2021-11-26	0.184622	-2.324064	0.332202	0.762957	457.082478	False	Normal	Highly Unstable	0
15	2021-12-27	0.163780	-2.384066	0.382658	0.777386	457.082478	False	Normal	Highly Unstable	0
16	2022-01-25	0.121765	-2.553293	0.524687	0.696196	457.082478	False	Normal	Highly Unstable	0
17	2022-02-23	0.154113	-2.840011	0.642973	0.653592	457.082478	False	Normal	Highly Unstable	0
18	2022-03-23	0.089488	-3.270827	0.816995	0.481072	457.082478	True	Anomalous	Semi-Stable	1
19	2022-04-21	0.077146	-3.660292	0.936535	0.386691	457.082478	False	Normal	Highly Unstable	0
20	2022-05-19	0.209986	-3.142494	0.817436	0.413630	457.082478	False	Normal	Highly Unstable	0
21	2022-06-17	0.344420	-2.794834	0.698093	0.567227	457.082478	False	Normal	Highly Unstable	0
22	2022-07-19	0.409899	-2.829794	0.687636	0.564703	457.082478	False	Normal	Highly Unstable	0
23	2022-08-16	0.452461	-2.812161	0.687805	0.546816	457.082478	False	Normal	Highly Unstable	0
24	2022-09-14	0.452792	-2.938879	0.729222	0.484273	457.082478	False	Normal	Highly Unstable	0
25	2022-10-12	0.522211	-2.946466	0.666497	0.528426	457.082478	False	Normal	Highly Unstable	0
26	2022-11-09	0.579185	-2.898152	0.637696	0.665700	457.082478	False	Normal	Highly Unstable	0
27	2022-12-08	0.519890	-2.847743	0.631685	0.688875	457.082478	False	Normal	Highly Unstable	0
28	2023-01-09	0.463163	-2.794834	0.625324	0.695086	457.082478	False	Normal	Highly Unstable	0
29	2023-02-07	0.346948	-3.180256	0.818538	0.525094	457.082478	False	Normal	Highly Unstable	0
30	2023-03-08	0.329206	-3.249980	0.788630	0.487533	457.082478	False	Normal	Highly Unstable	0
31	2023-04-05	0.307241	-3.278759	0.796629	0.517127	457.082478	False	Normal	Highly Unstable	0
32	2023-05-04	0.246099	-3.318006	0.795554	0.516311	457.082478	False	Normal	Highly Unstable	0
33	2023-06-02	0.253535	-3.129835	0.706110	0.535106	457.082478	False	Normal	Highly Unstable	0
34	2023-07-03	0.205169	-2.748482	0.639636	0.576441	457.082478	False	Normal	Highly Unstable	0
35	2023-08-01	0.278019	-2.619010	0.580356	0.596976	457.082478	False	Normal	Highly Unstable	0
36	2023-08-29	0.281827	-2.453699	0.476480	0.603628	457.082478	False	Normal	Highly Unstable	0
37	2023-09-27	0.331250	-2.361539	0.388317	0.669029	457.082478	False	Normal	Highly Unstable	0
38	2023-10-25	0.326804	-2.362601	0.396910	0.685439	457.082478	False	Normal	Highly Unstable	0
39	2023-11-22	0.269494	-2.330727	0.411866	0.709583	457.082478	False	Normal	Highly Unstable	0
40	2023-12-21	0.197467	-2.416034	0.512175	0.703935	457.082478	False	Normal	Highly Unstable	0
41	2024-01-23	0.151185	-2.666069	0.606219	0.587683	457.082478	False	Normal	Semi-Stable	0
42	2024-02-21	0.228705	-3.005278	0.685771	0.596969	457.082478	False	Normal	Highly Unstable	0
43	2024-03-20	0.167769	-3.274785	0.769261	0.514490	457.082478	False	Normal	Semi-Stable	0
44	2024-04-18	0.235623	-3.061338	0.718282	0.513846	457.082478	False	Normal	Highly Unstable	0
45	2024-05-16	0.288483	-2.626585	0.602744	0.513137	457.082478	False	Normal	Highly Unstable	0
46	2024-06-14	0.361842	-2.321513	0.436115	0.588431	457.082478	False	Normal	Highly Unstable	0
47	2024-07-16	0.508250	-2.283028	0.371844	0.662423	457.082478	False	Normal	Highly Unstable	0
48	2024-08-13	0.599238	-2.512381	0.399950	0.688089	457.082478	False	Normal	Highly Unstable	0
49	2024-09-11	0.594113	-2.729146	0.483335	0.634388	457.082478	False	Normal	Highly Unstable	0
50	2024-10-09	0.550892	-2.836594	0.559799	0.625188	457.082478	False	Normal	Highly Unstable	0
51	2024-11-06	0.535919	-2.830642	0.582920	0.624950	457.082478	False	Normal	Highly Unstable	0
52	2024-12-05	0.522234	-2.866021	0.606662	0.652309	457.082478	False	Normal	Highly Unstable	0
53	2025-01-06	0.475645	-3.026707	0.663895	0.521930	457.082478	False	Normal	Highly Unstable	0
54	2025-02-05	0.523574	-2.869540	0.618642	0.567705	457.082478	False	Normal	Highly Unstable	0
55	2025-03-06	0.544741	-3.011354	0.684325	0.584754	457.082478	False	Normal	Highly Unstable	0
56	2025-04-03	0.582570	-2.946466	0.698706	0.577857	457.082478	False	Normal	Highly Unstable	0

Figure 11. *Summary of Quantitative Data for Google Inc.*

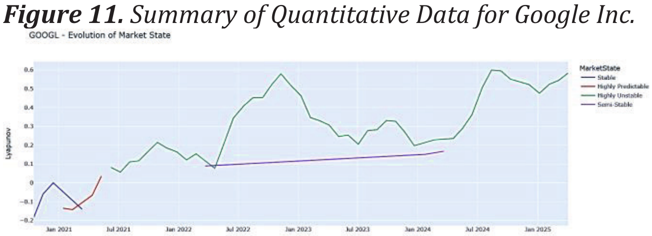


Figure 12. *Evaluation of Market State*

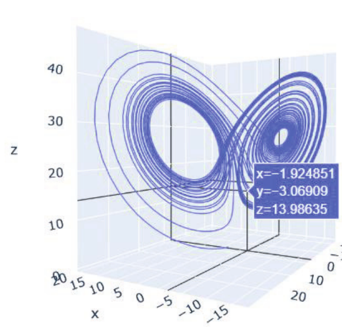


Figure 13. *Lorenz Attractor Reference*

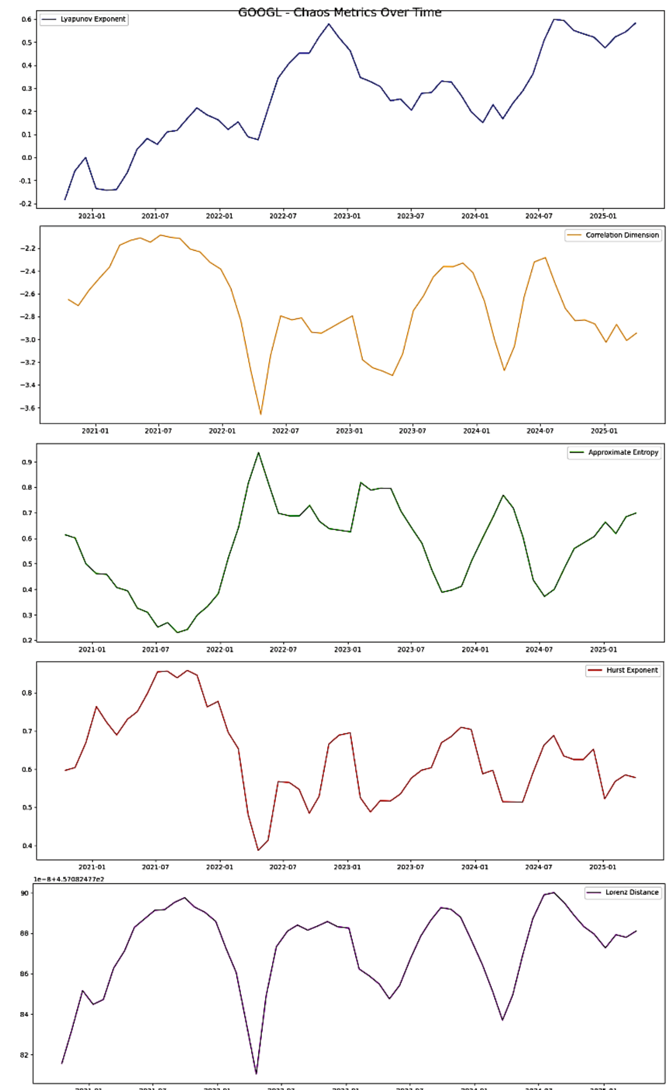


Figure 14. *Chaos Metrics Over Time*

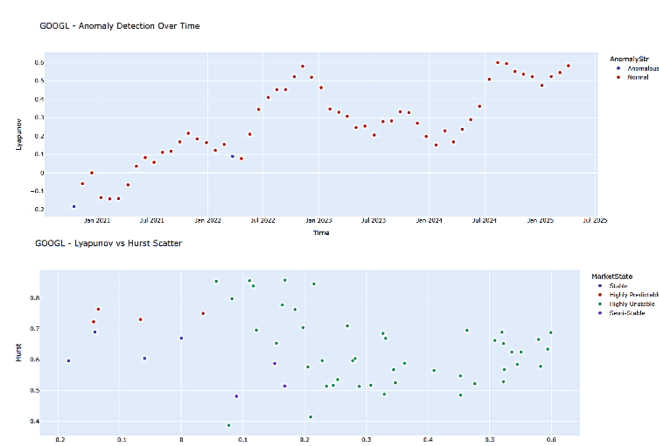


Figure 15. *Lyapunov vs Hurst Scatter and Anomaly Detection over Time for Google Inc.*

The following images show the results for Nvidia (Figure 16, Figure 17, Figure 18, Figure 19 and Figure 20).

Figure 16. *Summary of Quantitative Data for Nvidia Inc.*

	Time	Lyapunov	CorrDim	ApproxEntropy	Hurst	LorenzDist	Anomaly	AnomalyStr	MarketState	AnomalyNum
0	2020-10-16	-1.516418	-2.228638	0.308307	0.809663	457.082478	False	Normal	Highly Predictable	0
1	2020-11-13	-1.414973	-2.367390	0.356006	0.812027	457.082478	True	Anomalous	Highly Predictable	1
2	2020-12-14	-1.454680	-2.300338	0.339900	0.860766	457.082478	False	Normal	Highly Predictable	0
3	2021-01-13	-1.595619	-2.158701	0.348882	0.855196	457.082478	False	Normal	Highly Predictable	0
4	2021-02-11	-1.679495	-2.162606	0.441890	0.785348	457.082478	False	Normal	Highly Predictable	0
5	2021-03-12	-1.667840	-2.483807	0.583033	0.676208	457.082477	False	Normal	Stable	0
6	2021-04-12	-1.728801	-2.844300	0.751239	0.621360	457.082477	False	Normal	Stable	0
7	2021-05-10	-1.704675	-3.220753	0.798819	0.530165	457.082477	False	Normal	Stable	0
8	2021-06-08	-1.727176	-3.350267	0.814043	0.460051	457.082477	False	Normal	Highly Unstable	0
9	2021-07-07	-1.593036	-2.284009	0.627728	0.578418	457.082477	False	Normal	Stable	0
10	2021-08-04	-1.509227	-1.996020	0.479614	0.672799	457.082478	False	Normal	Stable	0
11	2021-09-01	-1.396544	-1.907675	0.374701	0.710051	457.082478	False	Normal	Highly Predictable	0
12	2021-09-30	-1.281497	-2.104349	0.365668	0.728695	457.082478	False	Normal	Highly Predictable	0
13	2021-10-28	-1.159940	-2.291398	0.379151	0.746410	457.082478	False	Normal	Highly Predictable	0
14	2021-11-26	-0.942138	-2.128002	0.256859	0.826054	457.082478	False	Normal	Highly Predictable	0
15	2021-12-27	-0.836678	-2.154812	0.289842	0.911811	457.082478	False	Normal	Highly Predictable	0
16	2022-01-25	-0.778259	-2.259765	0.345118	0.843460	457.082478	False	Normal	Highly Predictable	0
17	2022-02-23	-0.703317	-2.454863	0.425344	0.803969	457.082478	False	Normal	Highly Predictable	0
18	2022-03-23	-0.746869	-2.595280	0.574134	0.641656	457.082478	False	Normal	Stable	0
19	2022-04-21	-0.729123	-2.787499	0.674740	0.608298	457.082478	False	Normal	Stable	0
20	2022-05-19	-0.625910	-2.863389	0.684790	0.595312	457.082478	False	Normal	Stable	0
21	2022-06-17	-0.563070	-2.971528	0.694871	0.677859	457.082478	False	Normal	Stable	0
22	2022-07-19	-0.485207	-2.974460	0.603125	0.673475	457.082478	False	Normal	Stable	0
23	2022-08-16	-0.505065	-2.794017	0.584443	0.685261	457.082478	False	Normal	Stable	0
24	2022-09-14	-0.517700	-2.708675	0.553452	0.705523	457.082478	False	Normal	Highly Predictable	0
25	2022-10-12	-0.600521	-2.714697	0.517693	0.706714	457.082478	False	Normal	Highly Predictable	0
26	2022-11-09	-0.685207	-2.704930	0.566237	0.751550	457.082478	False	Normal	Highly Predictable	0
27	2022-12-08	-0.765018	-2.691562	0.583979	0.768341	457.082478	False	Normal	Highly Predictable	0
28	2023-01-09	-0.879903	-2.797291	0.640982	0.771222	457.082478	False	Normal	Highly Predictable	0
29	2023-02-07	-1.026633	-3.502400	0.816050	0.592316	457.082478	False	Normal	Stable	0
30	2023-03-08	-0.939866	-3.075317	0.703573	0.620882	457.082478	False	Normal	Stable	0
31	2023-04-05	-0.822256	-2.602002	0.502234	0.738440	457.082478	False	Normal	Highly Predictable	0
32	2023-05-04	-0.785178	-2.378657	0.413399	0.807818	457.082478	False	Normal	Highly Predictable	0
33	2023-06-02	-0.630976	-2.136012	0.291772	0.882697	457.082478	False	Normal	Highly Predictable	0
34	2023-07-03	-0.516774	-2.018346	0.196828	1.007162	457.082478	False	Normal	Highly Predictable	0
35	2023-08-01	-0.389524	-2.032749	0.174074	1.038478	457.082478	False	Normal	Highly Predictable	0
36	2023-08-29	-0.383713	-1.990881	0.205969	0.960089	457.082478	False	Normal	Highly Predictable	0
37	2023-09-27	-0.310675	-2.079242	0.226382	0.959896	457.082478	False	Normal	Highly Predictable	0
38	2023-10-25	-0.347659	-1.999337	0.261049	0.942420	457.082478	False	Normal	Highly Predictable	0
39	2023-11-22	-0.420166	-2.013467	0.302969	0.819668	457.082478	False	Normal	Highly Predictable	0
40	2023-12-21	-0.457298	-2.059835	0.353011	0.748656	457.082478	True	Anomalous	Highly Predictable	1
41	2024-01-23	-0.405623	-2.207048	0.414193	0.733788	457.082478	False	Normal	Highly Predictable	0
42	2024-02-21	-0.248144	-2.028939	0.339522	0.780970	457.082478	False	Normal	Highly Predictable	0
43	2024-03-20	-0.132551	-1.558388	0.240259	0.799397	457.082478	False	Normal	Highly Predictable	0
44	2024-04-18	-0.053887	-1.434960	0.206091	0.804113	457.082478	False	Normal	Highly Predictable	0
45	2024-05-16	0.094609	-1.595905	0.237021	0.791629	457.082478	False	Normal	Highly Unstable	0
46	2024-06-14	0.315525	-1.691326	0.193055	0.858122	457.082478	False	Normal	Highly Unstable	0
47	2024-07-16	0.512795	-1.828683	0.195648	0.956868	457.082478	False	Normal	Highly Unstable	0
48	2024-08-13	0.667430	-2.092527	0.272431	0.972230	457.082478	False	Normal	Highly Unstable	0
49	2024-09-11	0.731216	-2.273755	0.349229	0.898762	457.082478	True	Anomalous	Highly Unstable	1
50	2024-10-09	0.811011	-2.437546	0.426100	0.812334	457.082478	False	Normal	Highly Unstable	0
51	2024-11-06	0.852775	-2.583954	0.537027	0.735074	457.082478	False	Normal	Highly Unstable	0
52	2024-12-05	0.823278	-2.671116	0.589112	0.704049	457.082478	False	Normal	Highly Unstable	0
53	2025-01-06	0.820588	-2.863389	0.656433	0.662118	457.082478	True	Anomalous	Highly Unstable	1
54	2025-02-05	0.859735	-3.165928	0.711092	0.630640	457.082478	False	Normal	Highly Unstable	0
55	2025-03-06	0.752239	-3.718308	0.924913	0.426672	457.082478	False	Normal	Highly Unstable	0
56	2025-04-03	0.716767	-3.831596	0.914636	0.404473	457.082478	False	Normal	Highly Unstable	0

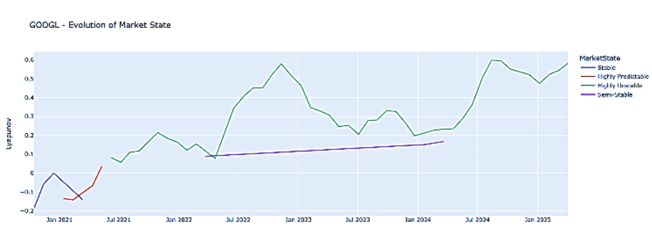


Figure 17. *Evaluation of Market State*

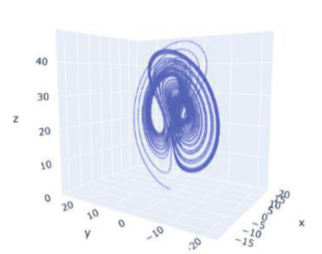


Figure 18. *Lorenz Attractor Reference*

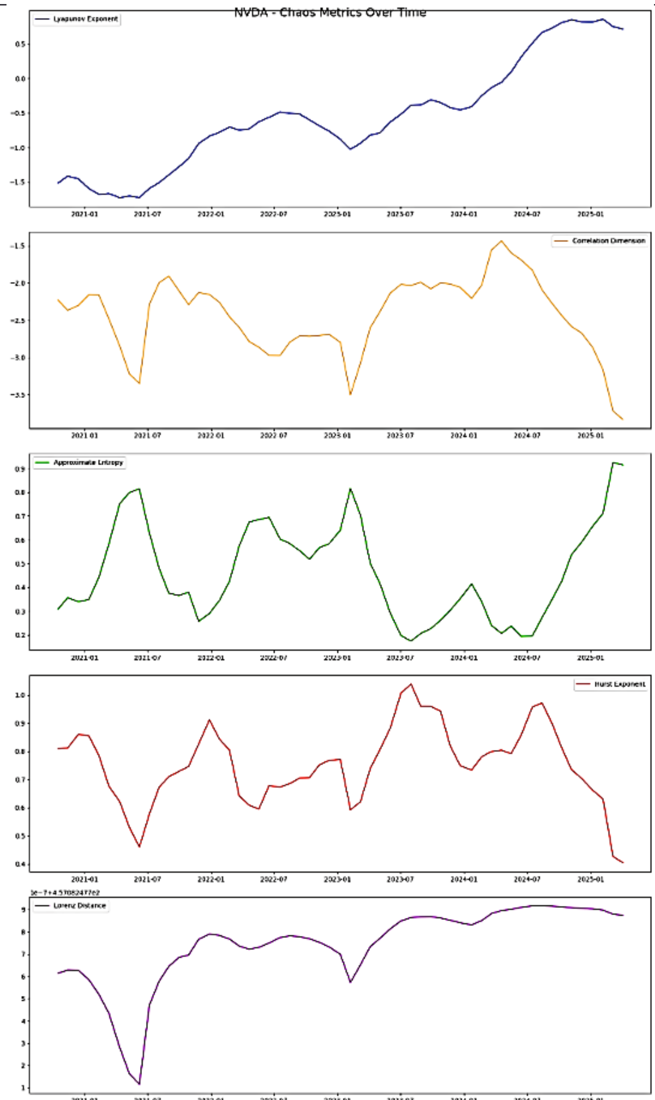


Figure 19. *Chaos Metrics Over Time*

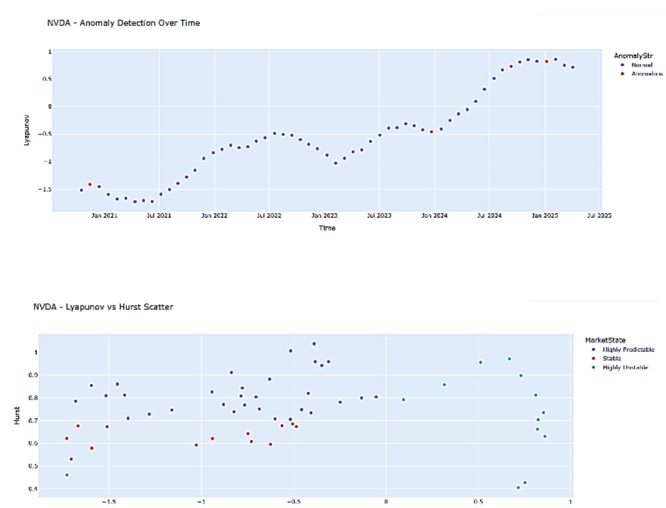


Figure 20. *Lyapunov vs Hurst Scatter and Anomaly Detection over Time for Nvidia Inc.*

The following images show the results for Intel. (Figure 21, Figure 22, Figure 23, Figure 24 and Figure 25).

	Time	Lyapunov	CorrDim	ApproxEntropy	Hurst	LorenzDist	Anomaly	AnomalyStr	MarketState	AnomalyNum
0	2020-10-16	-0.424003	-2.617638	0.615296	0.461965	457.082478	False	Normal	Highly Unstable	0
1	2020-11-13	-0.365253	-2.736064	0.603725	0.433928	457.082478	False	Normal	Highly Unstable	0
2	2020-12-14	-0.463912	-2.774591	0.586408	0.421324	457.082478	False	Normal	Highly Unstable	0
3	2021-01-13	-0.594427	-2.634219	0.593924	0.531664	457.082478	False	Normal	Stable	0
4	2021-02-11	-0.564841	-2.619010	0.543420	0.527267	457.082478	False	Normal	Stable	0
5	2021-03-12	-0.527621	-2.586607	0.549392	0.524231	457.082478	True	Anomalous	Stable	1
6	2021-04-12	-0.416762	-2.516707	0.482089	0.569540	457.082478	False	Normal	Stable	0
7	2021-05-10	-0.398117	-2.498904	0.485706	0.573017	457.082478	False	Normal	Stable	0
8	2021-06-08	-0.406062	-2.683480	0.513295	0.586593	457.082478	False	Normal	Stable	0
9	2021-07-07	-0.408022	-2.665350	0.532976	0.606203	457.082478	False	Normal	Stable	0
10	2021-08-04	-0.442134	-2.571445	0.551102	0.617262	457.082478	False	Normal	Stable	0
11	2021-09-01	-0.520105	-2.708675	0.566299	0.647833	457.082478	False	Normal	Stable	0
12	2021-09-30	-0.616904	-2.723037	0.632206	0.630392	457.082478	False	Normal	Stable	0
13	2021-10-28	-0.765735	-2.691562	0.652661	0.543662	457.082478	False	Normal	Stable	0
14	2021-11-26	-0.751226	-2.534832	0.562709	0.599812	457.082478	True	Anomalous	Stable	1
15	2021-12-27	-0.837840	-2.468935	0.585456	0.661675	457.082478	False	Normal	Stable	0
16	2022-01-25	-0.964396	-2.917383	0.750904	0.592964	457.082478	False	Normal	Stable	0
17	2022-02-23	-0.999443	-3.207071	0.789703	0.438736	457.082478	False	Normal	Highly Unstable	0
18	2022-03-23	-0.931909	-3.070995	0.796941	0.434188	457.082478	False	Normal	Highly Unstable	0
19	2022-04-21	-0.940983	-3.170681	0.811346	0.437230	457.082478	False	Normal	Highly Unstable	0
20	2022-05-19	-0.872867	-3.125272	0.764032	0.457901	457.082478	True	Anomalous	Highly Unstable	[illegible]
21	2022-06-17	-0.692758	-3.140180	0.752035	0.522622	457.082478	False	Normal	Stable	0
22	2022-07-19	-0.643413	-2.867779	0.674460	0.581415	457.082478	False	Normal	Stable	0
23	2022-08-16	-0.566535	-2.794834	0.643715	0.634148	457.082478	False	Normal	Stable	0
24	2022-09-14	-0.446042	-2.654628	0.579863	0.719178	457.082478	False	Normal	Highly Predictable	0
25	2022-10-12	-0.387693	-2.470117	0.427490	0.831444	457.082478	False	Normal	Highly Predictable	0
26	2022-11-09	-0.444529	-2.355722	0.407808	0.819190	457.082478	False	Normal	Highly Predictable	0
27	2022-12-08	-0.428713	-2.419400	0.374112	0.803202	457.082478	False	Normal	Highly Predictable	0
28	2023-01-09	-0.469132	-2.305339	0.347555	0.796780	457.082478	False	Normal	Highly Predictable	0
29	2023-02-07	-0.602910	-2.338471	0.471399	0.721487	457.082478	False	Normal	Highly Predictable	0
30	2023-03-08	-0.730077	-2.380276	0.498318	0.699116	457.082478	False	Normal	Stable	0
31	2023-04-05	-0.845793	-2.656051	0.639010	0.617885	457.082478	False	Normal	Stable	0
32	2023-05-04	-0.895849	-2.910013	0.682810	0.574831	457.082478	False	Normal	Stable	0
33	2023-06-02	-1.016584	-3.509061	0.845107	0.461520	457.082478	False	Normal	Highly Unstable	0
34	2023-07-03	-0.961298	-3.455390	0.794541	0.433807	457.082478	False	Normal	Highly Unstable	0
35	2023-08-01	-0.903960	-3.296162	0.768781	0.454380	457.082478	False	Normal	Highly Unstable	0
36	2023-08-29	-0.878629	-3.297513	0.769799	0.509466	457.082478	False	Normal	Stable	0
37	2023-09-27	-0.777034	-3.135569	0.713737	0.535082	457.082478	False	Normal	Stable	0
38	2023-10-25	-0.784289	-3.194793	0.722738	0.528052	457.082478	False	Normal	Stable	0
39	2023-11-22	-0.687330	-3.036034	0.665085	0.608918	457.082478	False	Normal	Stable	0
40	2023-12-21	-0.653755	-2.729146	0.546010	0.601356	457.082478	False	Normal	Stable	0
41	2024-01-23	-0.577596	-2.445590	0.482891	0.656050	457.082478	False	Normal	Stable	0
42	2024-02-21	-0.529785	-2.458362	0.506553	0.704824	457.082478	False	Normal	Highly Predictable	0
43	2024-03-20	-0.595460	-2.503784	0.522454	0.616056	457.082478	False	Normal	Stable	0
44	2024-04-18	-0.592923	-2.623135	0.545294	0.584867	457.082478	False	Normal	Stable	0
45	2024-05-16	-0.556113	-2.593941	0.488096	0.593260	457.082478	False	Normal	Stable	0
46	2024-06-14	-0.601854	-2.489216	0.476642	0.626265	457.082478	False	Normal	Stable	0
47	2024-07-16	-0.653104	-2.246914	0.432172	0.679632	457.082478	False	Normal	Stable	0
48	2024-08-13	-0.561591	-2.060620	0.385987	0.791299	457.082478	False	Normal	Highly Predictable	0
49	2024-09-11	-0.584276	-1.879771	0.280834	0.865620	457.082478	False	Normal	Highly Predictable	0
50	2024-10-09	-0.563648	-1.929471	0.244977	0.880438	457.082478	False	Normal	Highly Predictable	0
51	2024-11-06	-0.682677	-1.867723	0.228437	0.853912	457.082478	False	Normal	Highly Predictable	0
52	2024-12-05	-0.653207	-1.998599	0.283282	0.807598	457.082478	False	Normal	Highly Predictable	0
53	2025-01-06	-0.727740	-1.968437	0.294853	0.788419	457.082478	False	Normal	Highly Predictable	0
54	2025-02-05	-0.947497	-1.985769	0.392914	0.606146	457.082478	False	Normal	Stable	0
55	2025-03-06	-0.896578	-2.165653	0.472528	0.575898	457.082478	False	Normal	Stable	0
56	2025-04-03	-0.901776	-2.341066	0.555140	0.531655	457.082478	False	Normal	Stable	0

Figure 21. Summary of Quantitative Data for Intel Inc.

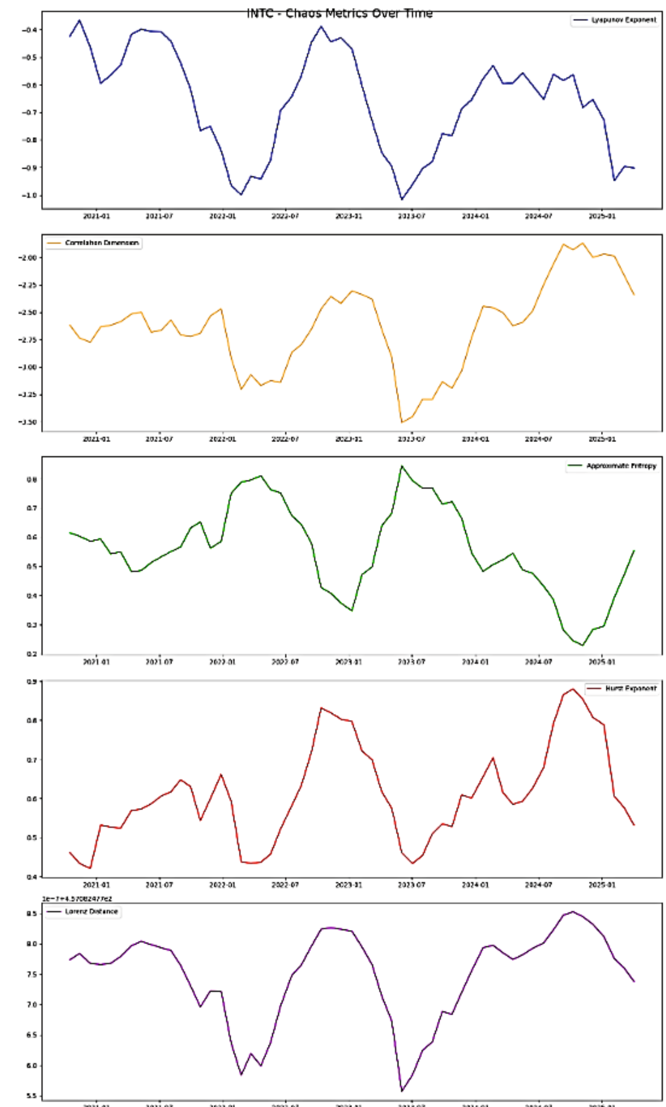


Figure 24. Chaos Metrics Over Time

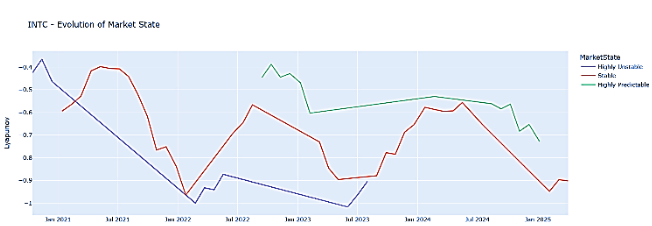


Figure 22. Evaluation of Market State

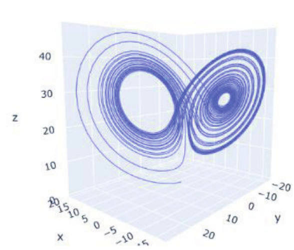


Figure 23. Lorenz Attractor Reference

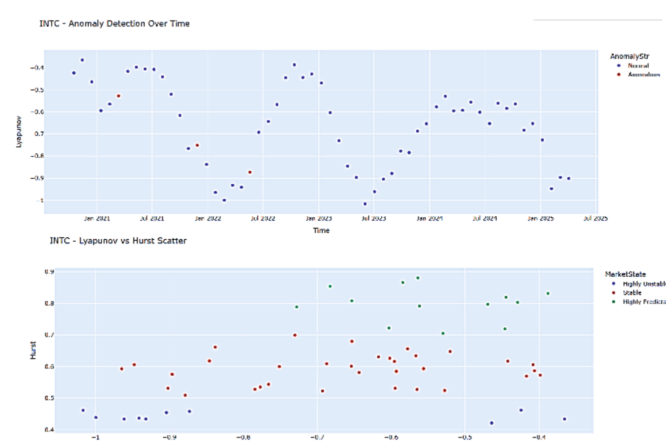


Figure 25. Lyapunov vs Hurst Scatter and Anomaly Detection over Time for Intel Inc.

The following images show the results for AMD (Figure 26, Figure 27, Figure 28, Figure 29 and Figure 30).

	Time	Lyapunov	CorrDim	ApproxEntropy	Hurst	LorenzDist	Anomaly	AnomalyStr	MarketState	AnomalyNum
0	2020-10-16	0.176849	-1.951400	0.438279	0.720629	457.082478	False	Normal	Highly Unstable	0
1	2020-11-13	0.218665	-1.988687	0.449416	0.724621	457.082478	False	Normal	Highly Unstable	0
2	2020-12-14	0.243738	-1.949642	0.398342	0.755767	457.082478	False	Normal	Highly Unstable	0
3	2021-01-13	0.180407	-1.913419	0.378247	0.779190	457.082478	False	Normal	Highly Unstable	0
4	2021-02-11	0.153969	-2.042724	0.443036	0.711267	457.082478	True	Anomalous	Highly Unstable	1
5	2021-03-12	0.191980	-2.332787	0.543326	0.697491	457.082478	False	Normal	Highly Unstable	0
6	2021-04-12	0.190319	-2.724561	0.696761	0.690294	457.082478	False	Normal	Highly Unstable	0
7	2021-05-10	0.040092	-3.712148	0.994198	0.566160	457.082478	False	Normal	Stable	0
8	2021-06-08	-0.002978	-3.820128	0.972819	0.378845	457.082478	False	Normal	Highly Unstable	0
9	2021-07-07	0.010259	-3.699940	0.934923	0.402972	457.082478	False	Normal	Highly Unstable	0
10	2021-08-04	0.083236	-3.450650	0.911282	0.516723	457.082478	False	Normal	Stable	0
11	2021-09-01	0.197064	-2.902697	0.723193	0.559688	457.082478	False	Normal	Semi-Stable	0
12	2021-09-30	0.265213	-2.770591	0.642122	0.630091	457.082478	False	Normal	Highly Unstable	0
13	2021-10-28	0.333767	-2.570138	0.544785	0.628131	457.082478	False	Normal	Highly Unstable	0
14	2021-11-26	0.521893	-1.942989	0.340646	0.679325	457.082478	False	Normal	Highly Unstable	0
15	2021-12-27	0.644571	-1.925691	0.336109	0.803188	457.082478	False	Normal	Highly Unstable	0
16	2022-01-25	0.766190	-2.187695	0.388629	0.793845	457.082478	False	Normal	Highly Unstable	0
17	2022-02-23	0.856774	-2.515469	0.493196	0.739579	457.082478	True	Anomalous	Highly Unstable	1
18	2022-03-23	0.884431	-2.695257	0.624405	0.666217	457.082478	False	Normal	Highly Unstable	0
19	2022-04-21	0.864215	-2.805525	0.714236	0.626454	457.082478	False	Normal	Highly Unstable	0
20	2022-05-19	0.917769	-2.839156	0.731082	0.570943	457.082478	False	Normal	Highly Unstable	0
21	2022-06-17	0.948981	-2.959883	0.768234	0.600836	457.082478	False	Normal	Highly Unstable	0
22	2022-07-19	1.077480	-3.062406	0.678418	0.595465	457.082478	False	Normal	Highly Unstable	0
23	2022-08-16	1.088351	-3.034993	0.676996	0.636597	457.082478	False	Normal	Highly Unstable	0
24	2022-09-14	1.024662	-2.953152	0.648532	0.652852	457.082478	False	Normal	Highly Unstable	0
25	2022-10-12	0.976886	-2.983310	0.656688	0.692988	457.082478	False	Normal	Highly Unstable	0
26	2022-11-09	0.830985	-2.981336	0.650294	0.678497	457.082478	False	Normal	Highly Unstable	0
27	2022-12-08	0.781405	-2.970552	0.650256	0.666867	457.082478	False	Normal	Highly Unstable	0
28	2023-01-09	0.694006	-2.958918	0.645611	0.662498	457.082478	False	Normal	Highly Unstable	0
29	2023-02-07	0.592481	-3.084017	0.739124	0.577614	457.082478	False	Normal	Highly Unstable	0
30	2023-03-08	0.534046	-3.044397	0.677939	0.602255	457.082478	False	Normal	Highly Unstable	0
31	2023-04-05	0.458397	-3.026707	0.660494	0.625490	457.082478	False	Normal	Highly Unstable	0
32	2023-05-04	0.465214	-3.051774	0.655494	0.620785	457.082478	False	Normal	Highly Unstable	0
33	2023-06-02	0.545820	-2.827256	0.574684	0.672328	457.082478	False	Normal	Highly Unstable	0
34	2023-07-03	0.622019	-2.564275	0.477691	0.726218	457.082478	False	Normal	Highly Unstable	0
35	2023-08-01	0.665257	-2.608092	0.435005	0.762348	457.082478	False	Normal	Highly Unstable	0
36	2023-08-29	0.668733	-2.687145	0.489260	0.731364	457.082478	False	Normal	Highly Unstable	0
37	2023-09-27	0.646609	-2.775393	0.525743	0.743210	457.082478	False	Normal	Highly Unstable	0
38	2023-10-25	0.602788	-2.958918	0.616665	0.695722	457.082478	False	Normal	Highly Unstable	0
39	2023-11-22	0.518003	-3.135569	0.692610	0.620610	457.082478	False	Normal	Highly Unstable	0
40	2023-12-21	0.544615	-3.113953	0.704346	0.560107	457.082478	False	Normal	Highly Unstable	0
41	2024-01-23	0.684008	-2.701944	0.569824	0.713655	457.082478	False	Normal	Highly Unstable	0
42	2024-02-21	0.738776	-2.242667	0.436919	0.726443	457.082478	False	Normal	Highly Unstable	0
43	2024-03-20	0.901121	-1.946485	0.364200	0.804022	457.082478	False	Normal	Highly Unstable	0
44	2024-04-18	0.928864	-2.033513	0.375662	0.808096	457.082478	False	Normal	Highly Unstable	0
45	2024-05-16	1.014580	-2.282047	0.402971	0.780488	457.082478	False	Normal	Highly Unstable	0
46	2024-06-14	1.029294	-2.474857	0.455833	0.805465	457.082478	False	Normal	Highly Unstable	0
47	2024-07-16	1.059269	-2.627969	0.505484	0.830206	457.082478	False	Normal	Highly Unstable	0
48	2024-08-13	1.075720	-2.904521	0.602173	0.810093	457.082478	False	Normal	Highly Unstable	0
49	2024-09-11	1.008192	-3.177854	0.712621	0.646069	457.082478	False	Normal	Highly Unstable	0
50	2024-10-09	0.945610	-3.393974	0.857893	0.548769	457.082478	False	Normal	Highly Unstable	0
51	2024-11-06	0.937043	-3.374799	0.842884	0.540013	457.082478	True	Anomalous	Highly Unstable	1
52	2024-12-05	0.928364	-3.194793	0.780557	0.549776	457.082478	False	Normal	Highly Unstable	0
53	2025-01-06	0.848236	-3.401447	0.806329	0.500364	457.082478	False	Normal	Highly Unstable	0
54	2025-02-05	0.888949	-3.248691	0.771911	0.559418	457.082478	False	Normal	Highly Unstable	0
55	2025-03-06	0.980338	-2.968604	0.672513	0.646788	457.082478	False	Normal	Highly Unstable	0
56	2025-04-03	1.013504	-2.900877	0.592331	0.666291	457.082478	False	Normal	Highly Unstable	0

Figure 26. *Summary of Quantitative Data for AMD Inc.*

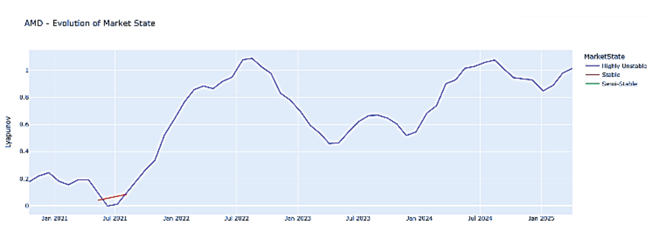


Figure 27. *Evaluation of Market State*

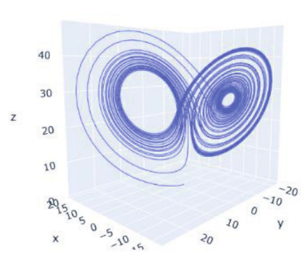


Figure 28. *Lorenz Attractor Reference*

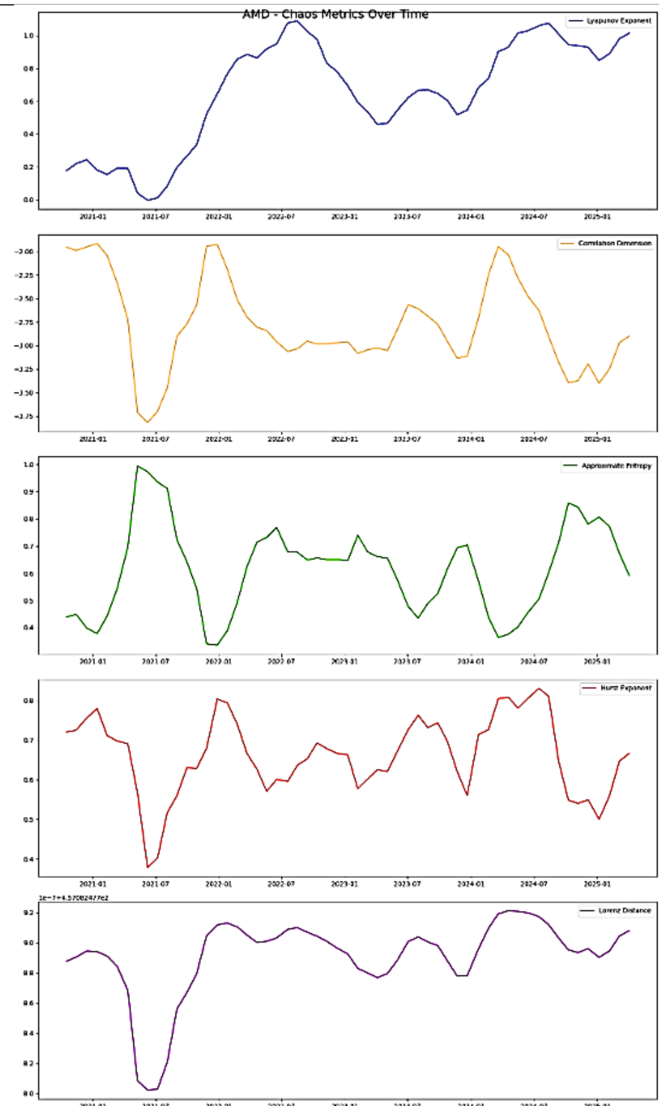
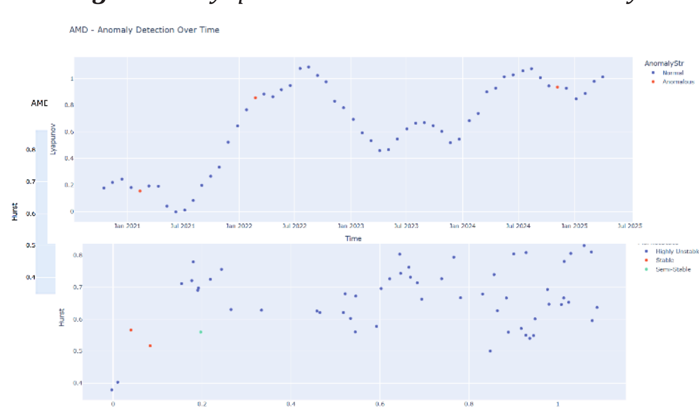


Figure 29. *Chaos Metrics Over Time*

Figure 30. *Lyapunov vs Hurst Scatter and Anomaly*



Detection over Time for AMD Inc.

The following images show the results for IBM. (Figure 31, Figure 32, Figure 33, Figure 34 and Figure 35).

	Time	Lyapunov	CorrDim	ApproxEntropy	Hurst	LorenzDist	Anomaly	AnomalyStr	MarketState	AnomalyNum
0	2020-10-16	0.153679	-2.700454	0.597262	0.571805	457.082478	False	Normal	Semi-Stable	0
1	2020-11-13	0.128770	-2.658189	0.631512	0.563277	457.082478	False	Normal	Semi-Stable	0
2	2020-12-14	-0.041398	-3.239716	0.791168	0.455410	457.082478	False	Normal	Highly Unstable	0
3	2021-01-13	-0.225441	-3.656412	0.903128	0.440570	457.082478	False	Normal	Highly Unstable	0
4	2021-02-11	-0.316814	-3.843197	0.916222	0.421014	457.082478	False	Normal	Highly Unstable	0
5	2021-03-12	-0.363144	-3.683892	0.921194	0.432346	457.082478	False	Normal	Highly Unstable	0
6	2021-04-12	-0.298086	-3.191139	0.807095	0.488751	457.082478	False	Normal	Highly Unstable	0
7	2021-05-10	-0.178667	-2.631436	0.622739	0.614146	457.082478	False	Normal	Stable	0
8	2021-06-08	-0.097929	-2.470117	0.551449	0.642535	457.082478	False	Normal	Stable	0
9	2021-07-07	-0.003700	-2.387871	0.485524	0.662577	457.082478	False	Normal	Stable	0
10	2021-08-04	0.001020	-2.406558	0.451725	0.704835	457.082478	False	Normal	Highly Predictable	0
11	2021-09-01	-0.181811	-2.314405	0.470522	0.627051	457.082478	False	Normal	Stable	0
12	2021-09-30	-0.194880	-2.406003	0.492800	0.626967	457.082478	False	Normal	Stable	0
13	2021-10-28	-0.209556	-2.346276	0.513602	0.579794	457.082478	True	Anomalous	Stable	1
14	2021-11-26	-0.271930	-2.482011	0.554112	0.573701	457.082478	False	Normal	Stable	0
15	2021-12-27	-0.344654	-2.844300	0.705953	0.496209	457.082478	False	Normal	Highly Unstable	0
16	2022-01-25	-0.383218	-2.807180	0.722781	0.449594	457.082478	False	Normal	Highly Unstable	0
17	2022-02-23	-0.395285	-2.846881	0.749306	0.462506	457.082478	False	Normal	Highly Unstable	0
18	2022-03-23	-0.337852	-3.096105	0.768597	0.442861	457.082478	False	Normal	Highly Unstable	0
19	2022-04-21	-0.430032	-3.077485	0.747925	0.410506	457.082478	False	Normal	Highly Unstable	0
20	2022-05-19	-0.293062	-3.147137	0.750554	0.392083	457.082478	False	Normal	Highly Unstable	0
21	2022-06-17	-0.148670	-3.212024	0.734011	0.419143	457.082478	False	Normal	Highly Unstable	0
22	2022-07-19	-0.068802	-3.162377	0.732993	0.414197	457.082478	False	Normal	Highly Unstable	0
23	2022-08-16	-0.076023	-3.220753	0.744571	0.451343	457.082478	False	Normal	Highly Unstable	0
24	2022-09-14	-0.126585	-3.444366	0.820191	0.429584	457.082478	False	Normal	Highly Unstable	0
25	2022-10-12	-0.167279	-3.658350	0.880073	0.376636	457.082478	False	Normal	Highly Unstable	0
26	2022-11-09	-0.120741	-3.664187	0.877068	0.391443	457.082478	False	Normal	Highly Unstable	0
27	2022-12-08	-0.000904	-3.177854	0.735899	0.435350	457.082478	False	Normal	Highly Unstable	0
28	2023-01-09	0.054888	-3.180256	0.729158	0.474707	457.082478	False	Normal	Semi-Stable	0
29	2023-02-07	0.059818	-3.225775	0.714628	0.498568	457.082478	False	Normal	Semi-Stable	0
30	2023-03-08	0.011210	-3.084017	0.684154	0.543982	457.082478	False	Normal	Stable	0
31	2023-04-05	0.008494	-3.065618	0.654464	0.544064	457.082478	True	Anomalous	Stable	1
32	2023-05-04	-0.054229	-2.885533	0.616764	0.576823	457.082478	False	Normal	Stable	0
33	2023-06-02	-0.046828	-2.899059	0.621956	0.563373	457.082478	False	Normal	Stable	0
34	2023-07-03	-0.037136	-2.961814	0.639722	0.541017	457.082478	False	Normal	Stable	0
35	2023-08-01	-0.114753	-3.013387	0.634249	0.559667	457.082478	False	Normal	Stable	0
36	2023-08-29	-0.193135	-2.825568	0.572542	0.499634	457.082478	False	Normal	Highly Unstable	0
37	2023-09-27	-0.117807	-2.732215	0.534254	0.563380	457.082478	False	Normal	Stable	0
38	2023-10-25	-0.139138	-2.685677	0.540017	0.591898	457.082478	False	Normal	Stable	0
39	2023-11-22	-0.065713	-2.533572	0.464027	0.603552	457.082478	False	Normal	Stable	0
40	2023-12-21	0.055764	-2.356250	0.320292	0.658896	457.082478	False	Normal	Stable	0
41	2024-01-23	0.094532	-2.321004	0.266765	0.747753	457.082478	False	Normal	Highly Unstable	0
42	2024-02-21	0.238865	-2.126743	0.209024	0.777966	457.082478	False	Normal	Highly Unstable	0
43	2024-03-20	0.258761	-1.995652	0.206978	0.772725	457.082478	False	Normal	Highly Unstable	0
44	2024-04-18	0.282725	-1.987957	0.209328	0.768171	457.082478	False	Normal	Highly Unstable	0
45	2024-05-16	0.286482	-2.092527	0.257830	0.721351	457.082478	False	Normal	Highly Unstable	0
46	2024-06-14	0.342998	-2.310365	0.289067	0.706929	457.082478	False	Normal	Highly Unstable	0
47	2024-07-16	0.405666	-2.440411	0.342588	0.714432	457.082478	False	Normal	Highly Unstable	0
48	2024-08-13	0.374435	-2.614218	0.432218	0.694211	457.082478	False	Normal	Highly Unstable	0
49	2024-09-11	0.365230	-2.730679	0.510443	0.604165	457.082478	False	Normal	Highly Unstable	0
50	2024-10-09	0.503669	-2.473077	0.403234	0.666040	457.082478	False	Normal	Highly Unstable	0
51	2024-11-06	0.548351	-2.365259	0.380164	0.653058	457.082478	False	Normal	Highly Unstable	0
52	2024-12-05	0.604561	-2.395523	0.342123	0.668824	457.082478	False	Normal	Highly Unstable	0
53	2025-01-06	0.632451	-2.365791	0.321045	0.683929	457.082478	False	Normal	Highly Unstable	0
54	2025-02-05	0.680835	-2.252130	0.299124	0.723799	457.082478	False	Normal	Highly Unstable	0
55	2025-03-06	0.758645	-2.300338	0.306637	0.752684	457.082478	False	Normal	Highly Unstable	0
56	2025-04-03	0.842590	-2.451956	0.362068	0.734304	457.082478	False	Normal	Highly Unstable	0

Figure 31. *Summary of Quantitative Data for IBM Inc*

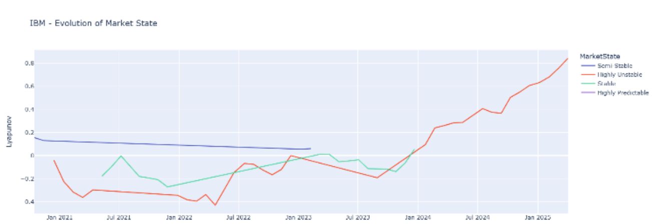


Figure 32. *Evaluation of Market State*

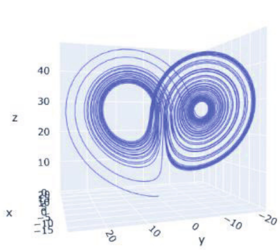


Figure 33. *Lorenz Attractor Reference*

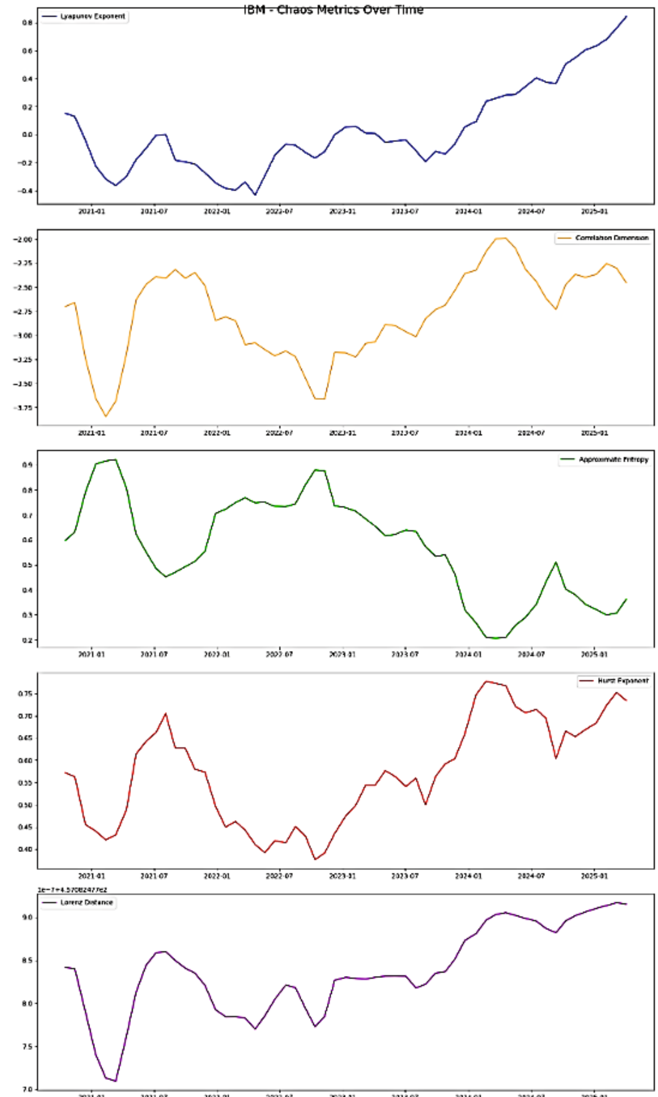


Figure 34. *Chaos Metrics Over Time*

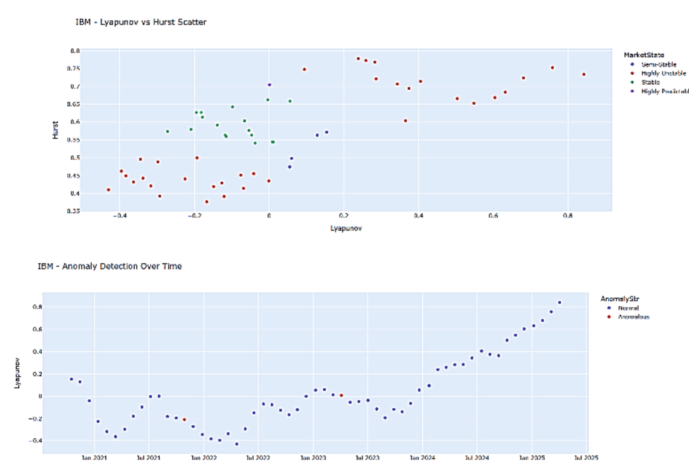


Figure 35. *Lyapunov vs Hurst Scatter and Anomaly Detection over Time for IBM Inc*

Discussion

The combination of chaotic metrics (such as the Lyapunov exponent, correlation dimension, approximate entropy, Hurst exponent, and Lorenz distance) with an artificial immune system enables efficient market classification based on various dynamic states. This methodology not only uncovers the chaotic characteristics of the market but also allows for market classification by identifying stable and unstable patterns. In this work, the algorithms are applied in two modes: one without false alarms, and another where false alarms are introduced to test the system's robustness under conditions of high volatility. The discussion below thoroughly examines the classification results by company, clearly indicating the use of both algorithms. For a summarized overview of the key metrics for each company, please refer to **Table 2**. Time series analysis for Apple indicates the presence of chaotic yet predictable patterns in market behavior. The Lyapunov exponent, with values ranging between 0.48 and 0.56, confirms the system's divergence and the presence of chaos, which is characteristic of dynamic and nonlinear systems. However, the Approximate Entropy, ranging from 0.33 to 0.40, shows a relatively low level of entropy, suggesting that price movement patterns are somewhat predictable. A high Hurst exponent (~0.79–0.86) further suggests the existence of long-term dependence and stable trends—when the price rises, there is a high probability that the upward trend will persist. The correlation dimension, although negative (likely due to a scaling error), indicates a high level of complexity in market behavior. The Lorenz distance, with a constant value around 457, points to a stable attractor distribution, and the absence of anomalies confirms that the market chaos is unfolding within expected bounds. Time series analysis for Microsoft reveals more pronounced chaotic characteristics compared to Apple. The Lyapunov exponent ranges from 0.68 to 1.0, indicating a higher degree of chaos and greater system divergence. The correlation dimension, with values between -2.5 and -2.9, also suggests a high level of complexity, although the negative values are likely due to a scaling error. Approximate Entropy, in the range of 0.57 to 0.72, reflects greater unpredictability of patterns compared to Apple, meaning that Microsoft's market behavior is harder to model. The Hurst exponent remains relatively high (0.69–0.76), confirming the presence of long-term dependencies, although somewhat less pronounced than in Apple's case. The Lorenz distance indicates lower attractor stability compared to Apple, further contributing to the depiction of a more dynamic and potentially more volatile market. Nevertheless, despite the stronger chaotic behavior, no anomalies were detected, indicating that Microsoft's market behavior—though complex and unpredictable—still occurs within expected bounds. Microsoft exhibits stronger chaotic characteristics and lower predictability compared to Apple, while maintaining fundamental structural stability. The Lyapunov exponent is negative (ranging from -0.18 to -0.00), indicating that the system is not divergent and does not exhibit chaotic characteristics—instead, the behavior is stable and predictable. The Hurst exponent, ranging from 0.5 to 0.6, suggests behavior close to a random walk, with no pronounced long-term dependence. Approximate Entropy falls within a moderate range (0.45–0.61), indicating a medium level of unpredictability—higher than Apple's, but lower than Microsoft's. The correlation dimension points to a complex structure, similar to the previous companies, suggesting multilayered dynamics despite the absence of chaos. The Lorenz distance remains stable, supporting the existence of a consistent attractor structure over time. No anomalies were recorded, further confirming the consistency of market behavior. Time series analysis for Google shows more stable dynamic behavior compared to Apple and Microsoft. In conclusion, Google stands out as a system with stable and relatively predictable patterns, lacking chaos and exhibiting less long-term dependence compared to Apple and Microsoft.The Lyapunov exponent for NVIDIA has extremely negative values (~-1.5 to -1.6), indicating an exceptionally stable system with no signs of divergence. The Hurst exponent ranges from 0.6 to 0.7, suggesting the presence of mild, mostly upward trends in the time series. Approximate Entropy, ranging from 0.30 to 0.44, indicates a relatively low level of unpredictability, meaning that behavioral patterns are clearly present and can be modeled with relative ease. NVIDIA demonstrates a high degree of stability with moderate trends and low entropy, making it a system with well-defined and predictable dynamics. The Lyapunov exponent for Intel ranges between -0.42 and -0.59, indicating stable system behavior without signs of divergence, though not as extremely stable as in NVIDIA's case. Approximate Entropy, ranging from 0.54 to 0.61, indicates a moderate level of entropy, meaning that Intel exhibits a moderate degree of predictability—patterns are present but not fully clearly defined. Approximate Entropy for AMD, ranging from 0.37 to 0.44, indicates a moderate level of predictability—behavioral patterns are present but not fully stable. The Lyapunov exponent, ranging from 0.17 to 0.24, shows a slightly divergent system with low but positive values, indicating a certain degree of chaotic behavior. In conclusion, AMD's market behavior is characterized by a balance between predictable patterns and mild instability, making it a moderate yet dynamic system. For IBM, Approximate Entropy shows a significant increase—from 0.59 to 0.91—which clearly indicates growing unpredictability in market behavior patterns. At the same time, the Lyapunov exponent shifts from positive (0.15) to negative values (-0.31), signaling a transition of the system from a mildly chaotic state toward more stable dynamics. This combination points to a complex change: while the system's structure is stabilizing in terms of divergence, its local patterns are becoming increasingly irregular and harder to predict. IBM is in a specific transitional phase—structurally moving toward stability, while simultaneously experiencing an increase in internal chaos.

Table 2. *Summary of Chaotic Metrics by Company*

Company	Lyapunov Exponent	Approx. Entropy	Hurst Exponent	Corr. Dimension	Lorenz Distance
AAPL	0.48 – 0.56	0.33 – 0.40	0.79 – 0.86	(error)	~457
MSFT	0.68 – 1.00	0.57 – 0.72	0.69 – 0.76	-2.5 to -2.9	Lower than Apple
GOOGL	-0.18 – -0.00	0.45 – 0.61	0.50 – 0.60	High complexity	Stable
NVDA	-1.5 – -1.6	0.30 – 0.44	0.60 – 0.70	N/A	Stable
INTC	-0.42 – -0.59	0.54 – 0.61	N/A	N/A	Stable
AMD	0.17 – 0.24	0.37 – 0.44	N/A	N/A	N/A
IBM	0.15 to -0.31	0.59 – 0.91	N/A	N/A	Stable

Microsoft showed the highest stability in terms of long-term predictability, indicated by its negative Lyapunov exponents and relatively low entropy values, suggesting a more consistent and predictable market behavior. Apple, on the other hand, demonstrated the best balance between growth and predictability, with chaotic traits combined with long-term stability and low entropy, indicating the potential for both stable trends and growth opportunities. NVIDIA and Google exhibited negative Lyapunov exponents and low to moderate entropy, reflecting their relatively stable and predictable dynamics, though their market behavior was somewhat less dynamic compared to companies like Apple and Microsoft. AMD, with more pronounced chaotic characteristics and lower predictability, was better suited for short-term and active trading strategies. Intel, offering moderate stability without significant fluctuations, represents a more conservative option with relatively predictable behavior. IBM, however, showed a sharp increase in entropy, signaling growing unpredictability despite indications of structural stability, suggesting that it may not be ideal for long-term positions.

Conclusion and Future Work

This work presents a comprehensive system for analyzing chaotic patterns in financial markets, combining classical chaos theory metrics with artificial immune system algorithms for anomaly detection and market classification. The system not only detects chaotic behaviors but also classifies market states into categories such as "chaotic," "stable," or "predictable," based on the calculated metrics. By utilizing indicators such as the Lyapunov exponent, correlation dimension, approximate entropy, Hurst exponent, and the distance from a reference Lorenz trajectory, the system enables both quantitative and qualitative assessment of market stability, predictability, and dynamic transitions between different market states over time. This classification framework provides a deeper understanding of market behavior, highlighting periods of instability and offering insights for market prediction and risk assessment. The analysis reveals clear differences in the dynamic behavior of the companies under consideration. While Apple and Microsoft exhibit more pronounced chaotic characteristics—marked by high Lyapunov and Hurst exponents indicating long-term dependencies—companies like NVIDIA and Google demonstrate more stable and predictable behavioral patterns. Particularly notable is IBM, which seems to be in a transitional phase—shifting from mild chaos towards greater structural stability, while also experiencing an increase in short-term unpredictability.

From an investment strategy perspective, the results enable a practical classification of market options. If maximum stability is the goal, NVIDIA and Google stand out as the most reliable choices due to their negative Lyapunov exponents and low to moderate entropy values, indicating consistent and predictable dynamics. For those seeking a balance between growth and predictability, Apple emerges as the optimal option—exhibiting chaotic traits along with stable long-term trends and low entropy. Microsoft and AMD, with more pronounced chaotic behavior and lower predictability, are better suited for active trading and short-term strategies. Intel offers a more conservative option—stable and moderately predictable, without significant fluctuations. After results analysis we can conclude that IBM is not recommended for long-term positions due to a sharp increase in entropy, which points to growing unpredictability despite signs of structural stabilization. The proposed algorithm, a combination of artificial immune systems and chaos theory metrics, proved effective in detecting anomalous behavior and dynamic shifts without generating false alarms, further confirming the robustness of the proposed system. Interactive visualizations enable intuitive interpretation of complex results and contribute to a better understanding of the nonlinear processes that characterize modern financial markets. This approach represents a step toward the development of advanced tools for early instability detection and potential crisis forecasting, with potential applications in financial engineering, risk management, and strategic investment planning. Future research will focus on refining the classification system by incorporating additional market factors and expanding the scope to include more diverse financial instruments, such as commodities and cryptocurrencies. Further improvements can be made to the anomaly detection algorithms, enhancing their sensitivity to subtle market shifts without increasing the risk of false positives. Additionally, exploring the integration of machine learning techniques to complement the chaos-based analysis could offer deeper insights into market behavior, improving both the accuracy and reliability of predictions. The system could also be expanded to support real-time market monitoring and decision-making, enabling proactive responses to emerging market conditions.

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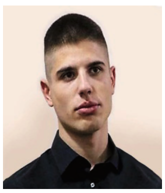
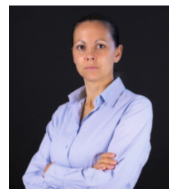
About the authors



Msc Marko Živanović is a doctoral student at the Faculty of Technical Sciences at the University of Čačak, specializing in Information Technology. He has completed both vocational and academic undergraduate and master's studies. His research interests include artificial intelligence, machine learning, and soft computing. Marko has written several scientific papers and works on industry projects. He is currently employed at the Faculty of Information Technology at Metropolitan University in Belgrade and also teaches part-time at a modern high school.



PhD Emilija Kisić is an Assistant Professor at Belgrade Metropolitan University, teaching at the Faculty of Information Technologies. She completed her undergraduate and master's studies at the School of Electrical Engineering, University of Belgrade, Signals and Systems department. She earned her PhD in 2016 from the School of Electrical Engineering, University of Belgrade, Signals and Systems department, specializing in the study module Systems Control and Signal Processing. Her doctoral dissertation focused on the field of statistical signal processing, predictive maintenance, and fault detection, titled "Application of T2 Control Charts and Hidden Markov Models in Predictive Maintenance of Technical Systems." Her research interests include artificial intelligence, machine learning, data analysis and statistical signal processing. She is the author and co-author of numerous papers published in national and international journals and presented at both domestic and international conferences and events of national or international importance.

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Comparative Analysis of Constructed and Simulation Optimized Yagi Antennas for LoRa 868 MHz Communication

Daniel Menićanin[1], Jelena Radanović[2], Dražen Marinković[3]

[1]*Pan-European University Apeiron, Faculty of Information Technology, Banja Luka, Bosnia and Herzegovina, daniel.menicanin1@apeiron-edu.eu, https://orcid.org/0009-0001-6311-4043*

[2]*Pan-European University Apeiron, Faculty of Information Technology, Banja Luka, Bosnia and Herzegovina, jelena.radanovic1@apeiron-edu.eu, https://orcid.org/0009-0001-5135-7662*

[3]*Pan-European University Apeiron, Faculty of Information Technology, Banja Luka, Bosnia and Herzegovina drazen.m.marinkovic@apeiron-edu.eu, https://orcid.org/0009-0006-8001-2168*

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Abstract: This paper investigates the impact of antenna design on the performance of LoRa communication systems through experimental and simulation-based analysis of three antenna models: a commercial omnidirectional antenna, a manually constructed Yagi antenna, and a simulation-optimized Yagi antenna, all designed for 868 MHz operation. The study focuses on evaluating critical communication parameters, including received signal strength (RSSI), signal-to-noise ratio (SNR), voltage standing wave ratio (VSWR), and packet loss under real-world conditions over a 2 km line-of-sight rural test range. The results demonstrate that directional Yagi antennas, especially those optimized via electromagnetic simulation tools, significantly outperform omnidirectional models in terms of signal reliability and link efficiency. The findings confirm that the integration of open-source design tools and accessible fabrication technologies enables the development of high-performance antennas suitable for deployment in decentralized, long-range IoT infrastructures.

Keywords: 868 MHz, IoT, LoRa, RSSI, SNR, VSWR, Yagi

Introduction

Low-power wireless communication technologies that enable reliable data exchange over long distances represent the technological foundation of modern Internet of Things (IoT) systems. Among them, LoRa [1] stands out in particular, utilizing chirp spread spectrum (CSS) modulation, which is known for its robustness in conditions of low signal strength and high interference. This characteristic enables stable communication in scenarios where traditional wireless networks exhibit significant performance limitations.

Thanks to the combination of long-range capability and low power consumption, LoRa technology is increasingly used in applications such as smart city systems, remote agricultural monitoring, industrial process control, critical infrastructure management, and environmental sensing. In all these cases, antenna performance is a key factor that directly affects transmission efficiency, link reliability, and the overall energy optimization of the system.

In scenarios where long-range communication is essential and systems are constrained by power and resources, high-gain directional antennas become an indispensable part of the architecture. Among the available solutions, Yagi antennas [2] stand out as particularly effective due to their ability to form a narrow radiation beam in a well-defined direction. Their geometry consisting of a reflector, an active dipole, and multiple directors enables energy focusing and reduced losses, resulting in higher signal-to-noise ratio (SNR)[3] and lower impact from reflected or scattered energy.

Practical applications and numerous experimental studies confirm that Yagi antennas are optimal for stationary LoRa nodes, where the orientation of the link is known and constant. Their key advantages include high gain, a directional radiation pattern, mechanical simplicity, and low manufacturing cost, making them suitable for both industrial use and research prototypes.

Although electromagnetic simulation tools such as 4NEC2 and MMANA-GAL, enable the design of antennas with a high degree of precision using methods like the Method of Moments (MoM) and Finite Element Method (FEM), their results often differ from real-world performance due to simplified assumptions. Factors such as mechanical tolerances, properties of the supporting materials, the quality of electrical connections, and the influence of the local environment significantly affect antenna behavior under real conditions.

For this reason, a combined experimental-optimization approach is increasingly applied in the modern development of antennas for LoRa systems. This approach involves an initial design based on theoretical models, prototype fabrication, followed by iterative optimization based on empirical measurements of parameters such as reflected power, standing wave ratio (SWR), input impedance, radiation pattern, and polarization.

This study addresses the following key research questions:

1. What are the performance differences between an empirically constructed and a simulation-optimized Yagi antenna for LoRa communication?
2. To what extent do antennas of different constructions contribute to improvements in signal strength, link stability, and packet loss reduction?
3. Is it possible to achieve performance levels that meet professional LoRa infrastructure standards using limited resources?

The aim of this work is to provide a practical insight into how the geometry and fabrication method of a Yagi antenna directly influence the reliability and range of LoRa networks, through a combination of field measurements and engineering analysis. This study relies not only on theoretical modeling and simulation but also on real-world testing, with the goal of offering a meaningful guideline for the future design of antennas in long-range IoT systems.

METHODS AND MATERIALS

As part of this research, two models of Yagi antennas were developed for an operating frequency of 868 MHz [4], with the goal of conducting a comparative analysis of their performance in long-range LoRa communication systems. A commercial omnidirectional antenna was also included as a reference point in the testing process to clearly highlight the differences between directional and non-directional solutions.

The first model was constructed using an empirical approach, without the use of simulation tools.

The construction was based on practical knowledge, references from the literature, and multiple tests conducted under real-world conditions. The mechanical structure of the antenna was realized using 3D printing, while the elements were made of 2 mm diameter copper wire, enabling simple and precise fabrication.

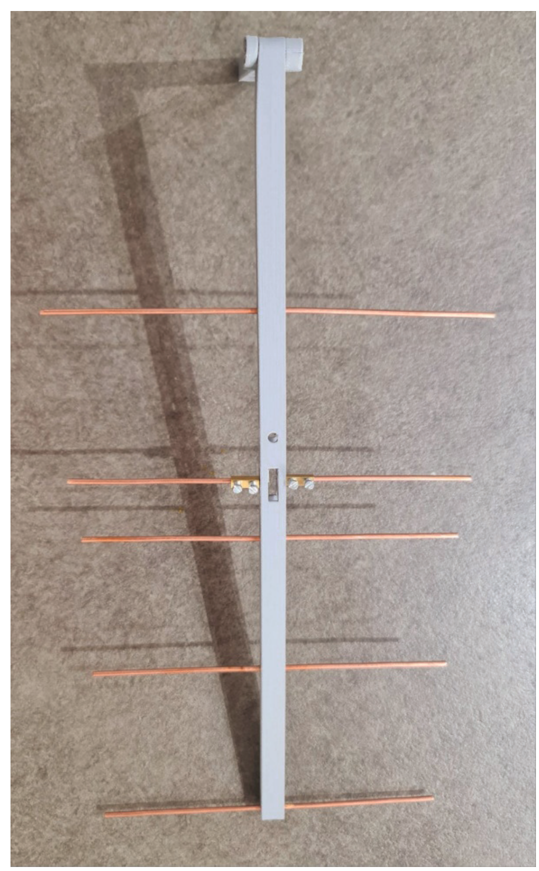

Figure 1. *Optimized 5-element Yagi antenna*

The antenna consists of five elements: one reflector, an active dipole, and three directors, as shown in Figure 1.

The reflector, with a length of 168 mm, is positioned at the beginning of the boom and directs electromagnetic energy forward, reducing backward radiation losses.

The dipole, measuring 159 mm in length, is positioned 69.1 mm from the reflector and has a gap between its arms (gap ≤ 4.6 mm), which allows for easy connection with a coaxial cable.

The directors measure 151 mm (D1), 149 mm (D2), and 147 mm (D3) in length, and are placed 95 mm, 157 mm, and 231 mm respectively from the reflector, thereby enhancing the focus of the radiation and increasing the antenna's directivity.

All elements are mounted on a 10 mm diameter boom made of ASA plastic due to its mechanical strength, UV resistance, and favorable dielectric properties that do not compromise RF performance. The total length of the antenna is 235 mm, and the expected gain is estimated at approximately 10 dBi, which was confirmed through preliminary measurements under real-world conditions.

The second model was designed based on theoretical calculations and optimized through simulations using software tools such as 4NEC2 [5] and MMANA-GAL [6], applying the Method of Moments for electromagnetic analysis. Through iterative simulations, the spacing between elements, their lengths, and the input impedance were precisely adjusted to achieve optimal matching and maximum antenna gain.

All three antenna models, the empirical Yagi, the simulation-optimized Yagi, and the commercial omnidirectional antenna were tested under identical conditions in an open field, along a path with clearly defined line-of-sight and a distance of exactly 2 kilometers. The locations were carefully selected to eliminate physical obstructions and minimize external electromagnetic interference, simulating real-world applications in rural environments such as precision agriculture, environmental monitoring, and remote IoT nodes.

During the testing, the following key parameters were measured:

1. Received Signal Strength Indicator (RSSI)
2. Signal-to-Noise Ratio (SNR)
3. Reflected power expressed through VSWR
4. Link stability and packet loss

In order to ensure the highest possible accuracy during the measurement process, a combination of specialized equipment was employed. The tinySA Ultra spectrum analyzer was utilized to assess the frequency characteristics and real-time behavior of the transmitted and received signals, enabling detailed insight into the spectral distribution and potential interference. In addition, the TZT SV4401A [7] vector network analyzer (VNA) was used for comprehensive analysis of antenna parameters, such as reflection coefficient, impedance matching, and standing wave ratio (VSWR), providing essential data for evaluating the performance and tuning of the antenna systems.

To further enhance measurement reliability and sensitivity, especially when capturing weak signals over long distances, low-noise amplifiers (LNAs) were integrated into the setup.

Specifically, the ZS-406 and ZK-06-BM LNAs were employed to amplify the received signals with minimal added noise, preserving signal integrity and enabling the detection of subtle variations in communication quality. The use of these devices ensured that even the smallest discrepancies in antenna performance could be accurately identified and analyzed.

Figure 2 presents the flowchart of the Yagi antenna construction process for the 868 MHz frequency, outlining all essential steps: from selecting the operating frequency and calculating the dimensions of the elements, through preparing and assembling the physical components, to verifying electrical connections, measuring performance, and completing the final assembly. The diagram also incorporates conditional logic, if the antenna is not properly tuned, the user is guided back to the step of adjusting the lengths and positions of the elements, followed by a new round of measurements. This clearly illustrates an iterative approach that ensures optimal antenna response and reliable performance under real-world conditions.[8]

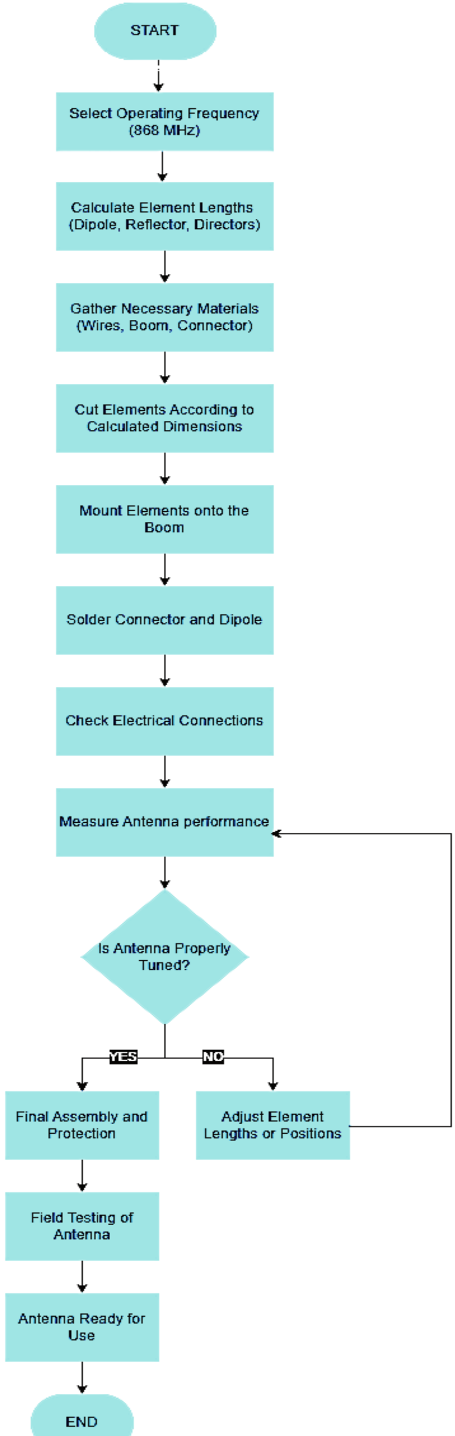

Figure 2. *Flowchart of Yagi antenna construction process*

RESULTS

The evaluation of antenna performance was conducted on March 28, 2025, under real-world conditions in the territory of the Republic of Srpska, along the Prijedor–Banja Luka route. The test site featured clearly defined line-of-sight visibility and an exact distance of 2 kilometers, located in a rural area with minimal electromagnetic interference.

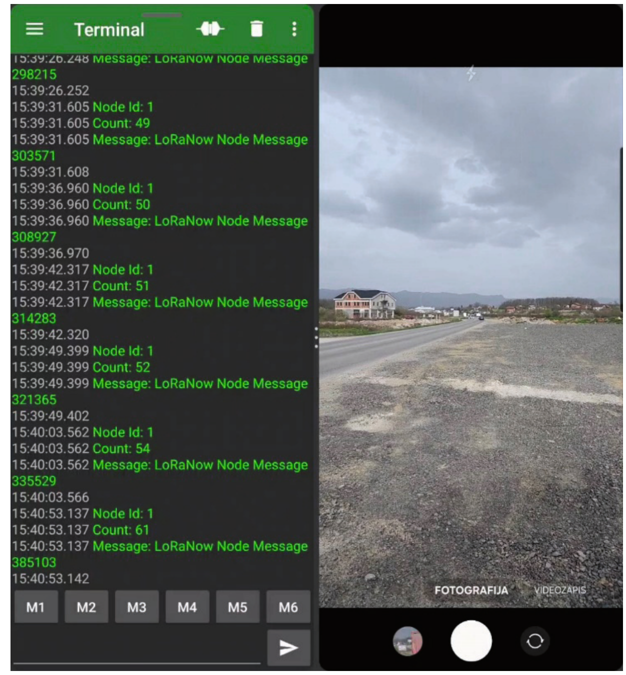

Figure 3. *LoRa communication test with visible line-of-sight at a 2 km distance, recorded on March 28, 2025.*

A visual representation of the test location and terminal interface showing successfully received packets is provided in Figure 3, clearly illustrating an open terrain with an unobstructed line-of-sight, as well as stable communication between the transmitting node and the receiving unit during the field test.

The test configuration included three antennas with different characteristics and gains, representing the antenna's ability to direct transmitted or received electromagnetic energy in a specific direction. Antenna gain, expressed in decibels relative to an ideal isotropic radiator (dBi), is one of the key parameters that directly affects communication efficiency, especially over long distances.[9]

High-gain antennas concentrate energy into a narrower radiation beam, which enables significantly greater range and higher signal strength in the targeted direction. This is particularly useful in point-to-point links, where precise antenna orientation is essential. On the other hand, low-gain antennas exhibit a wider radiation pattern, covering a larger area but with lower signal intensity, making them suitable for multi-node network applications where broad coverage is required.

During testing, antennas were carefully selected to cover different application scenarios from highly directional links focused on maximum range and minimal losses, to broadband configurations suitable for local signal distribution within a wider area.

Directional antennas, such as Yagi models, were used in point-to-point scenarios where precise alignment with the receiving node was possible, while omnidirectional antennas were used to test transmission reliability in multi-node networks, where uniform radiation in the horizontal plane was needed.

This diversity of configurations enabled a comprehensive evaluation of system performance in real-world conditions. During measurements, key parameters were analyzed, such as transmission reliability (number of successfully received packets without errors) and received signal strength expressed in dBm (RSSI) as well as link stability during continuous communication. Special attention was given to identifying signal quality fluctuations depending on antenna orientation, terrain configuration, and the specific type of antenna used. This provided a clear insight into the practical efficiency of each antenna under real-world environmental conditions.[10]

The commercial omnidirectional antenna, as a non-directional design with a nominal gain of approximately 2.15 dBi, is best suited for applications that require uniform circular coverage in the horizontal plane, such as networks with multiple nodes or systems where precise antenna orientation is not feasible. However, due to its dispersed radiation pattern, this antenna has a limited range and lower signal intensity in any particular direction, which significantly reduces its effectiveness in applications where focused transmission over long distances is required.

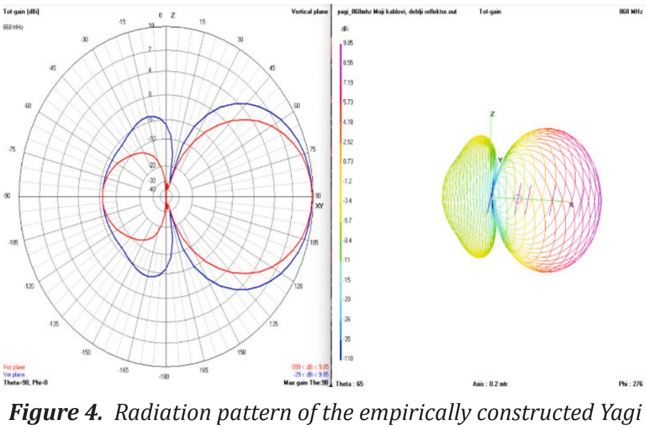

Figure 4. *Radiation pattern of the empirically constructed Yagi antenna at 868 MHz*

In contrast, the empirically constructed Yagi antenna, built without the use of simulation software, was designed based on practical knowledge and prior experience with directional antennas. This antenna provides a notable directional gain of approximately 9.85 dBi, enabling more efficient energy transfer in the desired direction. The radiation pattern of this empirical Yagi antenna is shown in Figure 4, clearly illustrating a pronounced main lobe oriented in the target direction of signal propagation, along with significantly reduced side lobes, which confirms its directive nature and suitability for point-to-point communication.

In addition to the main lobe, the radiation pattern also shows significantly reduced side lobes, indicating high selectivity and focused radiation characteristics. This radiation structure confirms the directive nature of the antenna and its ability to concentrate electromagnetic energy in a single direction, thereby minimizing losses caused by radiation in unwanted directions.

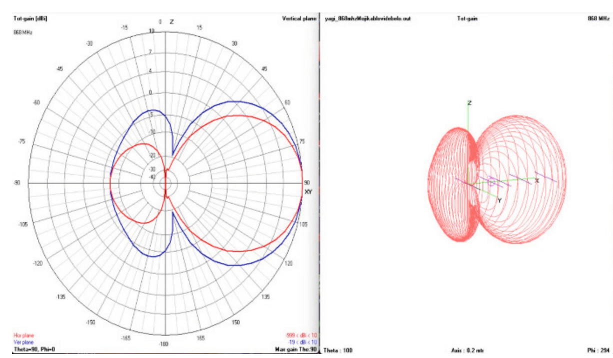

Figure 5. *Radiation pattern of the optimized Yagi antenna for 868 MHz*

As shown in Figure 5, the optimized Yagi antenna model was developed using electromagnetic simulation in the software tools 4NEC2 and MMANA-GAL. The model was carefully designed with precisely defined element lengths and optimized spacing, resulting in a high degree of radiation directivity. Simulation results confirm a gain of 10 dBi, which represents a significant improvement over the empirically constructed model and enables more efficient transmission of electromagnetic energy in the dominant direction.

The radiation pattern clearly shows a focused main lobe and minimal side lobes, indicating high design quality and suitability for long-distance communication with minimal losses.

The analysis of the received signal strength indicator (RSSI) revealed significant differences between the examined configurations. The omnidirectional antenna generated a signal in the range of –95 dBm to –90 dBm, with significant instability and variability in reception. The empirically constructed Yagi antenna demonstrated improved performance, with a stabilized signal level between –85 dBm and –82 dBm. The most favorable values were achieved with the optimized Yagi model, with a detected signal in the range of –80 dBm to –76 dBm and minimal fluctuation.

Measurement of the signal-to-noise ratio (SNR) further confirmed the advantage of directional antennas over omnidirectional ones. In the omnidirectional model, SNR fluctuated between –1 dB and +2 dB, while the empirical antenna reached up to +4 dB. The optimized model achieved stable values in the range of +6 dB to +8 dB, which directly contributes to improved communication link quality and data transmission reliability.

The impedance matching parameter, expressed as the voltage standing wave ratio (VSWR), showed a high reflected component for the omnidirectional model, with values around 2.0, indicating poor adaptation to the transmission system and higher losses. The empirical model achieved significantly lower values, between 1.5 and 1.7, while the optimized antenna recorded near-ideal matching with values ranging from 1.1 to 1.3, confirming the quality of the design and precise tuning.

Link reliability was further quantified by measuring the packet loss parameter. The highest packet loss rate up to 7 percent was recorded when using the omnidirectional antenna. The empirical design significantly reduced losses to below 3 percent, while the optimized model enabled almost uninterrupted communication with losses of less than 1 percent.

The combined analysis of all measured parameters clearly highlights the superiority of the software-optimized Yagi antennas, which consistently deliver better performance across all evaluated categories compared to other models.

The optimized design provides higher gain, more stable reception, a more favorable signal-to-noise ratio (SNR), lower voltage standing wave ratio (VSWR), and virtually negligible packet loss. While the empirically constructed antenna offers a functional solution under limited technical resources, its performance remains below that of precisely modeled antennas. On the other hand, omnidirectional antennas though easy to implement and useful in applications requiring coverage in all directions demonstrate clear limitations in link stability and range, especially in environments where high communication reliability is essential.

Discussion

The experimental results clearly demonstrate the technical superiority of directional Yagi antennas over commercial omnidirectional models in LoRa communication systems with direct line-of-sight conditions. Across all key communication parameters, Received Signal Strength Indicator (RSSI), Signal-to-Noise Ratio (SNR), Voltage Standing Wave Ratio (VSWR), and packet loss rate, the Yagi antennas provided more stable and efficient long-range transmission [11].

The software-optimized Yagi antenna, designed using electromagnetic simulation tools, achieved the most favorable results across all measured metrics. Fine-tuned geometric parameters, including the lengths and spacing of the reflector, driven element, and directors, along with precise impedance matching, led to highly focused radiation, minimal reflected power, and effective energy transfer toward the receiver.

Notably, the empirically constructed Yagi antenna, developed without simulation tools, still demonstrated remarkably good performance compared to the reference omnidirectional model [12]. However, the performance gap between it and the software-optimized version clearly highlights the importance of accurate electromagnetic modeling in antenna design.

Figure 6. illustrates the performance differences among the tested antennas, highlighting the technical superiority of the Yagi designs [13]. especially the one optimized through simulation.The optimized model consistently delivers the lowest signal losses and highest signal quality, while the empirical design proves that acceptable performance is achievable even without advanced tools, provided the physical dimensions are properly calculated and implemented.

In contrast, the omnidirectional antenna, while easy to deploy, exhibits limited capabilities due to its

Parameter	Commercial Omnidirectional	Empirical Yagi	Optimized Yagi
RSSI (dBm)	-95 to -90	-85 to -82	-80 to -76
SNR (dB)	-1 to +2	up to +4	+6 to +8
VSWR	approx. 2.0	1.5 – 1.7	1.1 – 1.3
Packet Loss (%)	up to 7%	< 3%	< 1%
Approx. Gain (dBi)	~2.15	~9.85	~10
Directivity	Low (omnidirectional)	High (directional)	Very high (optimized)

Figure 6. *Comparative performance of tested antennas across key communication parameters*

uniform radiation pattern and low gain. This makes it less suitable for scenarios that demand long-range, high-reliability IoT communication.

The empirically constructed Yagi antenna, although developed without precise simulations, demonstrated remarkably good performance compared to the omnidirectional reference. This confirms that even practically implemented, low-budget configurations when properly dimensioned and well-crafted can represent a viable solution for rural and stationary IoT nodes [14].

The observed performance gap between the empirically constructed and the software-optimized Yagi antenna models clearly highlights the importance of accurate electromagnetic modeling in antenna design.

Numerical optimization of key geometric parameters including element spacing, the lengths of the reflector, dipole, and directors, as well as precise impedance matching significantly contributes to improved energy directionality and reduced reflected power. This results in more efficient transmission and better alignment with the characteristics of the transceiver system [15].

In contrast, the omnidirectional antenna exhibits limited performance in terms of signal stability and directional energy efficiency, primarily due to its uniform radiation pattern and relatively low gain. While it is easy to deploy and suitable for specific network topologies, its effectiveness significantly diminishes in scenarios that demand long-range coverage and high communication reliability.

Conclusion

This research presents a methodological approach that combines numerical electromagnetic simulation with experimental validation for the development of a Yagi antenna optimized to operate in the 868 MHz band, which is essential for modern IoT systems and low-power wireless communication networks.

Through parallel analysis of an empirically constructed and a simulation-optimized antenna, it has been confirmed that the use of open-source software tools (4NEC2, MMANA-GAL) in conjunction with accessible manufacturing technologies can achieve significant directivity and gain, meeting the technical requirements of long-range communication in LPWAN networks.

The experimental results clearly demonstrate a performance improvement of the optimized model compared to the non-optimized version, thereby confirming the validity of the simulation methodology and its applicability in low-budget development environments. The contribution of this study lies in providing a concrete procedure for antenna design and evaluation, which can serve as a foundation for further application development in areas such as precision remote monitoring, agricultural automation, infrastructure management, and smart sensor systems.

Beyond its technical contribution, this work highlights the potential for decentralized development of advanced communication components in resource-constrained settings, thereby fostering scientific and technological inclusiveness. This approach is particularly valuable for research institutions, educational organizations, and development centers aiming to create functional and scalable solutions in the field of wireless communications.

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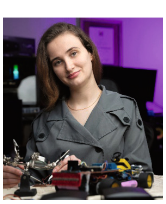
About the authors

Daniel Menićanin is a student of Programming and Software Engineering at the Faculty of Information Technology, Paneuropean University Apeiron. He is widely recognized for his innovative work in developing advanced technological solutions. For his outstanding contributions to education, science, and the arts, he was awarded the Plaque of the City of Banja Luka. Additionally, he received the Butterfly Innovation Award in the Youth category, granted by the Regional Cooperation Council. His current research interests include robotics, automation, and industrial machinery, where he continues to explore cutting-edge innovations with real-world impact.



Jelena Radanović is a highly motivated student of Programming and Software Engineering at Paneuropean University Apeiron, known for her creativity and dedication to technological innovation. She is the recipient of the Butterfly Innovation Award and the INOST Medal for her work on the Press Brake Software project, which highlights her ability to combine practical engineering with software design. Her work reflects a strong commitment to solving real industry problems through software-driven automation.

Dražen Marinković was born in 1978. He received his M.Sc. degree in 2015 and Ph.D. degree in 2020, both from the Faculty of Informatics at the Pan-European University Apeiron in Banja Luka, specializing in computer and informatics engineering. He is currently an associate professor at the Faculty of Informatics, Pan-European University Apeiron. His research interests include data science, computer networks, and related fields in modern computing technologies.

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IT Standardization in Education: A Comparison of ISO/IEC and IEEE Standards Price

Marija Krstić[1], Lazar Krstić[2], Valentina Stanković[3]
[1] *Academy of Vocational Studies Southern Serbia, Leskovac, Serbia, krsticmarija1989@gmail.com, https://orcid.org/0000-0003-3009-8400*
[2] *Academy of Vocational Studies Southern Serbia, Leskovac, Serbia, https://orcid.org/0000-0001-9131-6876*
[3] *Academy of Vocational Studies Southern Serbia, Leskovac, Serbia, https://orcid.org/0000-0001-7570-2267*

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Abstract: Standardization exists in all areas of human activity and is an essential factor in contemporary manufacturing, banking, healthcare, education, and other organizations. Its key role in education is seen in promoting system interoperability through the application of learning technologies, which enables continued development in the field. This paper discusses the standardization regarding the application of information technologies in education, including e-learning. This paper aims to examine, through statistical analysis, specifically by using an appropriate T-test, whether the prices between the two groups of standards, ISO/IEC and IEEE, differ significantly from a statistical perspective.

Keywords: analysis, education, information technology, standardization

Introduction

We live in an era of change, which makes it challenging to harmonize standardization with the development of a specific field [1]. Standardization can be described as activities that identify and align common elements from various inputs to support interoperability and create a level playing field for further innovation and technology adoption [2].

After reviewing the literature and related research, the concept of standardization and standards was presented. Then, attention was paid to the study of standardization in the application of information technologies in education, including e-learning, and a selection of standards published by international organizations for standardization was made. The work includes a statistical analysis of standards related to the research field published by selected international organizations for standardization.

Literature Review

Interest in applying information technologies in education has become particularly relevant in recent years. However, few analyses and works have been published regarding standardization in this area. Based on a review and detailed analysis of the available literature, several recent pertinent works in this field have been identified.

Hoel and Mason [1] discuss using digital technologies in smart learning environments, presenting two models of smart learning. These models are analyzed in the context of current advances in the standardization of learning, education, and training. The goal is to establish a basis for the development of a platform that supports new standards in this area.

Recent research has increasingly focused on standardization in digital education technologies. One study [1] examines smart learning environments through two conceptual models, analyzing them within current standardization frameworks for education and training to establish foundations for future standard development platforms.

A comparative analysis [3] evaluates e-learning standards from ISO alongside regional standards organizations, identifying significant similarities and differences in both publication patterns and pricing structures across jurisdictions.

Further research [4] investigates knowledge innovation patterns across standardized IT application domains through comparative analysis. Building on this work, a subsequent study [5] provides a systematic review of international e-learning standardization efforts, particularly examining ISO/IEC JTC 1 SC 36's work on education technologies and standards development for MOOCs.

Additional analysis [6] systematically examines both international and national standardization efforts in distance learning, with particular attention to development trends and organizational frameworks in the Serbian context, comparing local and global standardization practices.

A comprehensive regional study [7] analyzes e-learning standards published between 2004 and 2017, comparing international standards with national standards from Serbia and neighboring countries (Bosnia and Herzegovina, Croatia, North Macedonia, Montenegro, Albania, Hungary, Romania, and Slovenia). The research employs statistical methods to examine development trends, publication volumes, and pricing structures, revealing correlations between national and international standardization efforts.

Standardization and Standards

Standardization is the process of determining and applying specific rules to organize and regulate activities in a particular area, benefiting all interested parties and particularly aiming for overall optimal savings. This process takes into account functional purposes and technical security requirements [8]. The significance of standardization is evident in its role in stabilizing and establishing a foundation for improvements, based on the following principles [9]:

- voluntary participation of all interested parties in the process of adoption of standards;
- voluntary implementation of standards;
- harmonizing the views of interested parties regarding the technical content of the standard is achieved by consensus;
- publicity and transparency of the standard adoption procedure;
- mutual conformity of standards;
- achieving optimal benefits for society as a whole.

A standard is a document that provides conditions, specifications, guidelines, or characteristics that can be used to ensure that materials, products, processes, and services are fit for purpose. Standards are established by consensus and approved by recognized bodies [9].

International Standards

The International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) establish a specialized global standardization system. ISO has developed over 24438 international standards, all of which are included in the ISO standards catalog. The IEC prepares and publishes international standards for electrical, electronic, and related technologies, while the ISO also develops standards for other fields [10].

The Institute of Electrical and Electronics Engineers (IEEE) is a professional association for electronic and electrical engineering. IEEE is the leading standards development organization, developing and maintaining standards through the IEEE Standards Association (IEEE-SA). The IEEE-SA standards development process is open to both members and non-members. However, IEEE-SA membership allows participants to engage more deeply in the standards development process, providing additional opportunities for voting and participation. IEEE-SA also collaborates with global, regional, and national organizations to ensure the effectiveness and visibility of IEEE standards within the IEEE and the global community.

European standard

A European standard is a standard adopted by the European Organization for Standardization (CEN/CENELEC/ETSI). It is implemented as an identical national standard, requiring the withdrawal of all national standards that conflict with it. If the European standard was adopted at the request of the European Commission for use in the harmonized legislation of the European Union, it is referred to as a harmonized standard [9].

There are three regional organizations for standardization in the European Union [10]:

- European Committee for Standardization - CEN,
- European Committee for Electrotechnical Standardization - CENELEC
- European Telecommunications Standards Institute - ETSI.

Each body develops standards for different areas. CENELEC specializes in electrical engineering, ETSI in information and communication technologies, while CEN covers all other areas.

Serbian standard

The Serbian standard is a standard adopted by the Institute for Standardization of Serbia (ISS) as a national standards body and is available to the public. It is marked with a symbol that begins with the abbreviation SRPS. The application of Serbian standards is voluntary, which means that there is no automatic legal obligation to apply them. However, laws and technical regulations may refer to standards, making compliance with them mandatory.

Serbian standards can be original or can be created based on international, European, and other regional standards and related documents, as well as national standards and related documents of other countries, following the agreements signed with the national standardization bodies of those countries. Standards are developed and defined through the process of knowledge sharing and good practice and are built based on a consensus reached between experts who represent stakeholders in standards commissions [9].

Standardization in the field of application of information technologies in education

There are various possibilities for applying information technologies in education. According to the international classification for standards, the application of information technologies in education is ranked within the 35.240.90 subgroup (ISO 35.240.90 group of standards) [11].

IEEE is a leader in engineering and technology education that provides resources for pre-university, university, and continuing professional education [12]. IEEE Learning Technology Standards Committee - IEEE LTSC follows an open and transparent formal standards development process and fully supports IEEE's sponsorship of the OpenStand initiative [13].

For research purposes, the IEEE 1484 series of standards was selected. These standards cover a wide range of systems known as learning technology, education and training technology, computer-based training, computer-assisted instruction, and intelligent tutoring [14], [15]. The IEEE 1484 series of standards for eLearning Technologies specifies a high-level architecture for information technology-supported learning, education, and training systems that describes high-level system design and system components for the eLearning Technologies family of standards [16].

METHODS AND MATERIALS

Data Description

The goal of this research is to provide a snapshot of the state of standardization at the international level in the application of information technologies in education, including e-learning. To determine the actual state of standardization, two international organizations that extensively cover this research area were selected. Specifically, an analysis was conducted on the standards published by the International Organization for Standardization (ISO) and the Institute of Electrical and Electronics Engineers (IEEE).

Data on these published standards were gathered from the internet by searching the available catalogs on the official websites of ISO and IEEE. After identifying the appropriate group of standards, they were reviewed along with their current status, and standards that are not active were excluded from further analysis.

Data pre-processing

In the pre-processing stage, the data is prepared for analysis using one of the most popular software applications for statistical processing and data analysis, SPSS. This program was developed by the American company IBM in 2009 and now represents only a part of the suite of software products offered by this company for collecting, storing, and processing data. Standards differ from one another based on certain characteristics (label, price, date, status, etc.), which allows for comparison and analysis. Table 1 provides an overview of ISO/IEC and IEEE standards related to the research area, and information about them is entered into the software and prepared for further analysis. To ensure the comparability of the selected groups of standards and facilitate their processing, the t-test for independent samples was used for further analysis. This test compares the mean value of a continuous variable between two different groups of subjects. The analysis was preceded by an examination of the assumptions underlying the t-test.

Table 1. *Standards in the field of information technologies for learning, education, and training (extract from the table)*

Standard	Price (CHF)
ISO/IEC TR 4339:2022	65.00
ISO/IEC 12785-1:2009	.00
ISO/IEC 12785-1:2009/Cor 1:2013	.00
ISO/IEC 12785-2:2011	.00
ISO/IEC TR 127853:2012	.00
ISO/IEC TR 18120:2016	199.00
ISO/IEC TR 18121:2015	98.00
ISO/IEC 19479:2019	155.00
ISO/IEC 19778-1:2015	155.00
ISO/IEC 19778-2:2015	132.00
ISO/IEC 19778-3:2015	98.00
ISO/IEC 19780-1:2015	98.00
ISO/IEC 19788-1:2024	.00
ISO/IEC 19788-2:2011	132.00
ISO/IEC 19788-2:2011/Amd 1:2016	18.00
ISO/IEC 19788-3:2011	155.00
ISO/IEC 19788-3:2011/Amd 1:2016	155.00
ISO/IEC 19788-4:2014	98.00
ISO/IEC 19788-5:2012	155.00
ISO/IEC 19788-7:2019	221.00
ISO/IEC 19788-8:2015	155.00
ISO/IEC 19788-9:2015	132.00
IEEE 1484.11.1-2022	72
IEEE 1484.11.2-2020	60
IEEE 1484.12.1-2020	70
IEEE 1484.12.3-2020	80
IEEE 1484.13.1-2012	173
IEEE 1484.13.2-2013	131
IEEE 1484.13.3-2014	77
IEEE 1484.13.4-2016	62
IEEE 1484.13.5-2013	77
...	...

Selection of dependent and independent variables

After the pre-processing phase in which the data were prepared for processing, the next step involved the selection of dependent and independent variables (Table 2). The price of the standard was chosen as the dependent variable, while the other variables are independent. The data is grouped into one of two ISO/IEC or IEEE categories, and all prices are expressed in the same currency (Swiss Franc - CHF) for easy comparison.

Table 2. *Review of variables*

Name	Type	Values	Measure
Group	String	1-ISO/IEC 2-IEEE	Nominal
Label	String	/	Nominal
Name	String	/	Nominal
Price	Numeric	/	Scale

RESULTS AND DISCUSSION

Statistical analysis using the t-test method of independent samples in this paper was conducted in order to determine the price differences in the selected groups of standards. Namely, the research question was asked: Is there a statistically significant difference between the mean values of the prices of standards group 1 (ISO/IEC) and standards group 2 (IEEE)?

The results of price tests of ISO/IEC and IEEE standards were compared. In addition to the continuous dependent variable that indicates the price of the standard, a categorical variable that indicates the group of standards was determined (1 - group of ISO/IEC standards, 2 - group of IEEE standards).

The assumptions and hypotheses set during the analysis are as follows:

- H0: The price difference between ISO/IEC and IEEE standards is not statistically significant.
- H1: The price difference between ISO/IEC and IEEE standards is statistically significant.

After checking the fulfillment of the corresponding assumptions required by the t-test of independent samples, it was applied, and the results of the application of this statistical method are presented in Tables 3 and 4.

Table 3. *Group Statistics*

	Group	N	Mean	Std. Deviation	Std. Error Mean
Price	ISO/IEC	54	123.8333	56.19768	7.64754
	IEEE	12	91.9667	34.77777	10.03948

The Group Statistics table shows the number of samples (N) for both groups of standards, the mean value of the standard price, the standard deviation from that value for each group, and the standard error of the mean. The first part of Table 4 presents the results of Levene's test for equality of variances. As the value of Sig. is greater than 0.05 and is 0.054, it is

Table 4. *Independent Samples Test*

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Price	Equal variances assumed	3.852	.054	1.879	64	.065	31.86667	16.95739	-2.00962	65.74295
	Equal variances not assumed.			2.525	25.675	.018	31.86667	12.62046	5.90896	57.82437

concluded that the assumption of equality of variance is not violated.

To assess the significance of the difference between the mean values of the dependent variable (price) in each of the groups of standards, it is necessary to analyze the value of Sig. (2-tailed) In the t-test for the Equality of Means section. As it was established in the previous interpretation of the results that the assumption of equality of variance was not violated, it is necessary to look at the value of Sig. (2-tailed) listed in the first row of the table, which refers to the assumption of equality of variance. This value is 0.065, and since it is higher than the threshold value of 0.05 it should be concluded that there is no statistically significant difference between the average prices of the ISO/IEC and IEEE standards groups, i.e. the price difference between the two standards groups is not significant but random, which confirms the null hypothesis - H0.

In addition to the analyzed data, the Independent Samples Test table also contains data on the mean value of the difference between the two groups of Mean Difference standards, which is 31.86667, as well as the upper (65.74295) and lower (-2.00962) limits of the interval, which with a probability of 95% contain the real size of that difference.

When it comes to the results of related research, the conclusion is reached that there are more papers available that talk about standardization in the field of e-learning. The papers mainly talk about the development trends of standardization in the field of e-learning or deal with the analysis and comparison of standardization in the mentioned field at the national and international levels. However, no work was found that deals with the analysis and comparison of selected groups of international standards, so it is not possible to perform an adequate comparison of the obtained results.

Conclusion

Modern organizations rely heavily on IT standards to reduce costs, ensure flexibility, and facilitate the planning, implementation, and operation of information systems. In addition to great advances in the economy, the application of technology has contributed to the development of education in many ways. In fact, its role has proven to be the expansion of access to education. Standardization, as an important component of the quality management process, requires its presence in almost all areas of human activity, especially in the area of education, since quality education is the foundation of the progress of modern society. The application of information technology in education was of great importance when the world faced the coronavirus epidemic. These extraordinary circumstances brought significant challenges in the field of education.

Acceptance of innovations and significant progress in the adoption of information technologies in the field of education leads to the need for standardized sources of knowledge. To analyze the state of standardization in the field of application of information technologies in education at the international level, the data set used for analysis in this paper includes the world's standardized sources of knowledge, ISO/IEC and IEEE, in the previously mentioned field of research. Namely, after the research and analysis of collected data sources were conducted, a t-test of independent samples was conducted on the selected data set, and it was determined whether the price difference between ISO/IEC and IEEE standards was statistically significant. The results showed that the differences in the price of standards created by ISO/IEC and IEEE organizations are not statistically significant.

The statistical analysis includes all ISO/IEC standards within the 35.240.90 subgroup and all standards from the IEEE 1484 series of standards. Future research may be based on the inclusion of additional subgroups of standards or the expansion of data categories for analysis.

Based on the analysis of the state of standardization in the field of application of information technologies in education and the conducted research, it was observed that in this field of research, it is necessary to work on improving standardization. The need for cooperation in the field should be emphasized, both at the national and at the European and international levels.

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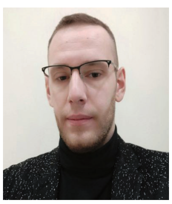
About the authors

Marija Krstić is a lecturer at the Department of Higher Business School Leskovac at the Academy of Vocational Studies Southern Serbia. She completed her undergraduate studies at the Faculty of Information Technology at Metropolitan University in Belgrade and her master's studies at the Faculty of Electronic Engineering at the University of Niš. She also pursued specialist studies at the Faculty of Organisational Sciences at the University of Belgrade. Currently, she is a doctoral student at the Faculty of Technical Sciences in Čačak at the University of Kragujevac. Marija is the author of numerous scientific and professional papers in Information Technology and Systems, which have been published in peer-reviewed journals and presented at international and domestic conferences.



Lazar Krstić is a lecturer at the Department of Higher Business School Leskovac at the Academy of Vocational Studies Southern Serbia. He completed his undergraduate studies at the Faculty of Information Technology at Metropolitan University in Belgrade and his master's studies at the Faculty of Electronic Engineering at the University of Niš. He also pursued specialist studies at the Faculty of Organisational Sciences at the University of Belgrade. Currently, he is a doctoral student at the Faculty of Technical Sciences in Čačak at the University of Kragujevac. Lazar is the author of several scientific and professional papers in Information Technology and Systems, which have been published in peer-reviewed journals and presented at international and domestic conferences.

Valentina Stanković is a lecturer at the Department of Higher Business School Leskovac at the Academy of Vocational Studies Southern Serbia. She graduated from the Faculty of Natural Sciences and Mathematics in Skopje, Department of Mathematics, specialising in Informatics, earning the title of Graduate Mathematician-Informatician. She completed her specialist and then master's studies at the Faculty of Natural Sciences and Mathematics in Niš, obtaining the title of Master of Mathematical Sciences. Her areas of interest are mathematics and programming.

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ENERGY EFFICIENCY AS A NEW PARADIGM IN SOFTWARE ENGINEERING

Pero Ranilović, Dražen Marinković
Pan-European University "Apeiron", Banja Luka, RS, BiH
{pero.d.ranilovic, drazen.m.marinkovic }@apeiron-edu.eu

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Abstract: This paper presents a comprehensive overview of energy efficiency as a modern engineering paradigm in software development. With growing demands on digital infrastructure and increasing energy consumption in information and communication technologies (ICT), optimizing software for energy performance has become a key quality requirement—alongside scalability, performance, and security. Drawing from international standards (such as ISO/IEC 25010), sustainability frameworks (e.g., Green Software Foundation), and relevant scientific literature, the paper analyzes how architectural choices, programming languages, software practices, and toolchains influence energy usage. It further highlights good engineering practices, comparative language benchmarks, and the integration of energy awareness into modern development workflows, such as DevOps and CI/CD pipelines. The aim is to raise awareness among software engineers and decision-makers about the importance of sustainable software design and to offer practical guidelines for building energy-conscious systems.

Keywords: CI/CD, DevOps, energy-efficient software, green software foundation, ISO/IEC 25010, programming languages, performance optimization, sustainable software engineering

INTRODUCTION

In the past decade, we have witnessed a significant increase in energy consumption within the field of information and communication technologies (ICT), driven by the rising use of mobile devices, data centers, smart systems, and the Internet of Things (IoT). Although hardware has become notably more energy-efficient, the overall energy consumption continues to grow—partly because software is still not designed with energy efficiency as a core principle. This phenomenon is known as the "rebound effect," where gains achieved in hardware efficiency are offset by increased demands placed on software systems [1].

Today, software not only governs the functionality of systems but also determines how energy is consumed across all layers of a system. Consequently, there is an emerging need for energy efficiency to be treated not as a secondary concern, but as a fundamental non-functional requirement of modern software—on par with security, scalability, and performance[2].

According to the ISO/IEC 25010 international standard, energy efficiency is defined as one of the sub-characteristics of performance efficiency in software. This requirement implies that the system should use a minimal amount of resources (including energy) to achieve the required functionality [3]. In this context, energy efficiency is not optional—it is an integrated component of overall software quality.

An increasing number of organizations and institutions, including the Green Software Foundation and IEEE, are advocating for the integration of energy optimization measures from the earliest stages of software development [4].

The aim of this paper is to provide a comprehensive overview of energy efficiency as a modern engineering paradigm in software development, drawing on relevant expert literature, technical standards, and current engineering practices. In addition, the paper includes selected analyses from contemporary scientific research to further support its conclusions.

The structure of the paper follows a logical progression—from defining theoretical and regulatory frameworks, through technical factors influencing energy consumption, to an analysis of tools, programming languages, and engineering practices that contribute to the development of energy-conscious software.

Standards and Theoretical Frameworks for Energy-Efficient Software

One of the foundational documents for defining software quality is the international standard **ISO/IEC 25010:2011**, which explicitly includes energy efficiency as a key subcharacteristic of performance efficiency, alongside system responsiveness and resource utilization[3]. According to the standard, energy efficiency refers to the degree to which a software product uses appropriate amounts of resources relative to the performance it delivers. This implies that efficient software should fulfill its functions while minimizing energy consumption—an especially important requirement in environments with limited computational capacity, such as embedded systems, mobile devices, and wireless sensor networks.

In addition to ISO standards, the field of energy-aware computing has seen increasing support through technical initiatives and environmental regulations. Notable among these are the **IEEE 1680.1** and **1680.2** standards, which address the environmental performance of electronic products, including software bundled with hardware (e.g., firmware, drivers). These standards provide guidance for evaluating the energy and environmental impact across the lifecycle of IT products [1] .

A more recent and influential initiative is the **Green Software Foundation**, which advocates for sustainable software engineering practices. Their principles emphasize energy measurability, design efficiency, data minimization, and climate impact awareness in software decision-making [4]. These concepts aim to embed sustainability into every phase of the software lifecycle—from design to deployment.

These efforts are further supported by **global policy frameworks**, such as the **United Nations Sustainable Development Goals (SDGs)**, particularly **SDG 9** (Industry, Innovation and Infrastructure) and **SDG 12** (Responsible Consumption and Production), which call for technological innovation aligned with environmental limits [2].

The concept of sustainability is now increasingly integrated into software engineering not only as a social responsibility but also as a strategic design objective. This is best exemplified in the growing adoption of **ESG (Environmental, Social, and Governance)** frameworks across the tech sector, where energy-efficient software contributes directly to the environmental pillar. Recent studies highlight how responsible AI, cloud infrastructure, and IoT systems are reshaping how developers incorporate energy considerations into software design from the outset [2].

As these frameworks and standards become embedded into standard development workflows, **energy efficiency is no longer a feature of innovation—it is a requirement of modern engineering responsibility**.

Factors Influencing Energy Consumption in Software Systems

Understanding what drives energy consumption in software systems is essential for engineers striving to build sustainable and resource-conscious solutions. Multiple interdependent factors shape how much energy is consumed—from system architecture and algorithm design to programming language, memory usage, and I/O behavior. Addressing these factors in a systematic way can substantially reduce the energy footprint of software.

One of the most fundamental influences lies in the **software architecture**. The decision between monolithic, microservice-based, or event-driven models has direct implications for energy use. Modular architectures often enable components to be independently paused or shut down during periods of low activity, thereby conserving power. However, microservices, while scalable and maintainable, introduce significant communication overhead, especially in distributed systems, leading to increased network traffic and energy usage [5].

Algorithmic efficiency is another central determinant. Efficient algorithms reduce the number of instructions executed by the processor, limiting both CPU cycles and memory accesses—two operations with high energy cost. For example, replacing linear search with binary search, or opting for a heap over a simple list when managing priority queues, significantly improves energy use. Memory-aware designs, such as tiling in matrix operations or optimized caching, have also been shown to cut energy costs across scientific workloads [7].

The **programming language** used in a project also plays a notable role. A well-known study by Pereira et al. (2017) compared 27 programming languages across ten standard algorithms, measuring execution time, memory use, and energy consumption. The study revealed that compiled, low-level languages like **C and Rust** consistently outperform interpreted languages like **Python** and **JavaScript** in terms of energy efficiency [6]. This is due to lower abstraction layers, reduced runtime overhead, and more granular memory control.

Functional programming languages (e.g., Haskell, Erlang) offer benefits in concurrency but may incur higher memory use due to immutable data structures. Therefore, the **paradigm** must align with the performance and energy profile of the application domain.

Among the most overlooked yet impactful contributors to energy waste are **input/output operations and memory access patterns**. File reads and writes, frequent memory allocations, and repeated network calls can drastically inflate energy costs. For example, making uncached HTTP requests in a loop or executing poorly batched database queries can more than double energy use compared to optimized versions [5].

Additionally, metrics like **cache hits/misses**, **context switches**, and **CPU migrations** have been shown to correlate strongly with energy consumption in empirical studies across multiple workloads. These metrics should therefore be monitored as part of any serious energy profiling effort.

In sum, optimizing for energy efficiency involves careful selection of architecture, algorithm, language, and system-level operations. Each design decision reverberates through the energy consumption chain, and only a holistic view can ensure effective improvements.

Good Engineering Practices for Energy-Efficient Development

Energy efficiency in software is not achieved by accident—it is the result of deliberate and thoughtful engineering practices. From the earliest design stages to deployment and testing, integrating sustainability-oriented strategies can significantly reduce the total energy consumption of software systems. As with performance and scalability, addressing energy use is most effective when it is embedded from the beginning of the development lifecycle.

Several well-established design principles have a particularly strong impact on reducing energy waste:

- **Minimizing complexity**: Simplified, clean code and well-structured logic reduce the computational overhead required for program execution. Reducing nested loops, redundant conditions, and unnecessary abstractions allows the processor to complete tasks with fewer operations and lower power demand.
- **Modularity**: Dividing software into smaller, independent modules enables more efficient control over component execution. Modules not currently in use can be unloaded or deactivated, particularly in mobile and embedded systems, thereby reducing background energy draw.
- **Data locality**: Ensuring that data is kept close to where it is processed (e.g., within the same memory hierarchy level or server node) significantly reduces the need for resource-expensive memory accesses and network requests. This practice not only reduces latency but also energy costs tied to I/O and communication operations [5].
- **Avoiding unnecessary computation**: Repetitive function calls, redundant loops, polling mechanisms without delays, and repeated data loading are common sources of waste. Optimizing these patterns—by introducing caching, memoization, and lazy evaluation—can lead to substantial reductions in CPU activity and memory usage.

Although these principles are not new, they are deeply rooted in software craftsmanship values. For instance, the well-known book *Clean Code* by Robert C. Martin emphasizes clarity, modularity, and simplicity—not with energy in mind, but for maintainability and robustness. Yet, their implementation naturally supports energy efficiency as a beneficial side effect [8].

Beyond good design, developers should be equally vigilant about eliminating **anti-patterns**—common but inefficient coding practices that contribute to unnecessary energy use. These include:

- Repetitive execution of logic within tight loops, especially when the logic can be precomputed or simplified;
- Repeatedly opening and closing files or database connections instead of reusing persistent sessions;
- Memory mismanagement, such as allowing object bloat or failing to deallocate unused memory, which leads to more frequent garbage collection and higher RAM usage.

Modern development environments offer powerful tools for detecting and addressing such inefficiencies. **Static code analyzers** (e.g., SonarQube, Pylint) and **profiling tools** (e.g., GreenScaler for Java, Intel VTune, VisualVM) allow developers to identify bottlenecks and measure how different segments of the code contribute to CPU usage, memory allocation, and energy drain [6].

Practical Examples of Energy-Aware Engineering

Research from the **Green Software Laboratory** and field studies [4] have identified several coding strategies that consistently reduce software energy consumption. These are summarized in the table 1 below:

Table 1. *Summary of Key Coding Practices for Energy-Efficient Software Development*

Practice	Description
Efficient algorithm selection	Replace costly operations (e.g., Bubble Sort) with optimized versions (e.g., Quick Sort).
Caching of results	Store computation results to prevent repeated expensive operations.
Lazy loading of components	Load modules or libraries only when they are actually required.
Data compression before transmission	Reduce data size before network transfer to lower bandwidth and CPU use.
Elimination of “busy wait” loops	Avoid while(true) loops that consume CPU without productive work.
Load-aware system scaling	Enable systems to downscale energy usage when demand is low.

Implementing these practices doesn’t necessarily require a shift in tooling or technology stack. In many cases, teams can begin by including energy-related checks in code reviews, defining internal guidelines that promote resource awareness, and using profiling data as part of standard QA procedures.

By embedding such practices into development culture, teams not only improve performance but also directly contribute to the global effort of reducing the carbon footprint of digital infrastructure.

Comparative Analysis of Programming Languages in Terms of Energy Efficiency

Programming languages vary significantly in their energy efficiency, which depends not only on how code is written but also on how it is compiled, executed, and optimized. Key factors include the language’s execution model (compiled vs. interpreted), memory management behavior, and compiler performance. When developing software for energy-constrained platforms—such as embedded systems, mobile devices, or large-scale servers—choosing the right programming language can substantially influence the overall energy footprint of an application.

Empirical Measurements of Energy Consumption by Language

One of the most comprehensive studies in this area is the work by Pereira et al. (2017), which analyzed 27 programming languages across ten common algorithmic tasks. The study measured execution time, memory usage, and energy consumption[6].

Table 2. *Comparative Analysis of Energy Efficiency, Execution Speed, and Memory Usage Across Programming Languages*

Language	Energy Consumption	Execution Speed	Memory Usage
C	Lowest	Fastest	Low
Rust	Very low	Fast	Low
Java	Medium	Moderate	High (GC overhead)
Python	High	Slow	Moderate
JavaScript	High	Slow	Moderate

Source: *Pereira et al., 2017*

These findings suggest that compiled, low-level languages like C and Rust are far superior in energy-critical applications (Table 2). C, due to its minimal runtime overhead and direct hardware access, consistently ranks highest for efficiency. Rust, while higher-level and type-safe, still achieves near-C performance due to its powerful compiler optimizations and memory safety features without garbage collection.

Languages such as Java and C# strike a balance by offering higher developer productivity through managed runtime environments. However, their memory usage tends to be higher, especially in long-lived applications where garbage collection processes introduce unpredictable spikes in CPU and memory activity [11].

In contrast, interpreted languages like Python and JavaScript perform the worst in terms of energy efficiency. Their dynamic typing, runtime interpretation, and rich—but heavy—standard libraries result in both slower execution and greater energy consumption [10].

Programming Paradigms and Their Energy Profiles

Besides language choice, the programming paradigm plays a vital role in determining energy behavior. Imperative languages such as C and Go allow fine-grained control over memory and computation, leading to predictable and efficient execution paths. Functional languages, such as Haskell or Erlang, often favor immutability and recursion, which can increase memory usage and stack depth—resulting in higher energy consumption unless carefully optimized [9].

Compiler behavior is also critical. For instance, enabling or disabling specific compiler optimizations can have a dramatic impact on energy consumption. In the case of Haskell, Kirkeby et al. (2024) found that disabling just a few of the Glasgow Haskell Compiler (GHC) optimizations led to significantly less efficient executables, both in terms of time and energy. Therefore, compiler configuration must be considered as part of language energy profiling—not all compilers are equal, and settings such as *-O2* or *-fno-** flags directly influence energy outcomes.

Furthermore, the compilation process itself—how and when code is translated—matters. Interpreted code or just-in-time compiled (JIT) code (like PyPy for Python) often leads to higher startup costs and runtime overhead, though dynamic recompilation techniques are improving these deficits over time [12].

Practical Implications for Language Selection

When selecting a language for an energy-sensitive system, developers must weigh several factors:

- Execution duration and frequency: For applications that run continuously (e.g., backend services), using efficient compiled languages (like C or Rust) can significantly reduce operational costs and environmental impact.
- Platform limitations: On devices with strict energy budgets (e.g., IoT sensors), interpreted languages are often unsuitable.
- Development priorities: In scenarios where rapid prototyping is more valuable than runtime efficiency, interpreted or semi-compiled languages may still be acceptable.

Nevertheless, energy efficiency should increasingly be considered a first-class requirement in system design. Balancing development speed with sustainable execution is becoming a defining challenge of modern software engineering.

Tools and Techniques for Measuring Energy Efficiency in Software

Measurability is the foundation of every meaningful optimization. In the context of energy-efficient software engineering, understanding how and where software consumes energy is critical for making informed design and development decisions. While energy consumption has traditionally been associated with hardware, today a broad ecosystem of tools and techniques is available to help engineers quantify and optimize the energy footprint of software—from the earliest coding stages to full deployment.

Some tools rely on direct hardware-based measurement using embedded sensors. For example, **Intel Power Gadget** enables precise monitoring of CPU energy use in real time on Intel platforms. These tools offer high measurement accuracy but are limited to specific hardware architectures, reducing their portability and broader applicability.

In addition to hardware-based tools, dynamic profiling solutions have become increasingly popular for capturing real-time energy behavior of software during execution. A notable example is **GreenScaler**, which automatically generates test cases to construct energy models of applications. This profiler helps developers detect energy regressions between software versions and is especially useful in mobile or resource-constrained environments [13].

For embedded systems and IoT applications, where energy is a critical constraint, static analysis tools provide a different type of insight. These tools estimate energy consumption by analyzing the program's control flow and logic without needing to execute the code. For instance, **EnergyAnalyzer**, developed under the European TeamPlay project, uses worst-case execution time (WCET) techniques to estimate the energy cost of software components. This helps developers identify energy hotspots early in development, potentially even before full implementation[14].

Another line of work is focused on **static energy modeling** at the source-code level. Research by **Haj-Yihia and Ben-Asher (2017)** demonstrates how symbolic execution and path analysis can be used to predict energy usage across various CPU architectures. Their approach includes modeling memory usage and cache behavior, which are critical for accurate estimation of total energy cost [15]. While technically demanding, such tools offer valuable guidance during code optimization and compilation.

More and more organizations are integrating these tools into their CI/CD workflows. By tracking energy metrics along with traditional KPIs like performance and security, energy efficiency becomes an embedded part of quality assurance. For example, GreenScaler can flag inefficient changes in new code commits, while static analysis tools help developers configure compilers or detect early inefficiencies.

Despite this progress, several challenges remain. Many tools are platform-specific and rely on non-standard metrics, making cross-platform comparison difficult. Furthermore, most solutions focus exclusively on CPU consumption, neglecting other critical components such as GPUs, memory buses, and network cards.

Looking ahead, the development of hybrid tools that combine static and dynamic analysis, along with standardized models for energy reporting, will be essential. Such advancements would not only improve precision but also allow engineers to compare results across platforms and programming environments.

Ultimately, the ability to measure energy use in software is no longer a luxury—it is a professional necessity. Engineers equipped with the tools and knowledge to assess their code's energy impact are better positioned to make sustainable, efficient, and forward-thinking design decisions in the digital age.

Integrating Energy Efficiency into the Software Development Lifecycle

As the awareness of sustainable engineering grows, software energy efficiency must be embedded not only in the product but also in the process. The integration of energy metrics into the software development lifecycle (SDLC) is becoming an emerging best practice, particularly within Agile and DevOps frameworks.

Modern development teams rely heavily on Continuous Integration and Continuous Delivery (CI/CD) pipelines to automate software testing and deployment. These automated pipelines are now evolving to include **energy profiling and optimization checkpoints**. By integrating tools like GreenScaler and static energy analyzers into CI/CD, teams can continuously track and optimize energy usage during software builds and releases [16].

This integration doesn't stop at tooling. Some organizations have begun defining **"green" acceptance criteria** as part of Agile user stories, ensuring that new features must meet both functional and energy efficiency requirements. This cultural shift promotes shared ownership of sustainability goals, aligning developers, testers, and operations teams under the same value system [17].

From a strategic standpoint, the most effective teams embed energy-awareness into three stages:

1. **Pre-development planning**: Estimating the energy cost of alternative implementation paths and choosing the most efficient.
2. **Development and testing**: Using profilers and simulators to test energy consumption during code changes.
3. **Post-deployment monitoring**: Logging real-time energy metrics to dashboards, much like performance logs or error tracking.

Some DevOps pipelines now include feedback loops where **energy regressions trigger alerts**, just like failing tests. In one case study, applying this principle led to a 22% reduction in overall cloud infrastructure costs simply by removing a memory-intensive module that previously went unnoticed in traditional code reviews [18].

Organizations are also increasingly integrating energy analysis into **code quality dashboards**, using metrics such as energy per transaction, energy per test suite, and deployment energy impact. These indicators provide clarity and accountability, enabling software teams to monitor their impact over time without disrupting their existing workflows [19].

Adopting energy-conscious practices within SDLC not only reduces environmental impact but also optimizes performance, infrastructure utilization, and cost. As tooling and awareness continue to mature, integrating energy metrics into Agile and DevOps processes is transitioning from a novelty to a necessity.

Experimental Validation of Energy-Efficient Coding Practices in .NET

To support the theoretical findings and recommendations outlined in this paper, a series of simple experiments were conducted using the .NET platform (C# language) in a local development environment. The goal was to observe and compare CPU resource utilization and execution time for different software operations. This practical component aimed to demonstrate how various implementation choices—particularly algorithm efficiency, I/O operations, and parallelization strategies—can influence energy-related metrics, even in small-scale desktop applications.

The rationale for measuring CPU usage stems from the fact that processor time is one of the most energy-intensive resources in computing systems. By monitoring CPU load during execution of selected methods, we obtain a proxy for energy consumption. Although these experiments do not measure energy in joules, they provide meaningful insights into computational efficiency, which strongly correlates with energy use in real-world scenarios. The implementation of the measurement logic is shown in Figure 1, where part of the source code demonstrates the usage of the Stopwatch class for execution time and the TotalProcessorTime property for calculating CPU usage. The testing was performed on a personal computer equipped with the following specifications:

- Processor: 11th Gen Intel(R) Core(TM) i7-1165G7 @ 2.80GHz
- RAM: 16 GB
- Operating System: Windows 10
- Development Framework: .NET 8 (C#)

The testing was done using the Stopwatch class from the System.Diagnostics namespace to measure execution time, and the TotalProcessorTime property from the current process to calculate CPU usage percentage (Figure 1). The measurements included:

- **Algorithm comparison**: A naïve implementation of the Bubble Sort algorithm was compared with the optimized built-in Array.Sort() method on arrays of 100,000 elements.
- **I/O operations**: Two standard methods for reading large text files were compared — File.ReadAllLines() vs. File.ReadLines() — to assess how different memory-loading strategies affect performance.
- **Parallel vs. serial execution**: LINQ-based data processing was executed in both serial and Parallel.ForEach configurations to investigate the tradeoff between parallelism and CPU usage.

```
{
    // SORTING TEST
    var rand = new Random();
    var array1 = Enumerable.Range(0, 100000).OrderBy(x => rand.Next()).ToArray();
    var array2 = (int[])array1.Clone();

    Measure("Bubble Sort", () => BubbleSort(array1));
    Measure("Array.Sort", () => Array.Sort(array2));

    // FILE I/O TEST
    string filePath = "data.txt";
    if (!File.Exists(filePath))
    {
        File.WriteAllLines(filePath, Enumerable.Range(0, 100000).Select(i => $"Line {i}"));
    }

    Measure("File.ReadAllLines", () => File.ReadAllLines(filePath));
    Measure("File.ReadLines", () => File.ReadLines(filePath).ToList());

    // LINQ SERIAL VS PARALLEL
    var numbers = Enumerable.Range(1, 100000).ToArray();

    Measure("Serial LINQ", () =>
    {
        var result = numbers.Select(x => Math.Sqrt(x)).ToArray();
    });

    Measure("Parallel LINQ", () =>
    {
        var result = numbers.AsParallel().Select(x => Math.Sqrt(x)).ToArray();
    });
}
```

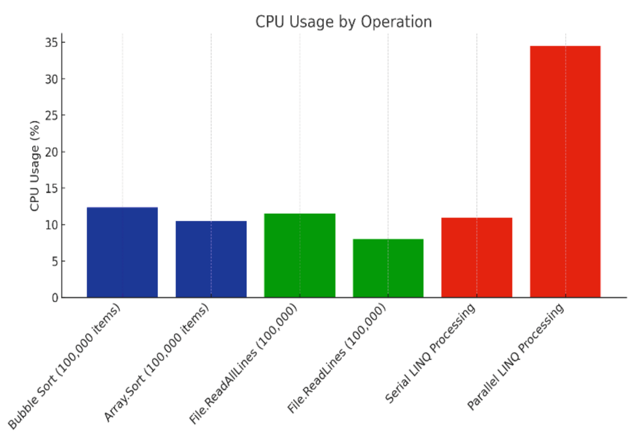
Figure 1. *Part of source Code for Experimental Measurements*

These experiments, though relatively simple and time-limited, were chosen to illustrate the real impact of code design decisions on resource consumption. They were executed under consistent conditions and without background processes, ensuring reliability of the results. The summarized results of all tests are presented in Table 3, showing both CPU usage percentage and execution time for each operation. Additionally, Graph 1 visualizes CPU usage by operation type, with color-coded categories to emphasize differences across algorithmic, I/O, and data processing domains.

These findings clearly demonstrate that more "optimized" or built-in solutions tend to consume fewer resources, while parallel execution, although potentially faster in theory, may introduce overheads that reduce energy efficiency for moderate workloads. The experiments underscore the importance of performance-conscious design choices and support the thesis that energy efficiency should be considered a core concern in everyday software development. The results were systematically recorded and summarized in the following table:

Table 3. *Comparative Analysis of Energy Efficiency, Execution Speed, and Memory Usage Across Programming Languages*

Operation	CPU Usage (%)	Time (ms)
Bubble Sort (100,000 items)	12.35%	42,434
Array.Sort (100,000 items)	10.45%	7
File.ReadAllLines (100,000)	11.49%	16
File.ReadLines (100,000)	8.03%	24
Serial LINQ Processing	10.93%	35.74
Parallel LINQ Processing	34.50%	101.89



Graph 1. *CPU Usage by Operation*

These experimental results, although limited in scope, offer compelling validation for the theoretical principles discussed throughout the paper. They highlight how even basic implementation choices can substantially affect CPU utilization and performance. Integrating such lightweight measurement strategies into standard development workflows can help teams build more energy-conscious software without requiring complex infrastructure or tools. Future research and practice should focus on expanding this methodology with more precise energy metering tools and broader test coverage across different platforms and workloads.

Conclusion

The integration of energy efficiency into software engineering marks a significant evolution in how digital systems are conceived, developed, and maintained. No longer relegated to low-level hardware concerns or experimental projects, energy-aware programming has become a critical aspect of responsible, modern software development. As demonstrated in this paper, energy efficiency must be treated as a first-class non-functional requirement—alongside performance, scalability, and security—especially as computing ecosystems grow increasingly complex and resource-intensive.

Global standards such as ISO/IEC 25010 and initiatives like the Green Software Foundation have laid a strong foundation for embedding sustainability into engineering processes (ISO/IEC 25010, 2011), (Green Software Foundation, 2022). Software design choices—from programming languages and data structures to CI/CD pipeline configurations—play a decisive role in shaping the energy profile of applications. Moreover, empirical studies have underscored the tangible impact that these decisions have on resource consumption across different execution environments [6].

Despite promising advances, several challenges remain. Tooling for real-time and fine-grained energy measurement is still fragmented and not yet standardized across platforms. Educational curricula have yet to fully integrate sustainable software practices, leaving a knowledge gap among new developers. Industry adoption is also uneven—particularly among small and medium-sized enterprises (SMEs)—due to the perceived overhead of incorporating energy metrics into workflows [20].

Looking forward, future research and practice should aim to address these gaps through:

- **Standardized tooling**: Developing cross-platform tools and APIs for measuring and visualizing energy usage in a consistent and vendor-neutral way.
- **Developer education**: Introducing energy-aware programming as a core module in software engineering education, supported by interactive labs and gamified challenges.
- **Policy integration**: Encouraging government and enterprise procurement policies to prioritize energy-aware software products.

- **Holistic frameworks**: Building unified models that integrate energy metrics into quality assurance, compliance, and continuous integration pipelines[18].

A simple experimental case study presented in this paper has further illustrated how basic code-level decisions—such as algorithm choice, file handling, or parallelization—can lead to measurable differences in CPU usage and execution time, reinforcing the importance of energy-conscious design.

The road to widespread adoption of energy-aware software engineering will require continued collaboration across academia, industry, and policy makers. However, the potential benefits—both ecological and economic—make this a worthy and necessary pursuit. Energy-efficient software is not only about conserving watts; it's about building a more sustainable digital future. It is also important to note that the availability of high-quality research on this topic remains limited, and future studies should focus on developing standardized methodologies and tools for measuring software energy efficiency.

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ABOUT THE AUTHORS

Pero Ranilović was born in Prijedor, Republic of Srpska, Bosnia and Herzegovina. He graduated from Grammar School "Petar Kočić" in Novi Grad. He earned his Bachelor's degree in Programming and Software Engineering from the Faculty of Information Technology at Pan-European University "APEIRON" in Banja Luka, where he also completed his Master's degree. Since 2018, he has been employed as a Software Developer at Lanaco. In addition, he works as a Teaching Assistant at Pan-European University "APEIRON". He is currently pursuing his PhD studies in the field of Information Technology at Pan-European University "APEIRON".

Dražen Marinković was born in 1978. He received his M.Sc. degree in 2015 and Ph.D. degree in 2020, both from the Faculty of Informatics at the Pan-European University Apeiron in Banja Luka, specializing in computer and informatics engineering. He is currently an associate professor at the Faculty of Informatics, Pan-European University Apeiron. His research interests include data science, computer networks, and related fields in modern computing technologies.

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The Role of Artificial Intelligence in Modern Information Systems Design: A Systematic Review

Olja Krčadinac[1*], Željko Stanković[2], Dragana Dudić[3], Lazar Stošić[4]

[1] *"Union – Nikola Tesla" University, Faculty of Informatics and Computer science, Belgrade, Serbia, okrcadinac@unionnikolatesla.edu.rs, https://orcid.org/0000-0002-6299-371X*

[2] *Pan-European APEIRON University, Banja Luka, B&H, stanz@medianis.net, https://orcid.org/0000-0002-9893-9088*

[3] *"Union – Nikola Tesla" University, Faculty of Informatics and Computer science, Belgrade, Serbia, ddudic@unionnikolatesla.edu.rs, https://orcid.org/0000-0001-8513-6529*

[3] *"Union – Nikola Tesla" University, Faculty of Informatics and Computer science, Belgrade, Serbia, lstosic@unt.edu.rs, https://orcid.org/0000-0003-0039-7370*

Review paper

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Abstract: The integration of Artificial Intelligence (AI) into Information Systems (IS) design is significantly reshaping traditional development processes, introducing automation, intelligent decision-making, and advanced data analysis capabilities. This systematic review explores the current landscape of AI-driven IS design, focusing on key AI techniques—such as machine learning, natural language processing, and generative models—that are increasingly applied across various stages of system development. The paper examines how these AI technologies are enhancing requirement engineering, system modeling, and process optimization. It also evaluates the benefits of AI in improving system efficiency, decision-making, and user experiences, while addressing challenges such as data quality, technical expertise, and ethical concerns. Finally, the review looks toward the future of AI in IS design, highlighting emerging trends such as low-code platforms and explainable AI. The findings emphasize the need for interdisciplinary collaboration and the development of transparent, responsible AI frameworks to fully realize the potential of intelligent, adaptive, and user-centric information systems.

Keywords: artificial intelligence, information systems design, intelligent system, system architecture

Introduction

The rapid advancements in Artificial Intelligence (AI) technologies have significantly transformed various industries, with Information Systems (IS) being no exception. Traditionally, the design and development of information systems have been human-centric processes, involving manual analysis, design, and decision-making. However, the integration of AI into the design phase of IS development has the potential to revolutionize the way systems are conceptualized, built, and optimized (Hassan et al., 2024).

Artificial Intelligence, through its various techniques such as machine learning, natural language processing, and automation, offers unprecedented opportunities to enhance the efficiency and accuracy of information system design. AI can automate repetitive tasks, assist in the generation of system architectures, and even make intelligent decisions based on large datasets, thus significantly improving the quality of the final product (Crawford et al., 2023; Pattam, 2023).

This paper provides a comprehensive review of the integration of AI in the design of modern information systems. The aim is to explore how AI is being utilized to streamline and enhance various stages of system development, including requirement analysis, system modeling, and process optimization. Additionally, this review discusses the benefits and challenges associated with the adoption of AI in this field, as well as provides insights into future trends and potential research directions (Hassan et al., 2024).

The Role of Artificial Intelligence in Information Systems Design

The integration of Artificial Intelligence (AI) into Information Systems (IS) design has undergone significant evolution in recent years. Traditionally, IS design was a human-centric process, requiring extensive manual intervention at every stage, from requirements gathering to system modeling and decision-making. However, advancements in AI technologies have enabled the automation of many of these tasks, leading to faster and more accurate system design (Safaei et al., 2024).

During the requirements gathering phase, AI tools such as Natural Language Processing (NLP) can analyze large volumes of unstructured data, including user feedback and business documents. This facilitates the automatic extraction of key requirements and identification of patterns that may not be immediately apparent to human analysts. NLP-based techniques also assist in creating user stories and use cases, streamlining the design process (Ofosu-Ampong, 2024).

In the system modeling phase, AI techniques like Machine Learning (ML) and evolutionary algorithms optimize system architectures. These models analyze historical design data to predict efficient architectural components and generate new designs based on predefined criteria. For instance, AI-driven design tools can create scalable and fault-tolerant systems by analyzing existing architectures and recommending improvements (Crawford et al., 2023).

AI also plays a pivotal role in process optimization. It automates tasks such as testing, debugging, and deployment, reducing the time and cost associated with these activities. Additionally, AI algorithms monitor system performance in real-time, making adjustments to optimize resource allocation and improve system efficiency (Pattam, 2023).

The integration of AI into IS design not only enhances development efficiency but also contributes to creating more intelligent, adaptable, and user-centric systems. As AI continues to evolve, its role in modern information systems design is expected to expand, enabling more innovative and automated approaches to system development (Safaei et al., 2024).

Key AI Techniques in Information Systems Design

The integration of artificial intelligence (AI) into information systems (IS) design goes far beyond simple automation; it represents a deeper transformation in how systems are conceptualized, built, and improved. Rather than relying solely on static logic and predefined rules, modern systems increasingly adopt adaptive, data-driven techniques to enhance both functionality and flexibility (Weisz et al., 2023).

One of the most influential developments in this space has been the rise of machine learning (ML). By analyzing large volumes of data, ML algorithms uncover patterns and trends that are often too subtle or complex for rule-based systems to detect. In IS design, this means that decisions regarding user behavior, resource allocation, or system architecture can be guided by empirical evidence rather than assumptions. ML enables predictive capabilities—such as anticipating user needs or detecting performance bottlenecks—making systems not only reactive but also proactively intelligent (Xu et al., 2023).

Natural language processing (NLP) represents another major advance, particularly in bridging the gap between human communication and machine logic. Because IS design often relies on interpreting complex user requirements, NLP tools are used to process unstructured inputs such as customer feedback, support tickets, and documentation. These tools can extract actionable insights that streamline requirement analysis and reduce the risk of misinterpretation. NLP also enhances user interfaces by powering intelligent assistants and context-aware search tools (Zhang & Müller, 2024).

More recently, generative models have introduced powerful new capabilities for automating and accelerating system design. Built on transformer-based architectures, these models are capable of generating code, user interface components, or even complete workflows from natural language prompts. This dramatically shortens the prototyping phase and supports rapid design iterations. Tasks that previously required days of manual work can now be executed in minutes with remarkable consistency (Majchrzak & Thies, 2023).

Taken together, these AI techniques do not replace human designers and engineers—they augment their abilities. By automating repetitive tasks and delivering intelligent suggestions, they enable design teams to focus on strategic and creative aspects of IS development. As these tools continue to mature and become more widely accessible, they are expected to become a standard part of the IS design process, supporting the creation of smarter, more adaptable systems that align with the evolving needs of businesses and users (Weisz et al., 2023).

Research Methodology

The research presented in this paper is based on a systematic literature review focused on recent developments in the application of artificial intelligence in the design of modern information systems. The selection of relevant sources was guided by the goal of identifying prevailing AI techniques, domains of application, and observed benefits and challenges.

The literature search was conducted using academic databases such as IEEE Xplore, ScienceDirect, and Google Scholar, targeting publications from 2018 onward. Keywords were selected to reflect the core concepts of the research, including combinations of terms like *artificial intelligence*, *information systems*, *system design*, and *AI methods*. The inclusion process prioritized peer-reviewed articles published in English, while works not directly addressing the intersection of AI and IS were excluded.

After filtering and reviewing the material, approximately thirty publications were selected as the basis for analysis. These works were examined with respect to their thematic focus, proposed approaches, and reported outcomes. Rather than following a strictly quantitative synthesis, the review aims to offer a structured yet flexible overview that highlights key patterns and relevant examples. Although the research provides a current snapshot of the field, it is limited by the scope of databases used and the exclusion of non-English or non-peer-reviewed material.

Case Studies and Applications

The practical integration of artificial intelligence (AI) into information systems is no longer a matter of theory or experimentation—it is actively shaping the architecture and functionality of real-world systems across industries. Several high-impact case studies illustrate how organizations are leveraging AI to enhance their information systems, demonstrating both the capabilities of current technologies and the diverse contexts in which they can be applied.

One prominent example is IBM Watson, a cognitive computing platform that combines machine learning, natural language processing, and data analytics to support decision-making in complex environments. Originally developed for open-domain question answering, Watson has since been deployed in domains such as healthcare, where it assists doctors in diagnosing conditions based on large datasets of clinical records. The system's ability to interpret medical literature and cross-reference patient data highlights how AI can be used to augment human expertise and improve information accessibility within a specialized IS (Devarakonda & Tsou, 2015, Shwedeh et al., 2023).

In the field of software development, tools such as Google's AutoML represent a shift toward automating parts of the AI design process itself. AutoML allows users to train machine learning models with minimal human intervention, making advanced AI more accessible to non-experts. Within information systems, this has enabled the creation of intelligent modules that adapt to changing data without requiring frequent manual updates. AutoML has been used to optimize logistics systems, personalize customer experiences, and automate fraud detection in financial services (Zhang et al., 2023).

Beyond individual platforms, entire industries are embracing AI-driven information systems. In banking, AI models are integrated into fraud monitoring systems that analyze transaction patterns in real time and flag suspicious activities. In education, adaptive learning platforms use student data to tailor content delivery, while institutions employ predictive analytics to anticipate dropout risks and improve retention. In healthcare, AI enhances electronic health records by enabling natural language input and decision support, streamlining both administrative and clinical workflows (Kabudi, 2023, Gopalakrishnan, 2023).

These applications illustrate that AI is not a one-size-fits-all solution but a versatile set of tools that can be tailored to specific organizational needs. What unites these cases is the strategic embedding of AI into the core of the system's architecture—moving from isolated features to intelligent systems that continuously learn and evolve. This trend is likely to continue as AI tools become more powerful, more transparent, and easier to integrate into existing information infrastructures (Poulain et al., 2024).

To better understand the practical impact of artificial intelligence in the design of information systems, we categorized the reviewed studies based on their primary application domains. This classification helps identify where AI is currently making the most significant contributions and highlights emerging areas of interest.

Table 1 provides a summary of the main domains, the number of papers identified in each, and representative examples from the reviewed literature.

Table 1 *Categorization of reviewed papers by application area*

Application Area	Number of Papers	Authors / Papers
Software Engineering	6	Crawford et al. (2023), Hassan et al. (2024), Pattam (2023)
Healthcare & Medical Systems	3	Devarakonda & Tsou (2015), Poulain et al. (2024), Shwedeh et al. (2023)
Transparency & Ethics	3	Brown et al. (2024), Kumar & Srinivasan (2023), Nguyen et al. (2023)
Business Information Systems	3	Smith & Jones (2024), Li et al. (2023), Gopalakrishnan (2023)
Digital Platforms	2	Majchrzak & Thies (2023), Tan & Lee (2025)
Natural Language Processing	3	IBM (n.d.), Springer (2024), Cambridge Advance Online (2024)
Regulatory & Socio-Technical	2	Safaei et al. (2024), Ofosu-Ampong (2024)
Generative AI	3	Gartner (n.d.), Weisz et al. (2023), Zhang et al. (2023)
Other	4	Kabudi (2023), Ahmed et al. (2024), Zhang & Müller (2024), Xu et al. (2023)

In addition to the tabular summary, the following chart (Figure 1) visualizes the distribution of reviewed papers across the identified application domains.

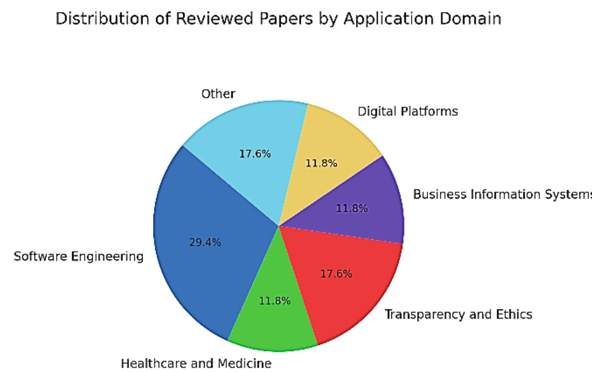

Figure 1 *Distribution of reviewed papers by application area*

Challenges, Opportunities, and Future Directions of AI in IS Design

The growing integration of artificial intelligence (AI) into the design of information systems presents a dynamic interplay between technological promise and practical complexity. As organizations increasingly embrace AI to enhance decision-making, optimize workflows, and deliver intelligent functionalities, it becomes essential to evaluate not only the benefits of this integration but also the limitations and future pathways.

Among the most evident advantages is the significant boost in system efficiency. AI-driven systems are capable of automating routine operations, processing vast volumes of data in real time, and continuously adapting to new information without human intervention. This adaptability translates into more agile and responsive information systems that can meet evolving business and user demands. Moreover, AI reduces the incidence of human error by providing consistent outputs based on data-driven models, particularly in areas such as diagnostics, risk analysis, and demand forecasting. In decision-making contexts, intelligent systems can synthesize complex data inputs, offering recommendations that are both timely and analytically robust (Smith & Jones, 2024, Li et al., 2023).

However, alongside these opportunities lie notable challenges. One of the foremost technical obstacles is the quality and availability of training data. AI models require extensive datasets to perform effectively, and the presence of biased or incomplete data can lead to skewed outcomes, undermining system reliability. Additionally, the integration of AI often demands specialized expertise in machine learning, data science, and system architecture—skill sets that may not always be present within traditional IS development teams. This creates a need for multidisciplinary collaboration, bringing together domain experts, engineers, and data professionals to co-design effective solutions (Garcia et al., 2023, Ahmed et al., 2024).

Ethical concerns also feature prominently in discussions about AI integration. Questions related to transparency, accountability, and data privacy are critical, especially in systems that make autonomous decisions or process sensitive personal information. There is an increasing demand for explainable AI, where the logic behind system outputs can be interpreted and audited by human stakeholders. Without such mechanisms, users may be reluctant to trust or adopt AI-enhanced systems, regardless of their technical sophistication. These concerns have spurred significant research into designing interpretable AI models, ensuring that decision-making processes are understandable and justifiable (Brown et al., 2024, Kumar & Srinivasan, 2023).

Looking ahead, the future of AI in information systems design appears both promising and complex. Advances in generative AI, federated learning, and reinforcement learning are likely to unlock new possibilities in how systems learn, evolve, and collaborate. In particular, low-code and no-code platforms powered by AI could democratize access to intelligent system design, allowing non-technical users to participate more actively in shaping digital solutions. At the same time, we can expect increased regulatory oversight and demand for ethical standards, prompting a more responsible and transparent approach to AI development (Tan & Lee, 2025, Nguyen et al., 2023).

To fully realize the potential of AI in IS design, future research should focus on developing hybrid methodologies that combine human expertise with machine intelligence in a balanced and explainable way. Additionally, fostering interdisciplinary education and practice will be essential to ensure that teams are equipped to address both the technical and human-centered dimensions of AI integration. As AI evolves, its transformative potential will require continuous adaptation, ensuring that these systems remain both ethically aligned and pragmatically efficient.

Ultimately, the road forward will require a careful blend of innovation and reflection. By acknowledging both the opportunities and the limitations, designers and organizations can build information systems that are not only more intelligent but also more aligned with the ethical, practical, and societal contexts in which they operate. This dual focus on progress and responsibility will guide the integration of AI in the coming years, enabling smarter, more effective, and ethically sound systems.

Conclusion

The integration of artificial intelligence (AI) into information systems design represents a fundamental shift in how these systems are conceived, developed, and maintained. Through the application of advanced AI techniques, such as machine learning, natural language processing, and generative models, organizations are achieving enhanced efficiency, data-driven decision-making, and more personalized user experiences. AI is enabling systems to evolve beyond static structures, becoming adaptive, intelligent, and capable of learning from data to address new challenges and opportunities.

However, as AI continues to transform the landscape of information systems, several challenges persist. The availability and quality of data, alongside the need for specialized expertise, remain significant barriers to realizing the full potential of AI. Additionally, ethical concerns, particularly regarding transparency, accountability, and privacy, must be carefully managed as AI systems become increasingly embedded in critical business and societal functions. Addressing these challenges will require interdisciplinary collaboration and the establishment of robust guidelines and standards for the responsible development and deployment of AI technologies.

Looking to the future, the role of AI in information systems design is poised to expand further with the advent of technologies like low-code platforms, federated learning, and explainable AI. These innovations will make AI more accessible and inclusive, allowing organizations to create systems that are not only more intelligent but also more human-centered and adaptable to evolving needs. As AI technologies continue to mature, they will empower organizations to build smarter, more efficient, and ethically aligned systems that contribute to both business success and societal progress.

In conclusion, while the integration of AI into information systems presents both exciting opportunities and inherent challenges, it is clear that AI will remain a transformative force in this field. By embracing its potential and addressing its challenges responsibly, organizations can harness AI to create systems that better align with the needs of users and society, paving the way for a more innovative and inclusive future.

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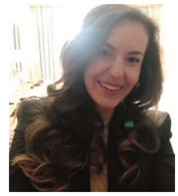
About the authors

Olja Krčadinac (Latinovic, maiden name) is assistant professor at "Union – Nikola Tesla" University - Faculty of Informatics and Computer Science. She earned her Ph.D. in biometric field from University of Belgrade – Faculty of Organizational science, where she conducted groundbreaking research on speaker recognition. In addition to her teaching responsibilities, Olja has authored numerous impactful publications in peer-reviewed journals, contributing valuable insights to the scientific community. Her research focuses on biometric, sensors, IoT and AI, addressing critical issues in AI and making significant contributions to the academic community.

Željko Stanković received his higher education in Cleveland, Ohio, USA, where he graduated in 1981. The topic of the thesis was "Reversible sound in halls". He defended his master's thesis ("Learning control system (LMS) based on ADL SCORM specifications") in 2006 at the University of Novi Sad, Faculty of Science, Department of Informatics. He defended his doctoral dissertation (Laser perception of defined objects and encapsulation of control and logic elements for an autonomous robotic teaching tool) at Singidunum University, Belgrade, in 2010. He has been programming since 1984, creating programs for his first Commodore 64 computer. She works as a full-time professor at Pan-European University "APEIRON". Robotics and bioengineering have been a field of work and interest for many years. He is the holder of the patent right for the teaching tool CD ROBI.



Dragana Dudić obtained BSc and MSc degree in Computer Science at the Faculty of Mathematics, University of Belgrade, and PhD degree in Computer Science at the Faculty of Information Technology, Pan – European University Apeiron Banja Luka. She is an assistant professor at Faculty of Computer Science and Informatics, University Union Nikola Tesla. Dragana is author of more than 20 scientific papers published in peer-reviewed journals, with research focus on bioinformatics, digital literacy and technology integration in education.

Lazar Stošić is a university professor at the Faculty of Informatics and Computer Science, University Union—Nikola Tesla, Belgrade, Serbia and the President of the Association for the Development of Science, Engineering and Education, in Serbia. He is also a leading researcher at the Center for Scientific Competence of DSTU, Department of Scientific and Technical Information and Scientific Publications Don State Technical University, Russia. His expertise includes computer science, IKT, editorial workflow management, conference organization, web technologies, web design, indexing, XML production, SEO, digital marketing, and new media technologies.

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CURRENT EXPERIENCES IN THE APPLICATION OF THE INTERNET OF THINGS IN THE FOOD INDUSTRY, REVIEW

Igor Grujić
Pan-European University "APEIRON" Banja Luka, Faculty of Information Tehnologies., Banja Luka, Bosnia and Herzegovina,
igor.r.grujic@apeiron-edu.eu, https://orcid.org/0009-0004-6263-2350

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Abstract: Modern agriculture and the food industry have a chance to apply modern technologies related to Industry 4.0. In this context, the review discusses the benefits that the food industry can have from incorporating Internet of Things (IoT) into its production processes and control system. The application of IoT will enable companies to more easily and efficiently achieve the set goals of the organization, produce high-quality and safe food and demand and expectations of consumers. This paper presents the latest knowledge about the potential application of IoT and its importance in the food production and processing sector, primarily in the food industry. In addition, the paper describes some barriers that obstruct the application of IoT in the food processing sector. Finally, the future trends of IoT research and application in this sector are listed. The Internet of Things has the potential to contribute to the improvement of the food industry and the food sector as a whole. This potential refers to: the overall practice of sustainability of the sector, improvement of working conditions, reduction of production costs, more efficient use of raw materials, reduction of energy consumption, reduction of the amount of waste and creation of environmentally friendly products.

Keywords: barriers and challenges, food processing, food and agribusiness sector, internet of things (IoT)

INTRODUCTION

The Internet of Things (IoT) are modern technologies in the field of information technology (IT). The application of IoT has revolutionized industry, society and everyday life [1]. IoT represent systems that can connect and communicate with other devices via the Internet. According to Dadhaneeya et al. [2], IoT is a system that enables connecting devices with anyone, anywhere and anytime. Mishra et al. [3] define IoT "as a global infrastructure for the information society, which enables advanced services by connecting (physical and virtual) things based on existing and developing interoperable information and communication technologies".

The Internet of Things (IoT) is a production concept within Industry 4.0. IoT encompasses a number of core technologies and services, which are part of a wider technological ecosystem of connected technologies (for example, artificial intelligence, cloud computing, next-generation cyber security, advanced analytics, big data, various connectivity/communication technologies, blockchain, etc.). The Internet of Things consists of an information technology infrastructure for the collection and distribution of data. The basic components of IoT technologies are endpoints and devices (sensors and actuators), IoT gateways (and device management) and IoT platforms. There are many parts in every IoT device: sensors, actuators, boards, antennas, chips, micro-electromechanical systems and more. Physical devices are interconnected with the Internet and other networks through recognizable IP addresses. IoT collects data from various applications and sends them to the network and application components for further processing and integration of the obtained information [4]. IoT enables the detection of objects (things) and their remote control through the existing network. In this way, IoT enables the collection and exchange of data between objects. Collected data is exchanged via wireless connection technologies. IoT-WSNs facilitate the provision of data to other layers of the IoT architecture.

The Internet of Things are devices that enable the fusing of information technologies (IT) and operational technologies (OT) as elements of the overall transformation of the industry within the framework of Industry 4.0. This can significantly affect the efficiency and performance of production systems. IoT devices can communicate with each other, collect and share data in real time [5], without the need for human intervention. IoT is a logical stage in the development of the Internet and represents the continuation of M2M (machine-to-machine) networks and technologies, mobile technologies, RFID (Radio-frequency identification) and a number of other devices and technologies.

The beginnings of IoT are related to the development and application of RFID, where in the 1990s RFID was only used to track items in various operations (for example, supply chain management and logistics). RFID technologies, sensors and several wireless innovations have influenced the development of multiple applications in connecting devices and "things" [6].

The food industry is a field of human activity in which agricultural products are processed into food products with an extended shelf life using various technical procedures. Modern agriculture and food processing, often included under the name food sector or agro-food sector, should apply modern technologies related to Industry 4.0. Within this, the food industry should use the technologies covered by the IoT.

IoT technologies are very present in agricultural production. They are applied in many places and ways (monitoring of soil moisture content, efficient irrigation systems, optimization of fertilizers, control of crop pests and diseases, optimization of energy use, and others). Recently, several platforms have been developed and put into practice that enable agricultural producers to better organize their business and monitor agricultural products in the food supply chain. However, the application of IoT in the food industry is just beginning. Although there are numerous opportunities, the mass application of IoT is prevented by barriers within the industry itself. This research is a continuation of earlier research in this area [6], and represents a comprehensive examination of the existing scientific literature regarding the application of IoT in the food industry. Clear recommendations are given here for the development of practical applications in the future, emphasizing the need to integrate advanced technologies in order to develop a smart food industry.

Application of IoT in the food sector

Regardless of the rapid progress and changes so far, the food industry faces a number of problems. This requires rapid reform and certain improvements that will increase efficiency and meet the requirements related to process modernization. IoT can help solve problems that are logged and create an environment to solve other problems as well. The opportunities for applying IoT in the food sector are constantly expanding. IoT encourages the management of companies from the food industry to create a new strategy that enables their access to Industry 4.0. A large number of IoT applications intended for the food industry have been developed. There are numerous examples of the use of these applications in companies in developed countries. IoT can strengthen and improve the food sector through various solutions, including real-time data analysis and simulation, remote monitoring and preventive analysis. Through IoT, users can give commands to robots that perform various manufacturing activities. IoT provides an advanced environment for food processing in the future.

Food safety and quality management, improvement of the efficiency of the production process, modernization of food packaging systems, and food supply chain management and food storage management are sectors of the food industry that require changes and in which the application of IoT can help management find better solutions and simplify the company's operations [7], [8]. According to Kodan et al. [9], IoT provides an advanced environment in all stages of production of the food sector (farms, food industries, warehouses, supply chains, prevention of food wastage and waste management, management of energy and other resources, etc.). In practice, IoT is used as sensor devices for data collection (for example, sensors for measuring temperature, relative humidity, light intensity, location, etc.) and as part of communication systems (Bluetooth, RFID, 4G, etc.). Radio Frequency Identification (RFID), Wireless Sensor Network (WSN) and M2M (machine to machine) are most often used to collect data in IoT blocks [10]. This enables easier data transfer to resources for data processing and storage (human resources, computers, etc.).

The IoT ecosystem collects, analyzes/processes and transmits data. IoT systems are divided into: data generation layer, data transmission layer, data processing layer and application layer [2], [11]. The data generation layer is important in the IoT system in the food industry. Cameras, 2-D barcodes, handheld devices, RFID tags, probes and other types of sensors are used as sensors [12]. The food industry uses mechanical, optical, electric magnetic, biological, chemical, acoustic, thermal and other sensors. Temperature sensor, humidity sensor and chemical sensors are most often used in the food processing sector. Sensors are installed on many machines (for example, heat exchangers, evaporators, drying chambers, vacuum ovens, lyophilization chambers, incubators, etc.). Through the transmission layer, a connection is established between the generation layer and the data processing layer [12]. In this way, different devices and components within the IoT ecosystem are connected and communication between them is achieved. Wi-Fi, ZigBee, Ethernet, LoRa, GSM, RFID and Bluetooth are the most widely used communication technologies. This phase is extremely sensitive to cyber attacks, which is why it is necessary that the data being transmitted is protected. The data processing layer is essential in dealing with the huge amount of data produced by sensors [13] . This layer collects data from the transport layer, decodes it, and stores it in the cloud, making the data available to authorized persons [14], [15]. Several cloud platforms are used in IoT systems. The fourth layer in the IoT architecture is known as the application layer. This layer provides concrete real services to the user (for example, human-machine interaction takes place here in this layer). Data can only be given to authorized users and must be protected from threats. This is achieved through authentication techniques: keys, passwords, Bio matric security OTP and other secret access codes [13].

Radio Frequency Identification (RFID)

RFID uses radio waves to transmit small amounts of data. RFID technology enables the design of chips for wireless data transmission. There are several categories of RFID technologies, each with its own advantages and disadvantages. The requirements of the application determine which RFID technology is appropriate for a particular case.

The use of RFID in the food industry has grown in recent years. A system based on RFID was used to collect information for the purpose of ensuring food safety [16], and to monitor and control various activities in the supply chain. RFID technologies are often used in traceability systems and food safety assurance in the food supply chain. RFID sensors are applicable in various applications for food quality evaluation [17], [18]. Several authors have proposed the simultaneous use of RFID and other technologies. Gaukler et al. [19] investigated the use of RFID technologies and sensor technologies to determine the expiration date of perishable food products. Zhang et al. [20] have developed an algorithm to monitor food contamination and return in case the existence of a cause for the occurrence of unsafe food is determined. Alfian et al. [17] developed a traceability system that uses RFID and Internet of Things sensors, where they used RFID technology to search and track perishable food, while they used IoT sensors to measure temperature and humidity during food storage and transportation. The use of RFID technologies, mobile user interfaces, machines with internet connection and ICT for identification of production status enables easier and more efficient production and implementation of automatic control in processes in agricultural production. This is very important for the efficiency of the application of management systems (MS).

Wireless technologies (WSN) for data collection, transmission and storage

The transfer of data from the sensor elements of information and communication technologies (ICT) to the place of data storage in the food industry takes place through advanced communication technologies (for example, LAN, WAN, ZigBee, Wifi, Bluetooth). WSN is used for a variety of applications, including information gathering, machine monitoring and maintenance, environmental monitoring, real-time automated monitoring of raw materials, semi-finished products, and finished products, and for ensuring food safety [21]. A wireless sensor network usually consists of radio frequency systems for transmission and reception, electronic based sensors, microprocessors and power sources. A WSN is a wireless sensor network and is a cooperative network organization in which a set of nodes can communicate wirelessly. Because they use inexpensive batteries that can last for years, low-power broadband networks (WANs) are being incorporated into IoT networks in industrial systems and commercial facilities. WANs are suitable for these applications, as they do not require high bandwidth and real-time results. ZigBee is a wireless standard of low power and data transmission speed that is higher than the speed achieved with LPWAN. ZigBee is used in short-range networks (less than 100 m). Bluetooth is a short-range communication network. It is widely used in smart portable medical devices (for example, oximeters), smart watches, personal devices (for example, phones), and smart home applications (for example, smart locks), etc. Wi-Fi is an IoT technology that is most often used in networks with devices permanently connected to the electrical grid. Wi-Fi technology supports high-speed data transfer (up to 9 Gbps). Wi-Fi infrastructure is represented in digital mobile services [9].

IoT-based applications

Bouzembrak et al. [22] analyzed in detail the application of IoT in the food sector. Li et al. [23] developed an application applicable to a traceability system for prepackaged perishable food, using integrated IoT technologies. Several authors have proposed solutions for information system architecture that uses IoT technology [24], [25]. IoT-based monitoring and control applications in the food supply chain have been developed. Maksimović et al. [26] proposed a system based on IoT, which is intended for tracking and tracking food packaging and transportation. The possibilities of using IoT for monitoring food safety and quality by determining dangerous ingredients in food [27], monitoring the freshness and shelf life of food along the cold supply chain using sensors for measuring temperature, relative humidity and pressure in products and RFID data transmission systems are being explored [28], gathering information from food packaging systems [26] etc.

Integrating IoT with other ICT technologies

The scientific literature describes several applications intended for use in the supply chain, in which IoT is used together with other technologies (for example, blockchain, big data, CC, CPS, etc.). Mededjel et al. [29] described an integrated approach that uses IoT and the cloud for the traceability system. Alfian et al. [30] presented a real-time monitoring system that uses IoT devices on a big data platform. In addition, several traceability systems for ensuring food safety are described, which are based on IoT and blockchain technology.

Blockchain

Blockchain is a cryptographically secured distributed ledger technology used to record the history of transactions. Each node on the blockchain system keeps a copy of all previous transactions/records that are transferred on that system. Blockchain provides auditability, immutability, smart contract, traceability and a trust worthy system [10]. Blackchain has so far been applied in systems for traceability, certification, management of information systems etc. [31], [32].

Big-Data

In the food supply chain, there are a large number of points at which data is generated, for which it is necessary to have an appropriate monitoring system. Such large data can hardly be processed by a computer using simple mathematical analysis. Big data is defined as a set of huge amounts of data that cannot be collected, saved and processed in real time with modern data analysis technologies [21]. Big data analysis, artificial intelligence, machine learning and others are used to process the collected data in practice. Big data is characterized by speed, veracity, volume, value and variety. This technology has enormous significance, because most of today's activities (for example, business, production, services and agriculture, etc.) are focused on the collection and processing of data.

Cloud computing (CC)

The National Institute of Standards and Technology has defined cloud computing as "a model that provides network access to a shared set of configurable computing resources (for example, networks, servers, storage, applications, and services) that can be quickly provisioned and released with minimal effort" or service provider interaction" [10]. Cloud computing provides a simple computing infrastructure for processing big data [21]. At client's request, Cloud Computing provides computing services (for example, storage, servers, networking, analytics, intelligence and software) over the Internet ("the Cloud"). Companies whose work generates a large amount of information use cloud computing. They use computer and network resources to store information. The main advantage of a cloud-based strategy is the ability to accumulate data from different locations and devices. Embedded hardware collects information coming from IoT equipment on site. Relevant information is transferred to the cloud level. In such frameworks, the definition of tasks plays a key role, and the optimized scheduling of requests affects the improvement of system performance and productivity [33].

In the food industry and primary food production, modern video surveillance systems (high-resolution, HD cameras) are often used for defect identification and inspection. In this way, a huge amount of data is created, which often needs to be processed and refined. IoT helps to separate important from irrelevant data. This enables the elimination of erroneous data obtained by manual measurement and the direct extraction of data from electronic sources, their safe transfer to the electronic system for keeping documentation [21]. Specific image processing software is used to process the data, which contains photos taken using cameras or optical sensor elements.

Artificial intelligence (AI)

A large amount of research is devoted to explaining the significance of the application of artificial intelligence (AI) in the automation of certain operations and procedures in agricultural production [34] and in the food supply chain [35]. Artificial intelligence and machine learning systems enable the collection and processing of large data important in food production and processing. The introduction of machines guided by artificial intelligence in agriculture and the food industry has resulted in a change in the way crops are grown, produced and processed. Automated mechanical robots are used in various processing operations (for example, sowing, irrigation and harvesting, and industrial processing and packaging of food products).

With recent technological advances and the increasing power of machine computing, artificial intelligence-driven technologies are increasingly being used to identify and solve specific types of business problems. This is very important for companies in the food production sector, where the impact of AI-driven technologies and systems creates new opportunities and challenges [36]. In support of various applications in the food production sector, artificial intelligence techniques have their contribution in the identification of knowledge models, service creation and decision-making processes [37]. AI offers general algorithms for prediction [38], accuracy and performance evaluation, as well as pattern classification that can help solve problems in the field of agriculture, such as pest identification and selection of treatment methods [39]. The integration of the most modern AI technologies with WSN represents the way to transform the food sector. It represents an opportunity to optimize production practices, improve the use of resources and significantly increase the volume of production.

Food sector and Industry 4.0 technologies

Industry 4.0 (I4.0) includes various forms of technological development and dynamization of the economy through the change of production lines, which increases the flexibility of production [21]. Industry 4.0 implies the application and integration of the latest developments based on digital technologies and the process of interoperability between them [39]. The fourth industrial revolution has already begun in the food industry [2]. Industry 4.0 technologies have the potential to provide better digital solutions to solve everyday problems. The adoption of various advanced technologies (for example, IoT, AI, big data, robotics, 3D printing, sensors and actuators, simulation and RFID) in the food sector is contributing to the change of food industries into Food Industry 4.0. The fourth industrial revolution in the food sector has been described quite effectively by Hassoun, Bekhit, et al. [40]. Many countries have started to implement certain elements of I4.0 in different stages of agricultural food production [41]. In practical application are smart machines, which, thanks to artificial intelligence and machine learning, perform many tasks (for example, sorting, packaging and quality control). Industry 4.0 technologies (digitalization, data analytics, robotization and automation) will facilitate the implementation of the most complex operations in food production and processing in the coming years [42].

The current situation in the application of IoT in the food sector

Theoretical and practical research on the internet of things (IoT) has been in great expansion in recent years. Several review papers have been published on the topic of IoT application in the food sector. In the work of Bouzembrak et al. [22] current knowledge on the application of IoT in the food sector is given. In addition, researchers have analyzed the use of ICT that can be integrated with IoT: working with big data [43], working with blockchain [44], etc. Rejeb et al. [45] list examples of scientific publications that systematize previously published research related to IoT and agriculture: the role of IoT in the food supply chain and food safety, food quality management, protected agriculture, IoT applications in agriculture, and others. Ben-Daya et al. [46] studied the potential, challenges and role of IoT and related technologies (for example, blockchain) for quality management of food supply chain during the analysis of published papers.

Dadhaneeya et al. [2] believe that IoT has a multiple role in the food industry. These authors state that IoT in the food sector enables two-way communication between food producers and consumers, product monitoring in a certain time and remote monitoring (this ensures that the user does not have to be physically present near certain processing plants or equipment for observation), process control in certain stages of food processing (for example, pasteurization, sterilization, cooling, freezing, packaging, etc.), increasing the safety of employees, goods and equipment from physical threats and reducing losses and damage, better functioning during the execution of certain activities, collection and storage of useful data (for example, data to assess food safety and quality), adapting processes and products according to individual consumer preferences and making the best decisions (for example, finding solutions to problems using artificial intelligence and making appropriate decisions). IoT finds application in all phases of the food sector. In this chapter, a brief overview of the forms of application in the key phases of the food sector will be given: agriculture, food processing, process and product quality analysis, product packaging, food supply chain management, data collection in data banks.

Application of IoT in agriculture

The Internet of Things (IoT) has led to a drastic change in the functioning of the agricultural sector and to the introduction of the term "smart agriculture". This term refers to the application of work procedures based on state-of-the-art technologies and data to improve agricultural operations and increase production per unit of work. Various sensors, actuators, big data analytics, cloud computing and, in recent years, artificial intelligence are in use in primary agricultural production. In addition, smart vehicles, drones and various machines that function with the help of IoT are in use. The application of IoT in agriculture enables the collection of a large number of very heterogeneous data (for example, measurement of meteorological data, land quality parameters, etc. [47]. Based on this data, irrigation systems can be optimized, the progress of crops, livestock movements, and human activities can be monitored. This data can be transmitted using wireless sensor networks, and stored and analyzed using cloud computing and other sophisticated analytical methods. IoT enables access to the system from remote locations via tablets or smartphones.

The advantage of the application of IoT and related technologies in agriculture, among other things, is reflected in the improvement of yields, reduction of costs, reduction of the impact of production on the environment, more efficient use of resources and better organization of work [11], identification and monitoring of products in the food traceability system [48], more efficient use of resources, increasing the efficiency and transparency of the supply chain, optimizing production, reducing costs and ensuring food safety and quality [45].

As challenges related to the application of IoT in agriculture in the coming years, Morchid et al. [11] states: ensuring superior efficiency; cost reduction while developing a cost-effective strategy for IoT application, developing a system that will use heterogeneous devices, and the ability to adapt devices to other devices in the environment, and improving the production and reliability of software and the development of portable devices.

The role of IoT in the food industry

IoTs are used in food processing processes in different ways [2]. The following possibilities are particularly emphasized in the literature: monitoring and control of processing equipment and predictive maintenance, process control, inventory management, process traceability monitoring, energy management, etc. IoT enables real-time monitoring of modern processing equipment (for example, furnaces, mixers, dryers and conveyors). In addition, IoT enables the adjustment of the parameters of the production system based on remote control, the timely prevention of errors that can lead to equipment damage or endangering the safety of the food product, and the prevention of downtime and the reduction of maintenance costs. IoTs are used to monitor and control numerous factors in the food industry, which affect product safety and quality [8]. IoT sensors in real time can provide information about product stocks, thereby influencing unnecessary accumulation of products or timely supply of the market with the necessary quantities of products. Through traceability, IoTs enable the visibility of flows in real time. This enables timely making of the best decisions in the entire supply chain. Finally, IoT devices provide automation of machines and equipment in industry (for example, using electricity for lighting or heating).

IoT in food supply chain management

Supply chain management is very complex and dynamic. Demands on the companies that make up the chain are increasing. A large number of researchers deal with this problem in order to help companies to fulfill numerous requirements faster, simpler and more efficiently. In the food supply chain, IoTs enable asset tracking, increasing supply chain visibility and predicting demand for specific food products. They influence the optimization of transport routes and better organization of logistics [49], [50].

Shoomal et al. [51] explored the current challenges and future directions of IoT deployment in supply chains, focusing on drivers and barriers to IoT deployment. They identified issues of security, privacy, interoperability, standardization and energy efficiency as barriers to effective IoT application in the supply chain. Khan et al. [52] investigated the barriers obstructing the application of IoT in the food supply chain. According to their findings, there are numerous batteries from which the authors single out: complex food supply system, legal and regulatory standards, data heterogeneity, lack of qualified personnel, absence of knowledge management system, lack of trust, poor IT infrastructure, low awareness of the benefits of IoT, accessibility of IoT , the high investment and maintenance costs of IoT systems and the absence of IoT vendors, especially in developing countries.

Núnez-Merino et al. [53] provided a detailed analysis of research on the application of Industry 4.0 in the manufacturing industry, with a focus on the supply chain. Integration of multiple technologies from Industry 4.0, according to Yadav et al. [10] provides low-cost solutions and enables the strengthening of the food supply chain. IoT devices and sensors are used to record information in traceability systems, after which the data is entered into the blockchain network. Data on the blockchain network is secure, time-stamped and cannot be used by a third party. It is not possible to manipulate and change data for the purpose of any kind of fraud. Blockchain technology has potential for application in traceability and food safety systems [54], [55]. A number of papers deal with traceability systems based on RFID and IoT [17], [56], [57]. In several papers [58], [59], the authors described the possibility of joint use of Blackchain and IoT.

Data banks

A lot of data collected by IoT is fed into databases. This enables improvement of food safety, insight into customer behavior and needs, identification of areas for improvement of production practices and adaptation of producers to meet consumer needs [49], [60].

Future research directions for IoT applications

In the near future, it will be necessary to invest significant efforts for a more efficient incorporation of IoT into existing ICT systems and the creation of a unified information infrastructure [7]. In this context, the attention of researchers should be directed in two directions: development of IoT architecture and adaptation to new fields of application. There are a few issues that come with the first segment. Network layer limitations include Internet connectivity, standardized interception, interference, transmission loss, transmission range, network management, communication protocols, and latency. Increasing the security and privacy of IoT systems will enable a better understanding and expansion of the area of their use in the food sector.

After the adoption of new food safety standards, there were new requirements for the development of IoT systems [61]. These systems should enable timely prediction and prevention of undesirable effects on contamination and product safety [62], [63]. In some extreme cases (for example, processing procedures or devices that function at high temperatures) the development of sensors is difficult. Sensors for these environmental conditions are sensitive and very expensive, which can prevent their wide application. In addition to high costs, an obstacle to the application of IoT in the food industry can be the lack of specialized experts for the maintenance of IoT systems [64]. Finally, it is necessary to emphasize the need to develop IoT technologies adapted to work in a wide range of production conditions and a large assortment of different products.

Future research should cover topics such as WSN, sensors, cloud computing, machine learning, AI, blockchain, UAVs and deep learning. Rejeb et al. [45] recommend that future research focus on artificial intelligence techniques, big data and blockchain. This leads to the strengthening of smart and precise food production and processing.

Among the topics for future research in the food sector, there are (1) topics related to the application of IoT for the development and functioning of technological infrastructure, namely: (a) interaction between IoT and Industry 4.0 technologies; (b) barriers that hinder the simultaneous application of IoT and Industry 4.0 in operations; (c) the impact of IoT on the performance of different technologies in the food industry and (2) IoT for establishing business relationships: (a) the potential of IoT to drive initiatives for eco-labeling and supplier certification in order to establish sustainable agri-food supply chains; (b) research on the impact of IoT on cooperation in the supply chain in the agri-food sector; (c) identifying how IoT can be applied to solve problems in target markets, improve customer satisfaction and provide sustainability information to stakeholders in the agri-food sector [39], [65], [66], [67], [68].

When it comes to trending topics in areas that combine IoT and the food sector, research on RFID, GPS, remote monitoring, Zigbee and SDN are of great importance [45]. In addition, it should be emphasized that new technologies (for example, cloud computing, AI, machine learning, big data and blockchain) have become essential in the process of digitization in agriculture and the development of smart agriculture [69]. Rajeb et al. [45] emphasize the need for additional research on the consequences of the use of IoT on the organization of practices in the food sector and policies in order to realize sustainable food supply chains.

In the near future, research should be directed towards the development of Internet of Nano Things (IoNT) and green Internet of Things (Green Internet of Things, Green IoT) [70].

Conclusion

This overview paper deals with the current state of application of IoT technologies in the food sector, primarily the food industry. Based on the analyzed literature, trends were determined and the potential of IoT to contribute to the faster development of the food sector at the beginning of its inclusion in Industry 4.0 was explored. The Internet of Things (IoT) provides significant opportunities for improving production procedures, improving sustainable work methods in all stages of production, improving food safety, improving traceability of products in the food supply chain, and more. The application of IoT as part of Industry 4.0 offers a quick response to customer requests, and contributes to improving productivity and making decisions in real time. However, there are still some problems in the development and functioning of IoT, which need to be solved before the direct application of IoT technologies in the food sector, including the food industry.

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About the authors

Igor Grujic is assistant professor at “Paneuropean Univercity Apeiron Banja Luka - Faculty of Informatic Technologies. He earned his Ph.D. in Computing and Informatics on Paneuropean Univercity Apeiron Banja Luka, Faculty of Information Technologies. Igor is author of more than 20 scientific papers published in peer-reviewed journals, with research focus on bioinformatics, using Digital technologies in education and manufacturing and technology integration..

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Internet and Digital Propaganda: Social Media

Darko Tadić
Assistant Professor, Faculty of Information Technologies, Apeiron University, Banja Luka, dtadic44@gmail.com

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Abstract: The development of modern digital communications, the Internet and the World Information Network at the end of the 20th and the beginning of the 21st century brought enormous development and progress in propaganda communications in all spheres of human society. Propaganda in digital media has been studied since the early days of the Internet and various digital platforms, which led to the emergence of completely new media specific to this area of communication, and a completely new way of producing and disseminating various types of propaganda content. Based on a discussion of key concepts and terminology, this review paper describes how new ways of deception and source obfuscation are emerging and spreading in digital and social media environments, and how these developments complicate the understanding and impact of propaganda on modern human life. The paper concludes with the assertion that the modern challenges of detecting and countering covert propaganda can only be solved if all actors of social life in the public sphere of social media are considered responsible and provide the necessary support for checking published information.

Keywords: covert propaganda, disinformation, deception, fake news, manipulation, social media

Introduction

Propaganda as a phenomenon in human history, and above all in the history of communication, has always captured the imagination of people. Like some secret weapon or miracle agent, which gives its owners incredible power to manipulate people, propaganda has gone through various phases of decline and rise throughout history. Although, like any other way or principle of communication, its character depended on the one who uses it, this specific form of human communication had a negative sign from the very beginning. Skill in the use of language, symbols and other means of communication was understood as a special power that was too often abused in history by individuals or elite sections of social communities. Even a superficial look at these historical processes reveals to us how much importance was attached to propaganda as a means of managing or achieving certain goals. From the Egyptian Pharaohs, through the Mayan culture, the medieval Catholic Church, all the way to the Nazi Third Reich and contemporary enlightened Western democratic societies, propaganda appears as a powerful ally and a valuable tool in gaining followers or enthronement of signs and messages about the power and greatness of smaller and larger rulers, dictators or special interest groups [1].

Although the roots and etymology of propaganda predate electronic communication by several centuries, scientific engagement on this topic has historically been inseparable from the rise of mass media technologies in the 20th century. Consequently, the field of propaganda traditionally defines propaganda as an intimate connection with media channels such as radio, television, film and newspapers. In his book "Public Opinion", [2] Walter Lippmann referred to the "production of consent" as "capable of great refinements", a process that can be understood and opened to every human being. Noam Chomsky in his influential work "Propaganda and Public Opinion" defines propaganda as a phenomenon that "requires the cooperation of the mass media" [3]. Similarly, Ellul argued that propaganda "cannot exist without using these mass media" [4]. Propaganda, manifested in the 20th century, is perceived as a distinctly modern phenomenon woven through mass communication channels. From this perspective, propaganda encompasses mass-mediated manipulation organized on a large scale to persuade the public. The goal of such persuasion is typically “closely aligned with elite interests” [5].

However, as Farkas and Neumayer state, not all researchers attribute propaganda exclusively to elite groups [6]. This is central to the topic of this paper, since the decentralized way of producing the content of modern digital media within the global digital information network and modern computer technologies challenges the perception that propaganda originates only from centralized sources. As a conceptual vocabulary for distinguishing between hierarchical and non-hierarchical propaganda, Ellul proposes the concepts of vertical and horizontal propaganda [7]. As part of a rigorous typology, he proposes this concept to distinguish between propaganda by social elites and that produced by small groups of citizens and interested individuals. Accordingly, not all propaganda is associated with political, military, or commercial organizations, although it is by far the most widespread. According to Ellul, vertical propaganda is characterized by its emanation from elites who rely on the mass media to persuade audiences into submission and action. One-to-many communication channels are vital in this regard, as they are means of mass mobilization of a crowd to do the bidding of a source (eg a government, a party leader, a general or a company). Vertical propaganda is particularly effective in agitation propaganda, which is designed to mobilize the crowd against the depicted enemy, “the source of all misery” [8]. Hitler’s campaigns against the Jews and Lenin’s campaigns against the Kulaks are examples of such propaganda. In practice, argues Ellul, agitation campaigns always originate from social elites. Nevertheless, agitational propaganda can be effective in getting the audience to take ownership of the constructed narrative, reinforcing and expanding it. If successful, agitational propaganda therefore does not necessarily rely on the continuous orchestration of the mass media, as “every person caught up in it” can in turn become their own “propagandist” [9].

Contrary to vertical and agitational propaganda, horizontal and integrative propaganda aims at stabilizing the social body, its unification, and strengthening. These forms of propaganda can originate both from social elites, such as governments seeking to stabilize societies during political crises, and from citizens. Horizontal propaganda relies on small, autonomous groups and individuals cooperating based on a common ideology. It differs in that it originates from within the population and not from the top. This form of propaganda is a rare phenomenon, non-existent before the 20th century. The decentralized propaganda of Mao’s China is highlighted as an example. Unlike vertical propaganda, which “requires a vast apparatus of mass media communication”, horizontal propaganda relies only on “a vast organization of people” [10]. Media control, in other words, is inseparable from vertical propaganda, but not similarly fundamental to horizontal propaganda.

Digital Media and Propaganda

At the end of the 20th and the beginning of the 21st century, with the development of the Internet and digital communications, propaganda got a completely new technical means of expression, which led to the further development of propaganda communication to unprecedented proportions, unknown to humanity until then. The democratization of communications brought about by the Internet now provides an opportunity for every participant in the communication process to produce and disseminate propaganda information. In the earlier period, propaganda was usually implemented by some kind of institution, large print and electronic media, and interested state and private organizations that were the owners of large and main communication channels. Today, through numerous Internet sites owned by individuals or small private groups, as well as the great development of social networks, it has enabled every individual to actively participate in the propaganda communication process. Digital media platforms in the form of individual blogs, websites and social networks, as well as the appearance of entire armies of bots in various forms, have enabled the spread of numerous misinformation and half-truths in an unprecedented scope and scope. Although at first glance the democratization of Internet communications seems like a place for the free dissemination of accurate and verified information, the reality shows something quite different. The Internet will continue to primarily serve elite and corporate interests. Consequently, the Internet functions more as a means of control for those already in power than as an instrument of mass communication for those who lack brand names, preexisting audiences and/or large resources. For this reason, it is necessary to build conceptualizations and terminology in the study of this social phenomenon in order to understand the consequences of covert propaganda in digital and social media.

The development of digital media technologies complicates the fundamental notion that covert propaganda de facto originates from large organizations through one-to-many communication channels. With the decentralized way of producing and distributing digital media content, the number of potential sources has increased dramatically. This complicates existing analytical frameworks for identifying and analyzing sources of covert propaganda. Nevertheless, the prominence of digital media should not be seen as "the end of a great propaganda orchestration" [11].

Propaganda And Social Networks

The emergence of the Internet, that is, social networks as a special form of communication between individuals and social groups, represents a special form of dissemination and exchange of information that had no counterpart in the previous individual and mass communication. Large media conglomerates and media companies quickly adapted to the newly emerging situation, although at first glance it seemed that their influence and importance would decline in the new communication age. The difference between the previous classic division into horizontal and vertical propaganda has become quite blurred and unclear, bearing in mind that the division between individuals, media groups, in the spread of propaganda influences is at first glance significantly reduced in the new online space. In fact, the exact opposite happened: political, economic, military and other organizations managed to significantly exploit the development of these modern digital communication technologies, by introducing strict control, censorship and propaganda influence in these new media.

With the emergence of strictly controlled communication channels such as Internet browsers and social networks under the control and ownership of a small number of digital companies, content and information control over social networks was achieved, which created the conditions for further successful dissemination of hidden propaganda content and influence on mass communication. In the last decade, the number of users of social networks has recorded an exponential growth, so for example one of the most popular social networks (Facebook) reached the number of three billion users in 2024. Human communication and exchange of information and other content - in the field of political events, economy, entertainment or everyday life - has become dominant in this media environment. This development of events has enabled propagandists new modalities and forms of horizontal and vertical propaganda, which is now additionally strengthened by users of social networks through the possibility to place comments, likes, retweets and freely share content.

This is how propaganda successfully changed its form: from the classic relationship of "one for all", it became a modern propaganda communication "all for all". In this way, with the permeation of new digital technologies, propaganda has become a form of communication of influence that combines digital technology and social relations into a new form of digital architecture. In this completely new context, the engagement of the average user on social networks, i.e. the "ordinary man", has become a central issue and the main feature of communication and the building of social relations, which requires a completely new approach to teaching propaganda influence in the modern digital society of the XXI century. First of all, concerning content producers, users, distributors of information and new platforms for exchanging content.

Social networks, as a new form of propaganda communication, introduced two key innovations important for propaganda action in the modern age: a two-way form of engaged communication and a reduction in content production costs. Creating websites and blogs, buying domains, and maintaining them has become available at a very low and affordable price. Internet access also becomes symbolic in a financial sense. Social networks are generally free for users, and available to everyone on mobile phones, personal computers, smart watches. This situation opens completely new opportunities for action by individuals and small social groups that have the ambition to achieve a certain social influence and market content of various kinds (personal popularity, economic and political influence, social movements, etc.). Guaranteed anonymity of content creators has become acceptable, without the need for additional verification of information. Social networks characterized by personal profiles of users, who have the opportunity to create personal social networks of different sizes, interests and content, have become an extremely convenient place for various forms of false or covert propaganda. Credibility and trustworthiness of hidden or fake user profiles enable the implementation of propaganda influence through user posts and comments that give them false credibility. Users who "like", comment, share content, and become "friends" of such profiles or pages contribute to the further spread and confirmation of the posted content. On the other hand, the situation is further complicated because large companies such as Facebook, Twitter, YouTube, or TikTok are often unable to identify, check, and manage problematic content due to the large number of users.

As a solution, these companies are forced to create and enforce various restrictions and rules that they impose on users, often with the help of commercial content administrators, but only at the request of users who report inappropriate content that drastically violates the rules regarding content posted by individual users or groups. The problem is that this type of action in preventing propaganda is not effective enough due to the small number of staff and the huge amount of content and users who operate on a social network. So the prevention of the spread of propagandistic content and its influence remains mainly on the users of these networks.

In such a situation, the key question is what can be done to prevent the harmful propaganda activities of various entities on social networks. Is the use of artificial intelligence (AI) in this domain adequate and possible? So far, things are not looking great, although the possibility remains that in the near future, improved AI will be of great use. The spread of hate speech, deception, and false information in the form of entertainment and unverified information, at this moment, depends on human judgment and decision, because algorithms are not yet able to analyze and evaluate the cultural and social context of each post or user comment. Accordingly, one of the solutions to this situation can be the formation of citizen groups that would actively fight against propaganda by reporting fake pages and profiles on these networks to the companies that own social media.

The challenges are numerous and great: the number of users and content, new forms of digital technologies and tools in content creation (text, video, images), represent a great difficulty and challenge in assessing whether manipulation is involved. Things are further complicated by the large decentralization of the social media structure, which makes it significantly more difficult to find and identify propaganda content and its dissemination to the public. However, the biggest challenge is the current business and social policy and the attitude of large companies that own social media, because they provide insufficiently effective support and limited opportunities for their users to react in the right way. Such an insufficiently active attitude only promotes the uncontrolled spread of propaganda on social networks and represents a key challenge in preventing the ongoing action that requires decisive measures and actions of all interested parties.

Discussion and Perspectives

The main tool in the spread of modern propaganda, in the form of disinformation, fake news, various types of fabricated events and "testimonies" of groups and individuals on their networks, have become the leading social networks, primarily "X" (Twitter), Facebook, Instagram, TikTok, but also platforms for private communication such as Viber, Whats Up and similar. Unlike the mainstream media, which can cause the consumer of information to be wary or hesitate in accepting and interpreting the content, these social networks rely on the spread of rumors, innovations, recommendations and similar methods that give false credibility to the published content, often in the form of fun, oddity, novelty. In this way, the official guard towards the source of information in the classic form is bypassed (political entities, large media, government bodies, organizations), and the spread of misinformation takes place horizontally on a friendly basis in the form of proposals, recommendations of interesting things, etc. Social networks are today, and with the prospect that they will be increasingly so in the future, becoming the main carriers of propaganda content in the form of fake news and other forms of disinformation and misinformation, further obscuring the influence of propaganda in modern societies.

Even a cursory review and comparative analysis of the content on these networks reveals a completely new dimension of online propaganda. This is especially visible on specialized platforms for publishing short private messages, such as platform “X” or its counterpart Telegram, where the content of individuals and informal civil groups on topics from political, social and economic events dominates. There, in the form of unverified and attractive information, various mainly negative contents related to the actions of persons or organizations that influence social life are placed, which can strongly influence the public’s perception of these events and direct the actions and activities of individuals or social groups in accordance with the propaganda agenda of the creators of these contents. These networks are thus often misused by the main actors of these events, following their interests and exerting a significant influence on public opinion in the modern online world. According to Guess and Lyons, “there is growing concern that misinformation spread via the rapid introduction of social media in developing countries, especially via mobile devices, is causing increasing social divisions and even violence”. [12]

So, what is the perspective of propaganda in the age of Artificial Intelligence (AI) and similar tools that already work on social networks? Bearing in mind the previous experience of the relationship between propaganda and technology, it is realistic to expect that the trend of spreading disinformation as the main form of propaganda action will spread at an ever faster pace, primarily horizontally, and that social networks will become the main carriers of this action. The focus of action is being shifted to the line of all participants in the creation of content, while the influence of the main mainstream media will gradually weaken and have a peripheral or corrective role in the production and consumption of information in the public sphere. The difference between producers and consumers of content will increasingly disappear, where propaganda will appear in both roles equally: we will all be both propagandists and consumers.

Conclusion

Modern propaganda has changed quite a bit since its beginnings in the 19th century: from mass printing for “one dinar”, through radio, television, and satellite communications in the 20th century, to the digital age in which we live today. Although it has undergone major technological changes, its essence has remained unchanged. Manipulation of information and influence on human behavior have only increased by the challenges of modern times. However, the emergence of the Internet and digital technologies has led to one key change: the boundaries between creators and consumers of propaganda messages have been erased, and now we are all creators and consumers of propaganda content. Also, digital propaganda and new Internet technologies call into question the classic division between vertical and horizontal propaganda, creating a new, unique online space in which the boundaries between reality and virtual reality are erased, which gives propaganda action a completely new dimension that should be taken into account.

Social networks have become a real example of this new age and a challenge for new watchmen who will now have to redefine understandings about the nature, essence and methods of operation of modern propaganda. Propaganda research must be expanded with new tools, concepts and challenges that the digital technological revolution and social reality pose to modern man. It remains to be seen whether propaganda and its techniques of communication and creating relationships between people will become our new reality. What remains as a clear fact and proof is that propaganda action in all areas of human life will continue to be an important phenomenon against which modern society must find appropriate solutions. Otherwise, propaganda and deception can very easily become our only reality in which there will no longer be a difference between real and fictional life.

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About the authors

Prof. Dr. Darko Tadić is a playwright and professor of creative writing. He works as an assistant professor at the Faculty of Information Technologies of Apeiron University in Banja Luka on the subject Creative Writing and as a professor at the ICEPS Vocational School in Belgrade, on the subject Advertising and PR. Doctorate at FDU in Belgrade on "Propaganda film and media". Worked in the advertising industry for 20 years and created advertising and propaganda campaigns of various kinds. Attended education in the field of psychodrama. He now teaches students and others who want to gain knowledge and enjoy the exchange of ideas on the topic of creative writing, as well as writing as a communication art in achieving spiritual, professional, and personal growth and development. He is the founder of the online workshop for Creative Writing and Writing Therapy. He is the author of several books and manuals in these fields.

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