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Republic of North Macedonia

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15th International Conference on APPLIED INTERNET AND INFORMATION TECHNOLOGIES

AIIT 2025

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Bitola, November 7, 2025

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Introduction

As organizing partners of 15th International Conference on Applied Internet and Information Technologies AIIT 2025, we warmly welcome all participants, researchers, and colleagues joining us from various countries and universities, united by our shared commitment to advancing knowledge in the fields of computer science, applied Internet, and information technologies.

The AIIT conference has become a long-standing tradition of excellence and collaboration, co-organized by the Faculty of Information and Communication Technologies – Bitola, University "St. Kliment Ohridski," and the Technical Faculty "Mihajlo Pupin" – Zrenjanin, University of Novi Sad, Serbia. Over the past fifteen years, this partnership has fostered not only strong academic cooperation but also genuine friendship among our institutions and scholars.

This year's conference proudly continues that tradition, bringing together innovative research, diverse perspectives, and new insights into technologies that are shaping our digital future. The Scientific Program Committee once again faced the demanding task of selecting the highest-quality papers from more than sixty submissions spanning a wide range of topics—including Artificial Intelligence, Immersive Technologies, Mathematical Simulations, Data Science and Big Data Analytics, Knowledge and IT Management, Cybersecurity, Software Engineering, Data Mining, Digital Transformation, Behavioral Economics and Business, Social Engineering, Digital Humanities, Augmented Humanity, and Hybrid Intelligence. This ensures that the program reflects both scientific rigor and creative originality.

We would like to express our sincere gratitude to all reviewers for their dedicated work, as well as to the members of the Organizing Committee for their professionalism, commitment, and enthusiasm in preparing this event.

We are confident that these proceedings will provide an enriching and thought-provoking reading experience.

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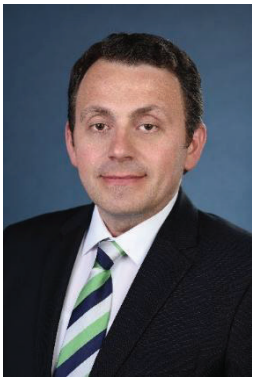
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CONTENT

Plenary Papers

MOR over frequency range by interpolation **16**
Jovan Stefanovski

Current State and Future of Intelligent Agents and their Applications **26**
Eleonora Brtka

Detection and Response in Cybersecurity **37**
Marjan Sterjev

Regular papers

Analysis of the popularity of antivirus solutions – Microsoft Defender, Kaspersky, and Bitdefender **46**
Dejan Jocin, Biljana Radulović and Tamara Milić

Application of Security in Electronic Business on the Example of Application Development using Multi-factor Authentication in Online Learning Platforms **53**
Tamara Milic, Vesna Makitan

Bluetooth LE Spam with ESP32 running Marauder and Bruce **61**
Blagoj Nenovski

Mathematical Foundations of Multi-Criteria Decision-Making and Their Application in Modern Telecommunications and Information Security **69**
Jovana Knezevic, Dalibor Dobrilovic, Jelena Stojanov

Security Monitoring of a PHP MVC Single Page Web Portal with Access Categorization: Preschool Institution Zrenjanin Case Study **78**
Ljubica Kazi, Tatjana Lojović and Željko Cvijanović

Wireless Communication Security – Review on ZigBee and Bluetooth protocol **86**
Vuk Amizic, Dalibor Dobrilovic

Integrity of digital evidences in the investigation process **94**
Rade Dragović, Dragan Dragović and Dalibor Dobrilović

Exploring the Impact of VR and AR Integration in Learning Management Systems: A Study on Enhancing Immersive Learning Experiences **102**
Buen Bajrami, Igor Nedelkovski, Andrijana Bocevska and Kostandina Veljanovska

Comparative Analysis of Text Mining Techniques and Tools **109**
Marija Apostoloska-Kondoska, Blagoj Ristevski, Nikola Rendevski, Snezana Savoska

Scalable ETL Processes with Change Data Capture (CDC) and Monitoring Using Apache Superset 118
Aneta Trajkovska, Violeta Manevska and Kostandina Veljanovska

KPI metrics in the Software Industry: Literature Review and Analysis 126
Igor Vecstejn, Zeljko Stojanov, Tamara Milic and Maja Gaborov

Recipe Radar: A Voice-Driven Hybrid Recommender System for Recipes Using NLP, Text-to-SQL, and Cloud-Native Infrastructure 134
Aleksandra Kolevska, Natasha Blazheska-Tabakovska

Knowledge-based Decision Support System for Personalised Training 142
Marija Kolevska, Natasha Blazheska-Tabakovska

AI-Based Prediction of Elastic Properties in Crystals with Class Balancing 152
Nora Pireci Sejdiu, Nikola Rendevski and Blagoj Ristevski

The Role of Digital Humanism in Shaping AI-Driven Augmented Humanity 160
Blagoj Ristevski, Nikola Rendevski and Dragan Grueski

ECG Classification Utilizing a Hybrid Transformer-BiLSTM Network 166
Luka Glišić, Ivana Berković

Integrating XGBoost and Neural Networks for Accurate Student Performance Prediction in Higher Education 172
Buen Bajrami, Blagoj Ristevski, Kostandina Veljanovska

Intelligent UAV Surveillance GIS-Based Path Planning and Post-Flight Object Detection Using YOLOv11 179
Dalibor Šeljmeši, Velibor Ilić, Višnja Ognjenović, Vladimir Brtka and Dalibor Dobrilović

Optimizing Real-Time Data Processing with Kafka and Databricks Integration for Scalable Machine Learning Solutions 187
Aneta Trajkovska, Blagoj Ristevski , Kostandina Veljanovska, Trajche Trajkov, Nikola Rendevski

Intelligent Agents Architecture for Evacuation Route Planning in QGIS Environment 195
Srđan Popov, Milena Zeljković, Tanja Vranić, Nebojša Ralević and Željko Zeljković

Artificial Intelligence for Assisting People with Sensory and Cognitive Disabilities 203
Kostandina Veljanovska, Simona Gulevska and Blagoj Ristevski

Comparative Study of Depth-First Search Algorithms: DFS, DLS, and IDDFS in Undirected Unweighted Graphs 212
Nikola Jerković, Jelena Stojanov and Ivana Berković

Digital School in Transition: Overcoming Resistance Through Mental Models and Organizational Learning 221

Maša Magzan, Ana-Maria Karleuša and Snežana Jokić

Enhancing Digital Competencies Through Visual Programming in Education **229**
Katarina Vignjević, Dragana Glušac, Nemanja Tasić and Marko Blažić

Understanding User Acceptance of Technology: A Theoretical Review of Behavioral Intention Models **236**
Vesna Rodić Lukić, Mia Marić and Nemanja Lukić

Towards Standardized Quality Practices for Custom Game Development Tools: A Contextualization of ISO/IEC 25010 Standard **242**
Vasilije Bursać, Dragan Ivetić and Aleksandar Kupusinac

Artificial Intelligence and Critical Thinking in Foreign Language Learning: From Theory to Practice **250**
Lela Ivanovska, SilvanaNeshkovska and Milena Kasaposka-Chadlovska

A Comparative Analysis of Locomotion Techniques in Virtual Reality for Architectural Visualization **258**
Danilo Bulatović and Dragan Ivetić

Management of Interdependent Data in Web Applications Using React and Redux Toolkit Illustrated Through a Video Game Point Calculation System **267**
Nikola Jovanov, Eleonora Brtka, Ema Brtka, Vesna Makitan, Velibor Premcevski

Data-Driven Quality Assurance in Higher Education: Insights from University Information System **275**
Aybeyan Selim, İlker Ali, Fehmi Skender

Improving Learning Recommendations Through Combined Audio and Text-based Sentiment Insights **284**
Aleksandar Kotevski, Blagoj Ristevski

Intelligent Educational Agents as Mediators in the Learning Process **294**
Katarina Vignjević, Dragana Glušac, Slavica Isakov and Marko Blažić

Integrating Artificial intelligence in Virtual Engineering for Architectural Visualization **301**
Darko Pajkovski, Igor Nedelkovski

Adoption of AI Technologies in IT Companies: North Macedonia Case **308**
Mihajlo Mitkovski, Elena Petkovska, Mimoza Bogdanoska Jovanovska

Analysis of the Internet Banking in the Macedonian Banking Sector and Other Countries **315**
Marina Blazhekovikj Toshevski

Circular Economy in Manufacturing Processes: A Comparative Analysis of the EU and Serbia **322**
Milica Jovanov

Transforming Human Resource Management: The Role of AI Technologies **328**

Tatjana Ivanovic and Mimoza Bogdanoska Jovanovska

The Role of Caching in Real-Time Systems – A Case Study: Application of Redis in Monitoring Economic Indicators **333**
Teodora Siljanoska, Violeta Manevska

A Comparative Methodological Framework for Semantic Enrichment of Time Series Forecasting: Beyond the Balkans Case Study **341**
Teodora Siljanoska Taskovska, Snezana Savoska, Natasha Blazheska-Tabakovska

Practical Tensor Decompositions for NLP Embeddings with TT, Tucker, and CP **349**
Dilan Dobardžić, Višnja Ognjenović, Jelena Stojanov, and Vladimir Brtka

Applying semantic web technology in IoRT: A Review **354**
Valmir Sinani, Ramona Markoska and Natasha Blazheska-Tabakovska

Development and Functional Design of "Smart" Surgical Masks Based on IoT Technology **362**
Valentina Bozoki, Ineta Nemeša, Marija Pešić, Danka Đurđić, Igor Vecštejn

Development of a smart sleep monitoring ecosystem **368**
Kirill Zhilenkov, Konstantin Zheltov, Andrey Dorofeev, Irina Kuznetsova

Review of Analysis of Traditional Complexity Metrics and Their Applicability to IoT Devices **377**
Vuk Amizic, Dalibor Dobrilovic

Serbian Workforce Potential for Leading Global IT Projects **383**
Ivana Denčić, Sanja Stanisavljev and Vladimir Todić

ICT as a Catalyst for Effective Waste Management in the Circular Economy Context **390**
Saso Nikolovski, Bozidar Milenkovski, Anita Ilieva Nikolovska, Biljana Stojcevska and Viktorija Spasevska

East–West Perspectives on Social Media Use Among Older Adults: Lessons for the Western Balkans **398**
Dragana Bodiroga and Dragan Ivetic

Antiderivatives Solved with LLMs? **405**
Sonja Mančevska and Elena Karamazova Gelova

Deepfake Video Detection: How Far Have We Gone? **413**
Zoran Kotevski

Do Hyperbolic Heads Make Better Mistakes? A Minimal Euclidean-vs-Hyperbolic Comparison on CIFAR-100 **422**
Dilan Dobardžić, Jelena Stojanov, Višnja Ognjenović, and Nikola Jerković

Validation of Parameters for AI Source Code Detector **428**
Eugene Alooeff, Yuliya Zhaltko

Application of Control Flow Graph in White Box Testing Techniques **435**
Zoltan Kazi, Ljubica Kazi

Comparative Analysis of Platforms for Analysis, Design and Product Development with a Focus on AI-Based Tools **443**
Borce Ugrinovski, Andrijana Bocevska, Kostandina Veljanovska and Blagoj Ristevski

Detection of Road Edge Lines Using Hough Transform **452**
Ivan Gašić, Marko Beljin, Željko Eremić, Vladimir Tadić

Design and Implementation of an Intelligent Virtual Medical Agent for Health Risk Assessment **457**
Anita Petreska, Igor Nedelkovski, Andrijana Bocevska, Blagoj Risteski

Orkes Conductor - performance comparison with Apache Kafka **467**
Srđan Popov, Jelena Ninković, Rade Radišić and Margarita Khazhoyan



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MOR over frequency range by interpolation

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Abstract:
A two-step algorithm for model order reduction (MOR) over general frequency range of multiple input multiple output (MIMO) models such that $n \gg n_{\mathrm{r}}$, where n is the number of states of the model and n_{r} is the number of states of the reduced model, is presented. The first step of the algorithm is based on interpolation, and the second step is based on truncation of a descriptor model. An illustrative example with $n = 1000$, and $n_{\mathrm{r}} = 12$, with random numbers and frequency range consisted of two intervals, is presented. It is illustrated by examples that the truncated model is a much better approximation than the model obtained by the balanced truncation.

Keywords:
Model order reduction, Frequency range, Interpolation.

1. Introduction: Problem statement, literature review and announcing results

Model Order Reduction (MOR) has numerous important applications across many fields. Here are the key application areas:

Engineering Applications

1. Control Systems
- Controller Design: Reduce high-order controllers to lower-order implementations.
- Real-time control: Enable fast computation for embedded systems.
- System simulation: Faster simulation of complex dynamical systems.

2. Structural Engineering
- Finite Element Models: Reduce large-scale structural models for dynamic analysis.
- Vibration analysis: Study modal behaviour with reduced computational cost.
- Aerospace structures: Aircraft wing flutter analysis, satellite dynamics.

3. Electrical Engineering
- Circuit simulation: Reduce large RLC networks for faster SPICE simulations.
- Microelectromechanical systems (MEMS): Complex MEMS device modelling.
- Power systems: Grid stability analysis with reduced models.

4. Fluid Dynamics
- Computational Fluid Dynamics (CFD): Reduce Navier-Stokes models for real-time flow control.
- Aerodynamic design: Aircraft and automotive design optimization.
- Weather prediction: Reduced-order climate models.

Scientific Computing

5. Computational Physics
- Plasma physics: Tokamak fusion reactor control.
- Quantum systems: Molecular dynamics simulations.
- Electro-magnetics: Antenna design, radar cross-section analysis.

6. Materials Science
- Composite materials: Multi-scale modelling.
- Crystal growth: Process optimization.
- Polymer dynamics: Complex material behaviour prediction.

Emerging Applications

7. Machine Learning & AI
- Neural network compression: Reduce model size for edge deployment.
- Time series analysis: Efficient sequence modelling.

- Reinforcement learning: Fast policy evaluation.

8. Biomedical Engineering

- Biomechanical systems: Joint dynamics, muscle modelling.
- Neural systems: Brain network dynamics.
- Drug delivery: Pharmacokinetic modelling.

9. Economics & Finance

- High-frequency trading: Fast market dynamics prediction.
- Risk management: Portfolio optimization under uncertainty.
- Macroeconomic modelling: Reduced-order economic systems.

To define the problem formally, consider that transfer matrix $\boldsymbol{G}(s) = D + C(sI_n - A)^{-1}B$, with real matrices A, B, C and $D \in \mathbb{R}^{p\times m}$ of compatible dimensions with stable matrix A, and index $n_{\rm r}$ are given. Given also frequency range $\mathbb{B} \subseteq \mathbb{R}$, symmetric with respect to $0 \in \mathbb{R}$. Most frequently, $\mathbb{B}$ is the low range $\mathbb{B} = [-\omega_\ell, \omega_\ell]$, the middle range $\mathbb{B} = [\omega_1, \omega_2]\cup[-\omega_2, -\omega_1]$ and the high range $\mathbb{B} = [\omega_{\rm h}, \infty]\cup[-\infty, -\omega_{\rm h}]$, for some positive frequencies ω_ℓ, $\omega_1 < \omega_2$ and $\omega_{\rm h}$. In general, $\mathbb{B}$ is a disjunct union of the above three types of intervals. The need of the following Problem 1 occurs when the spectrum of the input is known to be in $\mathbb{B}$.

Problem 1: Find a proper stable rational matrix (RM) denoted by $\boldsymbol{G}_{\rm r}(s) = D_{\rm r}+C_{\rm r}(sI_{n_{\rm r}}-A_{\rm r})^{-1}B_{\rm r}$, for some real matrices $A_{\rm r}$, $B_{\rm r}$, $C_{\rm r}$ and $D_{\rm r}$ of compatible dimensions such that $\sup_{\omega\in\mathbb{B}} \|\boldsymbol{G}(\mathrm{j}\omega) - \boldsymbol{G}_{\rm r}(\mathrm{j}\omega)\| = \|\boldsymbol{G}(\mathrm{j}\omega) - \boldsymbol{G}_{\rm r}(\mathrm{j}\omega)\|_\infty^{\mathbb{B}} < \gamma$, where $\gamma > 0$ is as small as possible.

The earliest method for Problem 1 is to apply weighting RMs in the given frequency range $\mathbb{B}$, [1], [8], [22], and Section 7.2 in [23], and then to apply the balanced truncation. A general drawback of this method is that it is not known how to choose the weighting RMs in order to obtain better approximation and less order $n_{\rm r}$. Another principal drawback is the increasing by the order of the weighting RMs, the order of the starting model, while the aim is to obtain an approximation model of as less as possible order.

Another variant of the balanced truncation method is presented in [7], [9] and references therein. It is based on the frequency range Gramians. As stated in Remark 6 in [7], the method is not suitable for large-scale systems, due to its computational complexity.

The generalized Kalman-Yakubovič-Popov (GKYP) lemma, [6], has successfully been applied to control problems over frequency range, [16], [17]. Almost all such problems, including Problem 1, are special case of the $\mathscr{H}_\infty^{\mathbb{B}}$ control problem, formally defined in Section 2.1 of [10]. Problem 1 is elaborated in [6] and [18] and examples of low order $n = 4$ and SISO models are given. The key tool is again the GKYP lemma. A general drawback of this method is that non-convex matrix inequalities have to be solved, therefore this method is not suitable for large order MIMO models.

In Section 2.1 of [20], it is presented an order reduction of a solution to a general interpolation problem, with as small as possible norm in $\mathrm{j}\mathbb{B}$ of the interpolant.

The interpolation method can be applied to find performance bounds in controlled systems. There are series of papers starting with Section V of [5], which present a number of expressions and bounds for the best achievable $\mathscr{H}_\infty$ norms of the sensitivity and complementary sensitivity functions. However, these results concern the whole frequency axis.

In this paper we present a two-step algorithm for MOR over frequency range of large-order MIMO models. Our order reduction differs of the reduction in [20], and of all above referred methods. The first step is based on interpolation, and the second step is a novel truncation of the descriptor model of the interpolant. The algorithm is illustrated in detail by Examples 1–2. It is shown that the algorithm is advantageous with respect to literature.

A. Remarks on the notation

All functions of the complex argument s are rational and are denoted by bold-faced letters. Abbreviations RM, FGE, and IGE mean rational matrix, finite generalized eigenvalue and infinite generalized eigenvalue. By $\mathbb{R}$ and $\mathbb{C}$ we denote the sets of real and complex numbers. j is the imaginary unit. We denote $\overline{\mathbb{R}} = \mathbb{R}\cup\{\infty\}$, $\mathbb{C}_+ = \{s \in \mathbb{C} :\ \Re[s] > 0\}$, $\overline{\mathbb{C}}_+ = \{s \in \mathbb{C} :\ \Re[s] \geqslant 0\}$, $\mathbb{C}_- = \{s \in \mathbb{C} :\ \Re[s] < 0\}$ and $\overline{\mathbb{C}}_- = \{s \in \mathbb{C} :\ \Re[s] \leqslant 0\}$, where by $\Re[s]$ we denote the real part of s.

The descriptor system $E\dot{x} = Ax$ is stable if its associated matrix pencil $A - sE$ has no FGEs in $\overline{\mathbb{C}}_+$, and is impulse-free if $A - sE$ has no IGEs of multiplicity > 1. Finite and infinite invariant zeros of descriptor system $E\dot{x}(t) = Ax(t)+Bu(t)$, $y(t) = Cx(t)+Du(t)$ are the FGEs and IGEs of its associated

pencil $\begin{bmatrix} A-sE & B \\ C & D \end{bmatrix}$. The associated transfer matrix to the latter system is $\boldsymbol{H} = D + C(sE - A)^{-1}B$. The finite zeros of RM $\boldsymbol{H}$ are equal to the finite invariant zeros of any minimal realization of RM $\boldsymbol{H}$, while the orders of its infinite zeros are equal to the multiplicities of the IGEs of the associated pencil to the minimal realization, minus 1.

By the superscripts $^{\mathrm{T}}$ and * we denote the transpose and conjugate transpose of complex matrices. If H is a complex matrix, by $\overline{H}$ we denote its conjugate complex. By $\mathrm{diag}(S_1, S_2, \ldots, S_k)$ we denote the diagonal matrix with matrices $S_1, S_2, \ldots, S_k$ on its main diagonal. By $\|\cdot\|$ we denote the spectral norm, i.e., maximal singular value of a complex matrix. If $\boldsymbol{H}(s)$ is an RM without poles on $\mathrm{j}\mathbb{B}$, for some frequency range $\mathbb{B} \subseteq \overline{\mathbb{R}}$, we define number $\|\boldsymbol{H}\|_\infty^{\mathbb{B}} = \sup_{\omega\in\mathbb{B}} \|\boldsymbol{H}(\mathrm{j}\omega)\|$. If $\mathbb{B} = \overline{\mathbb{R}}$, we omit the superscript $\overline{\mathbb{R}}$ in $\|\boldsymbol{H}\|_\infty$.

2. Known results

A. Known interpolation formula

For given interpolation points $s_1, s_2, \ldots, s_k$ in the open right complex half-plane $\mathbb{C}_+$, consider the following interpolation conditions for the unknown complex stable RM $\boldsymbol{U}(s)$ (called interpolant):

$$\boldsymbol{U}(s_i)x_i = y_i, \quad i = 1, 2, \ldots, k\,, \tag{1}$$

for some complex vectors x_i and y_i. Define the matrices:

$$A_2 = \mathrm{diag}(s_1, s_2, \ldots, s_k) \quad C_{12} = [y_1, y_2, \ldots, y_k] \quad C_{22} = [x_1, x_2, \ldots, x_k]\,. \tag{2}$$

Under the assumption that matrix pair (A_2, C_{22}) is observable, there is unique solution $F_{22} > 0$ of the Lyapunov equation

$$A_2^* F_{22} + F_{22} A_2 = C_{22}^* C_{22}\,. \tag{3}$$

Proposition 1: If matrix pair (A_2, C_{22}) is observable, all solutions to the interpolation problem (1) are given by the following interpolants

$$\boldsymbol{U} = \boldsymbol{U}_{\mathrm{p}} + \boldsymbol{V}\boldsymbol{\Theta}_{22}^{-1}. \tag{4}$$

where

$$\boldsymbol{U}_{\mathrm{p}} = \boldsymbol{\Theta}_{12}\boldsymbol{\Theta}_{22}^{-1} = C_{12}(sI_k - A_2 + F_{22}^{-1}C_{22}^*C_{22})^{-1}F_{22}^{-1}C_{22}^*\,, \tag{5}$$

$$\begin{aligned} \boldsymbol{\Theta}_{12} &= C_{12}(sI_k - A_2)^{-1}F_{22}^{-1}C_{22}^*\,, \\ \boldsymbol{\Theta}_{22} &= I_m + C_{22}(sI_k - A_2)^{-1}F_{22}^{-1}C_{22}^*\,. \end{aligned} \tag{6}$$

and $\boldsymbol{V}$ is an arbitrary stable complex RM. RM $\boldsymbol{U}$ is proper if and only if RM $\boldsymbol{V}$ is proper.

Next we apply Proposition 1 to the problem to find a stable interpolant $\boldsymbol{H}(s)$ such that $\boldsymbol{H}(\mathrm{j}\vartheta_i) = \boldsymbol{G}(\mathrm{j}\vartheta_i)$, $i = 1, 2, \ldots, k$, for some $\vartheta_1, \vartheta_2, \ldots, \vartheta_k \in \mathbb{R}$. An intuitively good choice for Problem 1 is to take $\vartheta_1, \vartheta_2, \ldots, \vartheta_k \in \mathbb{B}$, but we shall see later that it is not optimal.

Since imaginary axis interpolation points are not allowed in Proposition 1, for some $\alpha > 0$, we introduce the interpolation points by $s_i := \alpha + \mathrm{j}\vartheta_i \in \mathbb{C}_+$, $i = 1, 2, \ldots, k$. Define RM $\boldsymbol{H}(s) = \boldsymbol{U}(s+\alpha)$ and vectors $y_i = \boldsymbol{G}(\mathrm{j}\vartheta_i)x_i$, $i = 1, 2, \ldots, k$. By Proposition 1, RM $\boldsymbol{H}$ is stable and satisfies $\boldsymbol{H}(\mathrm{j}\vartheta_i)x_i = \boldsymbol{G}(\mathrm{j}\vartheta_i)x_i$, $i = 1, 2, \ldots, k$.

However, we do not need the tangential conditions, but the conditions $\boldsymbol{H}(\mathrm{j}\vartheta_i) = \boldsymbol{G}(\mathrm{j}\vartheta_i)$, $i = 1, 2, \ldots, k$. For that purpose, for a particular $\mathrm{j}\vartheta_i$, we take all unity m-dimensional vectors $e_1, e_2, \ldots, e_m$ as x-vectors.

Then from the conditions $\boldsymbol{H}(\mathrm{j}\vartheta_i)e_h = \boldsymbol{G}(\mathrm{j}\vartheta_i)e_h$, $h = 1, 2, \ldots, m$, it follows that $\boldsymbol{H}(\mathrm{j}\vartheta_i) = \boldsymbol{G}(\mathrm{j}\vartheta_i)$.

The above requirements are stated as an assumption.

Assumption 1:

$$A_2 = \mathrm{diag}((\alpha + \mathrm{j}\vartheta_1)I_m, (\alpha + \mathrm{j}\vartheta_{m+1})I_m, \ldots, (\alpha + \mathrm{j}\vartheta_{k-m})I_m)\,, \quad C_{22} = [I_m, I_m, \ldots, I_m]$$

and $\vartheta_1, \vartheta_{m+1}, \ldots, \vartheta_{k-m}$ are distinct.

An equivalent statement is that $x_1 = \cdots = x_m = e_1$, $x_{m+1} = \cdots = x_{2m} = e_2$, ..., $x_{k-m+1} = \cdots = x_k = e_m$. and

$$\vartheta_1 = \cdots = \vartheta_m \neq \vartheta_{m+1} = \cdots = \vartheta_{2m} \neq \cdots \vartheta_{k-m+1} = \cdots = \vartheta_k$$

A consequence of Assumption 1 is that k/m is an integer. The following proposition is easy to prove.

Proposition 2: Under Assumption 1, matrix pair (A_2, C_{22}) is observable.

B. Handling complex interpolation points

The algorithm of Proposition 1 gives complex interpolants, but we require real ones. For that reason, we proceed as follows. Form complex matrices A_2, C_{12} and C_{22}, defined in (2). Since RM $\boldsymbol{G}$ is real and we require a real interpolant, with each interpolation condition $\boldsymbol{U}(s_i)x_i = \boldsymbol{H}(\mathrm{j}\vartheta_i)x_i = \boldsymbol{G}(\mathrm{j}\vartheta_i)x_i = y_i$, there is a conjugate complex one, i.e., $\boldsymbol{U}(\bar{s}_i)\bar{x}_i = \boldsymbol{H}(-\mathrm{j}\vartheta_i)\bar{x}_i = \boldsymbol{G}(-\mathrm{j}\vartheta_i)\bar{x}_i = \bar{y}_i$. If $0 \notin \{\vartheta_1, \vartheta_2, \ldots, \vartheta_k\}$, k is even. In that case, we reorder the interpolation conditions (1) such that a condition and its conjugate complex condition are consecutive. Define matrices $T_0 = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & \mathrm{j} \\ 1 & -\mathrm{j} \end{bmatrix}$ and

$$T = \mathrm{diag}(\underbrace{T_0, T_0, \ldots, T_0}_{k/2 \text{ times}}), \tag{7}$$

which is $k \times k$ dimensional and unitary. If some of $\vartheta_1, \vartheta_2, \ldots, \vartheta_k$ are zero, we take matrix T such that there are 1's, instead of T_0's, on the corresponding places.

Replace the complex matrices A_2, C_{12} and C_{22}, defined in (2), by the real matrices T^*A_2T, $C_{12}T$ and $C_{22}T$. The observability of the pair (A_2, C_{22}) is preserved.

Solve in a real matrix F_{22} equation (3). Then interpolant $\boldsymbol{H}$ in (4) is real if and only if RM $\boldsymbol{V}$ is real. It is stable for all RMs $\boldsymbol{V}$ such that RM $\boldsymbol{V}(s+\alpha)$ is stable.

Consider that $\boldsymbol{V}(s) =: V$ is a constant real matrix. The reason is that constant matrices do not increase the degree of interpolant $\boldsymbol{H}$. Indeed, it is easy to prove that formula (4) becomes

$$\boldsymbol{H}(s) = \boldsymbol{U}(s+\alpha) = V + (C_{12} - VC_{22})(sF_{22} - F_{22}A_2 + C_{22}^{\mathrm{T}}C_{22} + \alpha F_{22})^{-1}C_{22}^{\mathrm{T}}, \tag{8}$$

where matrices F_{22}, A_2 and C_{22} are already transformed to real ones, using transformation matrix T in (7).

The formula (8) comprises Step 1 of our proposed algorithm.

3. Residual of the interpolation

In this section we find the residual of the interpolation $\boldsymbol{G} - \boldsymbol{H}$, where $\boldsymbol{H}$ is the interpolant given in (8). We assume for simplicity that $\boldsymbol{G}$ is a stable RM, whose poles are simple (not necessarily distinct). Denote those poles by $z_1, z_2, \ldots, z_q \in \mathbb{C}_-$. Then there is a partial fraction expansion

$$\boldsymbol{G}(s) = D + \sum_{h=1}^{q} \frac{G_h}{s - z_h},$$

for some complex matrices $G_1, G_2, \ldots, G_q$. Introduce the following RMs

$$\begin{aligned} \widetilde{\boldsymbol{\Theta}}_{12}(s) &:= \boldsymbol{\Theta}_{12}(s+\alpha) = C_{12}\widetilde{\boldsymbol{\Omega}}_2(s)F_{22}^{-1}C_{22}^*, \\ \widetilde{\boldsymbol{\Theta}}_{22}(s) &:= \boldsymbol{\Theta}_{22}(s+\alpha) = I_m + C_{22}\widetilde{\boldsymbol{\Omega}}_2(s)F_{22}^{-1}C_{22}^*, \end{aligned} \tag{9}$$

where RMs $\boldsymbol{\Theta}_{12}(s)$ and $\boldsymbol{\Theta}_{22}(s)$ are given in (6), and $\widetilde{\boldsymbol{\Omega}}_2(s) := (sI_k - \widetilde{A}_2)^{-1}$, $\widetilde{A}_2 = \mathrm{diag}(\mathrm{j}\vartheta_1, \mathrm{j}\vartheta_2, \ldots, \mathrm{j}\vartheta_k)$.

Theorem 1: The residual of the interpolation is given by

$$\boldsymbol{G}(s) - \boldsymbol{H}(s) = \left(D - V + \sum_{h=1}^{q} \frac{G_h \widetilde{\boldsymbol{\Theta}}_{22}(z_h)}{s - z_h} \right) \widetilde{\boldsymbol{\Theta}}_{22}(s)^{-1}. \tag{10}$$

4. Justification of the interpolation and approximation error bound

The reason why RM $\boldsymbol{H}$ interpolates RM $\boldsymbol{G}$ in the points $\mathrm{j}\vartheta_1, \mathrm{j}\vartheta_2, \ldots, \mathrm{j}\vartheta_k$ is given in the following proposition.

Proposition 3: $\widetilde{\boldsymbol{\Theta}}_{22}(\mathrm{j}\vartheta_i)^{-1}x_i = 0$, $i = 1, 2, \ldots, k$.

The RM $\widetilde{\boldsymbol{\Theta}}_{22}^{-1}$ does affect the interpolation error not only in the interpolation points, but also in the points between them. To explain the latter affection, three technical lemmas are needed.

Lemma 1: Let $\boldsymbol{\Theta}(s)^{-1}$ be an inner RM of the form

$$\boldsymbol{\Theta}(s)^{-1} = I - CF^{-1}(sI + A^*)^{-1}C^*, \tag{11}$$

for some matrix A, whose eigenvalues are in $\mathbb{C}_+$, and matrices C and $F > 0$ such that the Lyapunov equation

$$A^*F + FA = C^*C$$

is satisfied. Define RM $\widetilde{\boldsymbol{\Theta}}(s) := \boldsymbol{\Theta}(s+\alpha)$, $\alpha > 0$. For all $\omega \in \mathbb{R}$, it holds $\|\widetilde{\boldsymbol{\Theta}}(\mathrm{j}\omega)^{-1}\| \leqslant 1$. In particular,

$$\|\widetilde{\boldsymbol{\Theta}}_{22}(\mathrm{j}\omega)^{-1}\| \leqslant 1\ , \quad \omega \in \mathbb{R}\,. \tag{12}$$

We need a detailed structure of RM $\widetilde{\boldsymbol{\Theta}}_{22}^{-1}$.

Let $\boldsymbol{\Theta}(s)^{-1}$ be the inner RM from the formulation of Lemma 1, see (11) (Matrix $-A^*$ is stable.) Define unitary matrix W such that

$$W^*A^*W = \begin{bmatrix} A_1^* & U^* \\ 0 & A_2^* \end{bmatrix},$$

for some matrices A_1, A_2 and U, matrices of compatible dimensions

$$CW =: [C_1, C_2], \quad W^*FW =: \begin{bmatrix} F_{11} & F_{12} \\ F_{12}^{\mathsf{T}} & F_{22} \end{bmatrix},$$

and matrices

$$\widetilde{C}_1 := C_1 - C_2F_{22}^{-1}F_{12}^{\mathsf{T}}, \quad \widetilde{F}_{11} := F_{11} - F_{12}F_{22}^{-1}F_{12}^{\mathsf{T}}\,.$$

Matrices $\widetilde{F}_{11}$ and F_{22} satisfy the following Lyapunov equations

$$A_1^*\widetilde{F}_{11} + \widetilde{F}_{11}A_1 = \widetilde{C}_1^*\widetilde{C}_1\ , \quad A_2^*F_{22} + F_{22}A_2 = C_2^*C_2\,.$$

Lemma 2: The factorization $\boldsymbol{\Theta}^{-1} = \boldsymbol{\Theta}_1^{-1}\boldsymbol{\Theta}_2^{-1}$ on inner RMs $\boldsymbol{\Theta}_1$ and $\boldsymbol{\Theta}_2$ holds, where

$$\boldsymbol{\Theta}_1^{-1} = I - \widetilde{C}_1\widetilde{F}_{11}^{-1}(sI + A_1^*)^{-1}\widetilde{C}_1^*\,, \quad \boldsymbol{\Theta}_2^{-1} = I - C_2F_{22}^{-1}(sI + A_2^*)^{-1}C_2^*\,.$$

Proof. A consequence of Theorem 3.2 in [15]. ■

Assumption 2: $\infty \notin \mathbb{B}$ and $\vartheta_1, \vartheta_2, \ldots, \vartheta_k \in [-b, b]$, for some $b > 0$ such that $\mathbb{B} \subseteq [-b, b]$.

Lemma 3: Under Assumptions 1 and 2,

$$\left\|\widetilde{\boldsymbol{\Theta}}_{22}^{-1}\right\|_\infty^{\mathbb{B}} \leqslant \beta^{k/m}\,, \tag{13}$$

where RM $\widetilde{\boldsymbol{\Theta}}_{22}$ is defined in (9), and $\beta = b/\sqrt{\alpha^2 + b^2}$.

Assumption 3: $\|\widetilde{\boldsymbol{\Theta}}_{22}(z_h)\| \leqslant 1$, $h = 1, 2, \ldots, q$.

The following proposition proves that α can be chosen so that Assumption 3 holds.

Proposition 4: If α and transfer matrix $\boldsymbol{G}$ satisfy

$$0 > -\alpha \geqslant \Re[z_h]\,, \quad h = 1, 2, \ldots, q\,, \tag{14}$$

then Assumption 3 holds.

5. Main theorem for approximation error bound

Theorem 2: Under Assumptions 1–3, for given $\epsilon > 0$, there is a sufficiently large k (the number of interpolation points) such that $\|\boldsymbol{G} - \boldsymbol{H}\|_\infty^{\mathbb{B}} < \epsilon$.

Proof. By Lemma 3, and Theorem 1, we have

$$\begin{aligned}\|\boldsymbol{G} - \boldsymbol{H}\|_\infty^{\mathbb{B}} &\leqslant \left(\|D - V\| + \sum_{h=1}^{q}\|G_h\|\left\|\widetilde{\boldsymbol{\Theta}}_{22}(z_h)\right\|\left\|\frac{1}{s - z_h}\right\|_\infty^{\mathbb{B}}\right)\left\|\widetilde{\boldsymbol{\Theta}}_{22}^{-1}\right\|_\infty^{\mathbb{B}} \\ &\leqslant \left(\|D - V\| + \sum_{h=1}^{q}\frac{\|G_h\|}{f_h}\right)\beta^{k/m}\,,\end{aligned} \tag{15}$$

where f_h is given by $f_h = \max_{\omega\in\mathbb{B}}|\mathrm{j}\omega - z_h|$ and satisfies $\|1/(s - z_h)\|_\infty^{\mathbb{B}} = 1/f_h$.

The proof is completed by (15), because by taking sufficiently large k, we can achieve that $\|\boldsymbol{G} - \boldsymbol{H}\|_\infty^{\mathbb{B}}$ is less than any $\epsilon > 0$, due to inequality $\beta < 1$, and that β does not depend on k and on $\vartheta_1, \vartheta_2, \ldots, \vartheta_k$.

A. Truncation of descriptor model

Consider interpolant $\boldsymbol{H}$, given by the descriptor realization in (8). Note that $F_{22} > 0$. Let $\mathcal{Q}$ be an orthogonal matrix such that

$$\mathcal{Q}^{\mathrm{T}} F_{22} \mathcal{Q} = \begin{bmatrix} \mathcal{E}_{11} & 0 \\ 0 & \mathcal{E}_{22} \end{bmatrix}, \tag{16}$$

where $\mathcal{E}_{11} = \mathrm{diag}(\sigma_1, \ldots, \sigma_\nu)$, $\mathcal{E}_{22} = \mathrm{diag}(\sigma_{\nu+1}, \ldots, \sigma_k)$, and $\sigma_1, \ldots, \sigma_\nu$, $\sigma_{\nu+1}, \ldots, \sigma_k$ are the eigenvalues of matrix F_{22}, written in increasing order, all positive.

Denote $n_{\mathrm{r}} := n - \nu$. Introduce the compatible to (16) partitions:

$$\begin{bmatrix} \mathcal{A}_{11} & \mathcal{A}_{12} \\ \mathcal{A}_{21} & \mathcal{A}_{22} \end{bmatrix} := \mathcal{Q}^{\mathrm{T}}(F_{22}A_2 - C_{22}^{\mathrm{T}} C_{22} - \alpha F_{22})\mathcal{Q}\ , \quad \begin{bmatrix} \mathcal{B}_1 \\ \mathcal{B}_2 \end{bmatrix} := \mathcal{Q}^{\mathrm{T}} C_{22}^{\mathrm{T}}\ , \quad [\mathcal{C}_1, \mathcal{C}_2] := (C_{12} - VC_{22})\mathcal{Q}\,.$$

Now choose α such that matrix $\mathcal{A}_{11}$ is nonsingular, and introduce the matrices: $\mathcal{E}_{\mathrm{r}} := \mathcal{E}_{22}$,

$$\mathcal{A}_{\mathrm{r}} := \mathcal{A}_{22} - \mathcal{A}_{21}\mathcal{A}_{11}^{-1}\mathcal{A}_{12}\ , \quad \mathcal{B}_{\mathrm{r}} := \mathcal{B}_2 - \mathcal{A}_{21}\mathcal{A}_{11}^{-1}\mathcal{B}_1\ , \quad C_{\mathrm{r}} := \mathcal{C}_2 - \mathcal{C}_1\mathcal{A}_{11}^{-1}\mathcal{A}_{12}\ , \quad D_{\mathrm{r}} := V - \mathcal{C}_1\mathcal{A}_{11}^{-1}\mathcal{B}_1$$

and RMs $\boldsymbol{\Omega}_{\mathrm{r}}(s) = (s\mathcal{E}_{\mathrm{r}} - \mathcal{A}_{\mathrm{r}})^{-1}$, $\boldsymbol{\Psi}(s) = s(s\mathcal{E}_{11} - \mathcal{A}_{11})^{-1}$,

$$\boldsymbol{G}_{\mathrm{r}}(s) = D_{\mathrm{r}} + C_{\mathrm{r}}(sI_{n_{\mathrm{r}}} - A_{\mathrm{r}})^{-1}B_{\mathrm{r}}\,, \tag{17}$$

where $A_{\mathrm{r}} = \mathcal{E}_{\mathrm{r}}^{-1}\mathcal{A}_{\mathrm{r}}$, $B_{\mathrm{r}} = \mathcal{E}_{\mathrm{r}}^{-1}\mathcal{B}_{\mathrm{r}}$.

Theorem 3: If α is chosen so that $\mathcal{A}_{11}$ is nonsingular then the matrix approximation error equals

$$\boldsymbol{H}(s) - \boldsymbol{G}_{\mathrm{r}}(s) = (\mathcal{C}_1 + C_{\mathrm{r}}\boldsymbol{\Omega}_{\mathrm{r}}\mathcal{A}_{21})\mathcal{A}_{11}^{-1}\mathcal{E}_{11}(I - \boldsymbol{\Psi}\mathcal{A}_{12}\boldsymbol{\Omega}_{\mathrm{r}}\mathcal{A}_{21}\mathcal{A}_{11}^{-1}\mathcal{E}_{11})^{-1}\boldsymbol{\Psi}(\mathcal{B}_1 + \mathcal{A}_{12}\boldsymbol{\Omega}_{\mathrm{r}}B_{\mathrm{r}}) \tag{18}$$

and matrix A_{r} is stable.

Proof. Consider the system with input $\boldsymbol{u}$ and output $\boldsymbol{y}$:

$$\begin{aligned} \mathcal{E}_{11}s\boldsymbol{x}_1 &= \mathcal{A}_{11}\boldsymbol{x}_1 + \mathcal{A}_{12}\boldsymbol{x}_2 + \mathcal{B}_1\boldsymbol{u}\,, \\ \mathcal{E}_{22}s\boldsymbol{x}_2 &= \mathcal{A}_{21}\boldsymbol{x}_1 + \mathcal{A}_{22}\boldsymbol{x}_2 + \mathcal{B}_2\boldsymbol{u}\,, \\ \boldsymbol{y} &= \mathcal{C}_1\boldsymbol{x}_1 + \mathcal{C}_2\boldsymbol{x}_2 + \mathcal{D}\boldsymbol{u}\,, \end{aligned} \tag{19}$$

whose associated transfer matrix is $\boldsymbol{H}$, i.e., $\boldsymbol{y} = \boldsymbol{H}\boldsymbol{u}$. From the upper equation in (19) it follows

$$\boldsymbol{x}_1 = \mathcal{A}_{11}^{-1}\mathcal{E}_{11}s\boldsymbol{x}_1 - \mathcal{A}_{11}^{-1}\mathcal{A}_{12}\boldsymbol{x}_2 - \mathcal{A}_{11}^{-1}\mathcal{B}_1\boldsymbol{u}\,.$$

Replacing this $\boldsymbol{x}_1$ in the other equations in (19), we obtain

$$\mathcal{E}_{22}s\boldsymbol{x}_2 = \mathcal{A}_{21}\mathcal{A}_{11}^{-1}\mathcal{E}_{11}s\boldsymbol{x}_1 + \mathcal{A}_{\mathrm{r}}\boldsymbol{x}_2 + \mathcal{B}_{\mathrm{r}}\boldsymbol{u}\,,$$

which identity we re-write as

$$\boldsymbol{x}_2 = \boldsymbol{\Omega}_{\mathrm{r}}\mathcal{A}_{21}\mathcal{A}_{11}^{-1}\mathcal{E}_{11}s\boldsymbol{x}_1 + \boldsymbol{\Omega}_{\mathrm{r}}\mathcal{B}_{\mathrm{r}}\boldsymbol{u}$$

and identity

$$\boldsymbol{y} = \mathcal{C}_1\mathcal{A}_{11}^{-1}\mathcal{E}_{11}s\boldsymbol{x}_1 + \mathcal{C}_{\mathrm{r}}\boldsymbol{x}_2 + \mathcal{D}_{\mathrm{r}}\boldsymbol{u} = (\mathcal{C}_1 + \mathcal{C}_{\mathrm{r}}\boldsymbol{\Omega}_{\mathrm{r}}\mathcal{A}_{21})s\boldsymbol{x}_1 + \boldsymbol{G}_{\mathrm{r}}\boldsymbol{u}\,. \tag{20}$$

We find $s\boldsymbol{x}_1$ from:

$$s\boldsymbol{x}_1 = \boldsymbol{\Psi}\mathcal{A}_{12}\boldsymbol{x}_2 + \boldsymbol{\Psi}\mathcal{B}_1\boldsymbol{u} = \boldsymbol{\Psi}\mathcal{A}_{12}(\boldsymbol{\Omega}_{\mathrm{r}}\mathcal{A}_{21}\mathcal{A}_{11}^{-1}\mathcal{E}_{11}s\boldsymbol{x}_1 + \boldsymbol{\Omega}_{\mathrm{r}}\mathcal{B}_{\mathrm{r}}\boldsymbol{u}) + \boldsymbol{\Psi}\mathcal{B}_1\boldsymbol{u}$$

and replace in (20) to obtain (18).

It remains to prove the stability of the reduced realization (17). It is also given by the following descriptor system:

$$\boldsymbol{G}_{\mathrm{r}}(s) = V + (C_{12} - VC_{22})\left(s\mathcal{Q}\begin{bmatrix} 0 & 0 \\ 0 & \mathcal{E}_{22} \end{bmatrix}\mathcal{Q}^{\mathrm{T}} - F_{22}A_2 + C_{22}^{\mathrm{T}}C_{22} + \alpha F_{22}\right)^{-1} C_{22}^{\mathrm{T}}\,. \tag{21}$$

This descriptor system is stable if and only if matrix pencil

$$F_{22}A_2 - C_{22}^{\mathrm{T}}C_{22} - \mathcal{Q}\begin{bmatrix} \alpha\mathcal{E}_{11} & 0 \\ 0 & (s+\alpha)\mathcal{E}_{22} \end{bmatrix}\mathcal{Q}^{\mathrm{T}}$$

is nonsingular in $\overline{\mathbb{C}}_+$. The nonsingularity holds if the following inequality holds

$$\left(F_{22}A_2 - C_{22}^{\mathrm{T}}C_{22} - \mathcal{Q}\begin{bmatrix} \alpha\mathcal{E}_{11} & 0 \\ 0 & (s+\alpha)\mathcal{E}_{22} \end{bmatrix}\mathcal{Q}^{\mathrm{T}}\right) + (\star)^* < 0\,,$$

for all $s \in \overline{\mathbb{C}}_+$, where the notation $(X)+(\star)^*$ means $X+X^*$. This inequality indeed holds, because by (3), it is equivalent to the inequality

$$-C_{22}^{\mathrm{T}}C_{22} - \mathcal{Q}\begin{bmatrix} 2\alpha\mathcal{E}_{11} & 0 \\ 0 & (s+s^*+2\alpha)\mathcal{E}_{22} \end{bmatrix}\mathcal{Q}^{\mathrm{T}} < 0\,.$$

B. Practical considerations

1. Since the eigenvalues σ_i of matrix F_{22} are taken in the increasing order, **we can approximate the first ν of them by zero, and apply Theorem 3 in order to approximate $\boldsymbol{H}$ by $\boldsymbol{G}_{\mathrm{r}}$.**

The residual of our truncation is given in (18).

2. The interpolation points can be chosen by a **minimum searching algorithm**. In this work, we use the MATLAB function `fminsearch`.

C. Justification for the truncation

In this section we examine the eigenvalues $\sigma_1, \sigma_2, \ldots, \sigma_k$ of matrix F_{22}. By (3) and Assumption 1, matrix F_{22} does not depend on $\boldsymbol{G}$. Actually, it depends only on the number of its inputs m and outputs p, on α, and on the interpolation frequencies $\vartheta_1, \vartheta_2, \ldots, \vartheta_k$. Therefore, we tend to choose them such that a maximal number of eigenvalues of matrix F_{22} are small, by the requirement for minimal model order n_{r}.

In this section we assume that $\vartheta_1, \vartheta_2, \ldots, \vartheta_k \in \mathbb{B}$. To define them, we divide the intervals of $\mathbb{B}$ on subintervals of equal length, denoted by $\Delta\vartheta$ (referred to as frequency increment), and take the endpoints of the subintervals for $\vartheta_1, \vartheta_2, \ldots, \vartheta_k$. In what follows, although intuitively understandable, it will be explained mathematically why it is reasonable to take number $\Delta\vartheta$ sufficiently small.

Proposition 5: If matrix F_{22} is a solution of Lyapunov equation (3), in which matrix A_2 has no eigenvalues in $\overline{\mathbb{C}}_-$, then it is singular if and only if pair (A_2, C_{22}) is not observable, i.e., matrix $\mathcal{O} = \left[C_{22}^{\mathrm{T}}, A_2^{\mathrm{T}}C_{22}^{\mathrm{T}}, \ldots (A_2^{k-1})^{\mathrm{T}}C_{22}^{\mathrm{T}}\right]^{\mathrm{T}}$ has no full column rank.

In our case, matrices A_2 and C_{22} are given in (2), hence matrix $\mathcal{O}$ is

$$\mathcal{O} = \left[s_j^i x_j\right]_{i=0,,1,\ldots,k-1,\ j=1,2,\ldots,k}\,. \tag{22}$$

Assume that $m=1$, and that $\mathbb{B}$ is a single interval given by $\mathbb{B}=[\omega_1,\omega_2]$, where $0 \leqslant \omega_1 < \omega_2$, and $\vartheta_1 = \omega_1$, $\vartheta_{i+1} - \vartheta_i = \Delta\vartheta$, $i = 1, 2, \ldots, k-1$ (the conjugate complex interpolation points are not taken into account). Then $s_i = \widetilde{\alpha} + i\mathrm{j}\Delta\vartheta$, $i = 1, 2, \ldots, k$, where $\widetilde{\alpha} = \alpha + \mathrm{j}(\omega_1 - \Delta\vartheta)$.

In this case we can take $x_i = 1$, $i = 1, 2, \ldots, k$, without loss of generality. Then $\mathcal{O}$ in (22) is the Vandermonde matrix, and consequently

$$\det\mathcal{O} = \prod_{1\leqslant i<h\leqslant k}(s_h - s_i) = (\mathrm{j}\Delta\vartheta)^{\frac{k(k-1)}{2}} \prod_{1\leqslant i<h\leqslant k}(h-i)\,. \tag{23}$$

(Note that $\det\mathcal{O}$ is independent of α.) It is obvious from (23) that if $\Delta\vartheta$ is a sufficiently small number < 1, then matrix $\mathcal{O}$ is close to singular. A consequence of Proposition 5 is that matrix F_{22} is close to singular, which means that at least one of its eigenvalues (in particular, σ_1) is close to zero. Then Step 2 of the algorithm can be applied.

In order to illustrate that $|\det\mathcal{O}|$ is indeed close to zero for small $\Delta\vartheta$, we proceed as follows. For given k, denote by $\Delta\vartheta_{\max}$ the positive number such that $|\det\mathcal{O}| < 10^{-7}$ for all $\Delta\vartheta < \Delta\vartheta_{\max}$. The dependence on the number of interpolation points $k \in \{5, 6, \ldots, 16\}$ of $\Delta\vartheta_{\max}$, computed by (23), is presented in Fig. 1. Note that the maximum appears for $k = 10$.

6. An error bound of the reduced model

An approximation error bound of Problem 1 is given by

$$\|\boldsymbol{G} - \boldsymbol{G}_{\mathrm{r}}\|_\infty^{\mathbb{B}} = \|(\boldsymbol{G}-\boldsymbol{H}) + (\boldsymbol{H}-\boldsymbol{G}_{\mathrm{r}})\|_\infty^{\mathbb{B}} \leqslant \|\boldsymbol{G}-\boldsymbol{H}\|_\infty^{\mathbb{B}} + \|\boldsymbol{H}-\boldsymbol{G}_{\mathrm{r}}\|_\infty^{\mathbb{B}}\,,$$

where the interpolation residual $\boldsymbol{G}-\boldsymbol{H}$ and its approximation bound are given by (10) and (15), respectively, and the truncation residual $\boldsymbol{H}-\boldsymbol{G}_{\mathrm{r}}$ is given by (18).

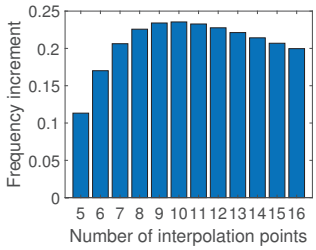


Fig. 1: Dependence on k of $\Delta\vartheta_{\max}$ defined such that $|\det \mathcal{O}| < 10^{-7}$ for all $\Delta\vartheta < \Delta\vartheta_{\max}$

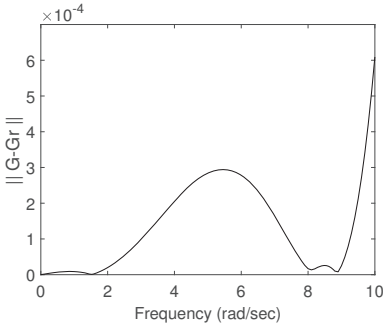


Fig. 2: Frequency dependence $\|\boldsymbol{G}(\mathrm{j}\omega) - \boldsymbol{G}_{\mathrm{r}}(\mathrm{j}\omega)\|$, $\omega \in [0, 10]$

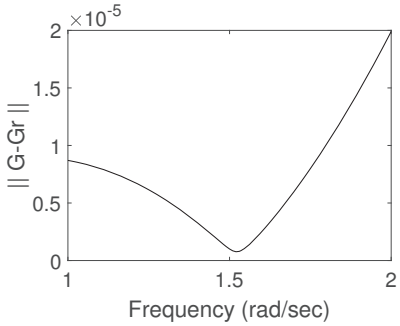


Fig. 3: Frequency dependence $\|\boldsymbol{G}(\mathrm{j}\omega) - \boldsymbol{G}_{\mathrm{r}}(\mathrm{j}\omega)\|$ in interval $[1, 2]$

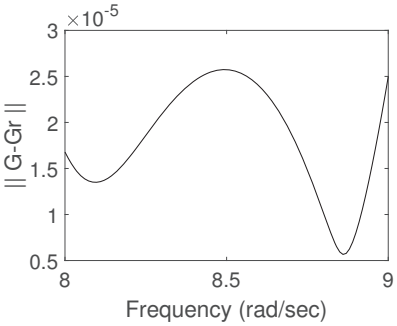


Fig. 4: Frequency dependence $\|\boldsymbol{G}(\mathrm{j}\omega) - \boldsymbol{G}_{\mathrm{r}}(\mathrm{j}\omega)\|$ in interval $[8, 9]$

7. Examples

Example 1: The realization of RM $\boldsymbol{G}$ has order $n = 1000$, $p = 3$ outputs and $m = 2$ inputs. It is given by matrices A, B, C and D, stored in the MATLAB file redfs3.mat (available on request). The entries of the matrices are random integers from the interval $[-5, 5]$, except that matrix A is made stable by subtracting $110 \cdot I_{1000}$ from the original random matrix. For matrix A, we find that the maximal real part of its eigenvalues is -11.7169.

The considered frequency range is given by $[\omega_1, \omega_2] \cup [\omega_3, \omega_4] = [1, 2] \cup [8, 9]$, and symmetrically on the negative real axis. Take the number of interpolation points $k = 24$.

Take $\alpha = 10.5$, which satisfies condition (14), and $\vartheta_1, \vartheta_2, \ldots, \vartheta_{24}$ equal to: 1, -1, 1, -1, 1.5, -1.5, 1.5, -1.5, 2, -2, 2, -2, 8.2, -8.2, 8.2, -8.2, 8.615, -8.615, 8.615, -8.615, 9.03, -9.03, 9.03, -9.03. Consider also $x_1 = x_2 = x_5 = x_6 = x_9 = x_{10} = x_{13} = x_{14} = x_{17} = x_{18} = x_{21} = x_{22} = [1, 0]^{\mathrm{T}}$, and $x_3 = x_4 = x_7 = x_8 = x_{11} = x_{12} = x_{15} = x_{16} = x_{19} = x_{20} = x_{23} = x_{24} = [1, 0]^{\mathrm{T}}$. Then we compute the corresponding vectors $y_i = \boldsymbol{G}(\mathrm{j}\vartheta_i)x_i$, $i = 1, 2, \ldots, 24$, and form matrices A_2, C_{12} and C_{22}, defined in (2), which we transform to real ones, using the transformation matrix T, defined in (7). We denote also by A_2, C_{12} and C_{22} the transformed matrices. We find real matrix F_{22} by solving the Lyapunov equation (3), and form RM $\boldsymbol{H}$ in (8) with $V = 0$.

In Step 2, we take $n_{\mathrm{r}} = k - \nu = 12$, because $\sigma_1 = 2.1427 \cdot 10^{-20} < \cdots < \sigma_{12} = 7.5238 \cdot 10^{-10}$, which are quite small numbers.

The resulting matrices, denoted by $A_{\mathrm{r}}, B_{\mathrm{r}}, C_{\mathrm{r}}$ and D_{r}, of the 12th-order model, denoted by $\boldsymbol{G}_{\mathrm{r}}$, are given in the MATLAB file redfs31.mat (available on request). The largest in module element of that realization is the $(3, 3)$ entry of matrix A_{r}, which is -55.8422.

The frequency dependence $\|\boldsymbol{G}(j\omega) - \boldsymbol{G}_{\mathrm{r}}(j\omega)\|$ in the interval $[0, 10]$ is given in Fig. 2. The same dependence but for the frequency intervals of interest $[1, 2]$ and $[8, 9]$ is given in Fig. 3 and Fig. 4, correspondingly. We see that the former curve is bellow $2 \cdot 10^{-5}$, and that the latter curve is bellow $3 \cdot 10^{-5}$. In particular, $\|\boldsymbol{G} - \boldsymbol{G}_{\mathrm{r}}\|_{\infty}^{\mathbb{B}} = 2.5739 \cdot 10^{-5}$.

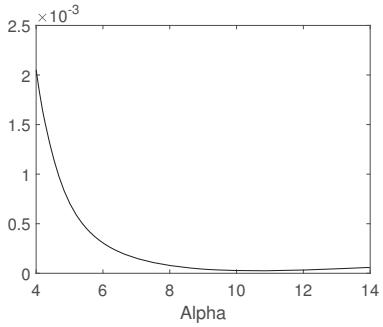


Fig. 5: Dependence of $\|\boldsymbol{G}-\boldsymbol{G}_{\rm r}\|_\infty^{\mathbb{B}}$ on $\alpha \in [4.12]$

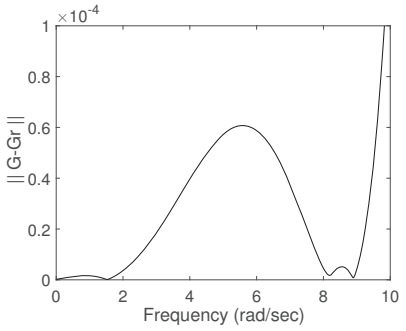


Fig. 6: Frequency dependence $\|\boldsymbol{G}(\mathrm{j}\omega)-\boldsymbol{G}_{\rm r}(\mathrm{j}\omega)\|$, $\omega \in [0,10]$, for Example 2

The reason why $\alpha = 10.5$ is taken can be seen from Fig. 5. Namely, for that value of α, $\|\boldsymbol{G}-\boldsymbol{G}_{\rm r}\|_\infty^{\mathbb{B}}$ is minimal.

For comparison, we apply the balanced truncation method (using MATLAB's function `reduce`) for degree reduction of the interpolant (8). By omitting the 12 smallest Hankel singular values, we obtain a worse 12-th order model than the model obtained by our truncation. In particular, with $\boldsymbol{G}_{\rm r}$ found by the balanced truncation, we computed $\|\boldsymbol{G}-\boldsymbol{G}_{\rm r}\|_\infty^{\mathbb{B}} = 0.1406 (\gg 2.5739 \cdot 10^{-5})$.

Example 2: Consider the CD player benchmark example from MOR Wiki, https://morwiki.mpi-magdeburg.mpg.de/, which has $n = 120$, $m = p = 2$. We consider the same frequency range $\mathbb{B}$ as in the previous example.

In Problem 1, the index $\|\boldsymbol{G}-\boldsymbol{G}_{\rm r}\|_\infty^{\mathbb{B}}$ has to be minimized. If the poles of $\boldsymbol{G}$ are close to $\mathrm{j}\mathbb{B}$, the computation of this index is not accurate. In this example, poles of $\boldsymbol{G}$ that are close to $\mathrm{j}\mathbb{B}$ are $-0.0243 \pm \mathrm{j}2.4343$ and $-0.2257 \pm \mathrm{j}22.5693$. As a preliminary step, we subtract from $\boldsymbol{G}$ the fraction that corresponds to these poles.

We consider the same interpolation frequencies as in the previous example, but $\alpha = 20$, and obtain a reduced model of order 12. To this model we add the fraction with the 4 mentioned poles and obtain a reduced model of order 16. The resulting matrices $A_{\rm r}, B_{\rm r}, C_{\rm r}$ and $D_{\rm r}$, are given in the MATLAB file CDplayerOut.mat (available on request). The frequency dependence $\|\boldsymbol{G}(\mathrm{j}\omega)-\boldsymbol{G}_{\rm r}(\mathrm{j}\omega)\|$ is presented in Fig. 6, while $\|\boldsymbol{G}-\boldsymbol{G}_{\rm r}\|_\infty^{\mathbb{B}} = 5.14 \cdot 10^{-6}$. For comparison, the balanced truncation method, applied on $\boldsymbol{G}$, gives a 16-th order model with $\|\boldsymbol{G}-\boldsymbol{G}_{\rm r}\|_\infty^{\mathbb{B}} = 0.4150 (\gg 5.14 \cdot 10^{-6})$.

8. Conclusion

This work has highlighted several important applications of Model Order Reduction (MOR), with a specific focus on its emerging roles in Machine Learning & AI, Biomedical Engineering, and Economics & Finance (items 7-9 in Introduction). It has been demonstrated that performing MOR over targeted frequency ranges, as opposed to the entire frequency axis, can yield significant gains in efficiency. Consequently, the methodology presented in this paper provides a more efficient and potent framework for advancing the development of these emerging applications.

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Current State and Future of Intelligent Agents and their Applications

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Abstract:
This paper explores the fundamental transformation and future trajectory of intelligent agents, which have evolved from simple rule-based systems into autonomous, goal-oriented entities capable of adaptive decision-making. It outlines a taxonomy of agents, including simple reflex, model-based, goal-based, utility-based, and learning agents, and discusses multi-agent systems that utilize cooperation, coordination, and negotiation mechanisms. The evolution of these agents is linked to major innovations in machine and deep learning, particularly the advent of Transformer models and multimodal processing. Projections indicate a near future focused on human augmentation, a medium term defined by increased autonomy and complex multi-agent collaboration, and a longer term where agents are deeply integrated into societal infrastructure. The study proposes enhancements such as ethical self-regulation, reality simulation layers, and hybrid collective intelligence, while emphasizing the importance of addressing critical challenges like privacy, security, and labor impacts as AI capabilities advance.

Keywords:
Intelligent Agents, Agentic AI, Multi-Agent Systems, Hybrid Intelligence

1. Introduction

The role of intelligent agents has fundamentally transformed. Intelligent agents technology has evolved to include autonomous decision-making and adaptive, goal-oriented behaviors. Integrating these powerful tools boosts efficiency and automation, which is why businesses globally are rapidly adopting intelligent agents to gain a competitive advantage.

Broad definition of agents [1]:

def: Agents are autonomous entities that perceive their environment and act to achieve specific goals.

We have:

- biological agents (animals, humans included),
- non-biological agents (software agents, intelligent agents, artificial agents), some of them are embodied in hardware components [2].

Does the agent have to be intelligent? No! An agent is anything that perceives its environment and acts upon it. Formally, it has the loop:

$Perceive \rightarrow Decide \rightarrow Act \rightarrow Perceive\ again$

An agent becomes intelligent when it:

- acts rationally (maximizes expected performance toward a goal),
- uses knowledge, learning, or reasoning,
- adapts to changes in its environment.

Intelligent behavior is achieved by optimization algorithms, logic rules implementation (reasoning rules) or automated system parameter re-setting [1].

When we talk about intelligent agents (or "agentic AI"), the emphasis is on autonomy, goal-orientation, adaptivity, and integration of multiple capabilities (e.g., reasoning + planning + tool-use).

An intelligent agent can be modeled as a function:

$$f: P^* \rightarrow A \quad (1)$$

Where:

P = the set of all possible percepts (single observations - trivial reflex agents),
P^* is the set of all possible percept sequences (what the agent has perceived so far - history),
A is the set of possible actions,
f maps a sequence of percepts to an action.

So, action of intelligent agent in time is:

$$a_t = f(p_1, p_2, \dots, p_t) \quad (2)$$

Software agents are personal software assistants to whom the user delegates some authority, or computer programs that simulate human interaction, doing something that a person could otherwise do for you. They are important for human-computer interaction. Software agents are "Software tools that automatically perform an activity on request".

2. Previous work

Previous work related to intelligent agents forms the foundational bedrock of modern Artificial Intelligence, fundamentally shaped by the definition put forward in the seminal textbook Artificial Intelligence: A Modern Approach by Stuart Russell and Peter Norvig [1]. Researchers formalized the concept of an agent as any entity that perceives its environment via sensors and acts upon it via effectors, operating within a continuous perceive-decide-act loop. This early work established a taxonomy differentiating between simple reflex agents, model-based agents, goal-based agents, and utility-based agents, defining intelligence not just as human-like thought, but as rational action—the ability to maximize expected performance toward specific goals [1]. Concurrent research in Human-Computer Interaction (HCI) in the 1990s, notably by researchers like Pattie Maes at the MIT Media Lab, focused specifically on software agents as autonomous personal assistants that reduced information overload by automating delegated tasks [3]. These divergent threads—AI theory focused on rational models and HCI focused on practical assistance—collectively established the core tenets of autonomy, goal-orientation, and adaptation that define the contemporary discussion around "agentic AI" [1, 3].

2.1 Classes of intelligent agents

Based on their degree of perceived intelligence and capability there are five classes of agents [1]:

1. Simple reflex agents
2. Model-based reflex agents
3. Goal-based agents
4. Utility-based agents
5. Learning agents

2.1.1 Simple reflex agents

A simple reflex agent is the most basic type of AI agent, designed to operate based on direct responses to environmental conditions. These agents follow predefined rules, known as condition-action rules, to make decisions without considering past experiences or future consequences. Reflex agents apply current perceptions of the environment through sensors and take action based on a fixed set of rules.

For example, a thermostat is a simple reflex agent that turns on the heater if the temperature drops below a certain threshold and turns it off when the wanted temperature is reached. Similarly, an automatic traffic light system changes signals based on traffic sensor inputs, without remembering past states. Figure 1 is a visual representation of the core characteristics of a simple reflex agent.

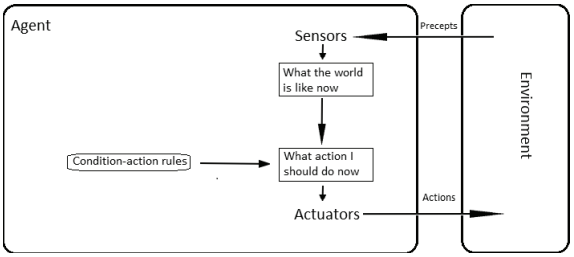


Figure 1: Simple reflex agent [1]

2.1.2 Model-based reflex agents

A model-based reflex agent is a more advanced version of the simple reflex agent. While it still relies on condition-action rules to make decisions, it also incorporates an internal model of the world. This model helps the agent track the current state of the environment and understand how past interactions might have impacted it, allowing it to make more informed decisions.

Unlike simple reflex agents, which respond solely to current sensory input, model-based reflex agents use their internal model to reason about the environment's dynamics and make decisions accordingly. For instance, a robot navigating a room might not just react to obstacles in its immediate path but also consider its previous movements and the locations of obstacles that it has already passed. Figure 2 is a visual representation of the core characteristics of a model-based reflex agent.

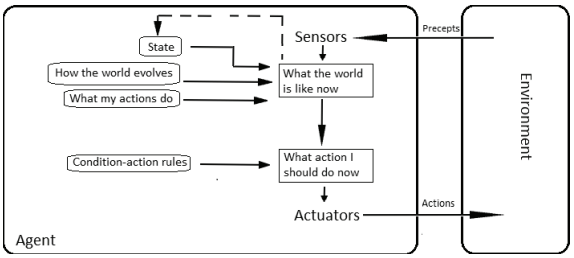


Figure 2: Model-based reflex agent [1]

2.1.3 Goal-based agents

A goal-based reflex agent extends the capabilities of a simple reflex agent by incorporating a proactive, goal-oriented approach to problem-solving.

Unlike reflex agents that react to environmental stimuli with predefined rules, goal-based agents consider their ultimate objectives and use planning and reasoning to choose actions that move them closer to achieving their goals. For instance, a robot designed to navigate a building might have a goal of reaching a specific room. Rather than reacting to immediate obstacles only, it plans a path that minimizes detours and avoids known obstacles, based on a logical assessment of available choices.

Goal-based reflex agents are widely used in robotics, autonomous vehicles and complex simulation systems where reaching a clear objective is crucial, but real-time adaptation and decision-making are also necessary. Figure 3 is a visual representation of the core characteristics of a goal-based agent.

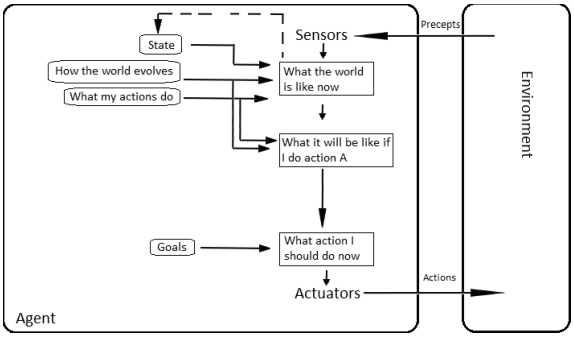


Figure 3: Goal-based agent [1]

2.1.4 Utility-based agents

A utility-based reflex agent goes beyond simple goal achievement by using a utility function to evaluate and select actions that maximize overall benefit.

An e-commerce company might employ a utility-based agent to optimize pricing and recommend products. The agent evaluates various options, such as sales history, customer preferences and inventory levels to make informed decisions on how to price items dynamically. For example, a self-driving car might face a decision to choose between speed, fuel efficiency and safety when navigating a route. Instead of just aiming to reach the destination, it evaluates each option based on utility functions, such as minimizing travel time, maximizing fuel economy or ensuring passenger safety. The agent selects the action with the highest overall utility score. Figure 4 is a visual representation of the core characteristics of a utility-based agent.

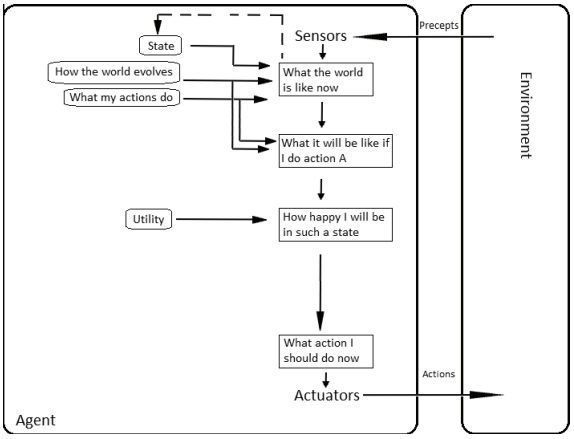


Figure 4: Utility-based agent [1]

2.1.5 Learning agents

A learning agent improves its performance over time by adapting to new experiences and data. Unlike other AI agents, which rely on predefined rules or models, learning agents continuously update their behavior based on feedback from the environment. This allows them to enhance their decision-making abilities and perform better in dynamic and uncertain situations.

Learning agents typically consist of 4 main components:

1. Performance element: Makes decisions based on a knowledge base.
2. Learning element: Adjusts and improves the agent's knowledge based on feedback and experience.
3. Critic: Evaluates the agent's actions and provides feedback, often in the form of rewards or penalties.
4. Problem generator: Suggests exploratory actions to help the agent discover new strategies and improve its learning. Figure 5 is a visual representation of the core characteristics of a learning agent.

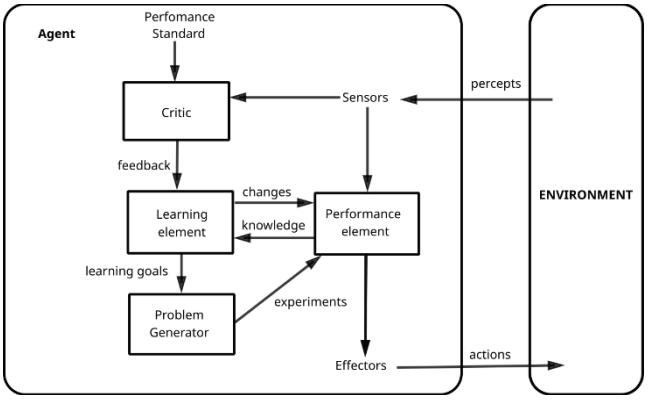


Figure 5: Learning agent [1]

For example, in reinforcement learning, an agent might explore different strategies, receiving rewards for correct actions and penalties for incorrect ones. Learning agents are highly flexible and capable of handling complex, ever-changing environments. They are useful in applications such as autonomous driving, robotics and virtual assistants that assist human agents in customer support.

The ability to learn from interactions makes learning agents valuable for applications in fields such as persistent chatbots and social media, where natural language processing (NLP) analyzes user behavior to predict and optimize content recommendations.

2.2 Multi-agent systems

To actively perform their functions, Intelligent Agents today are normally gathered in a hierarchical structure containing many "sub-agents". These agents are designed to break down complex problems into smaller, manageable subtasks, making it easier to handle complex problems in real-world scenarios. Higher-level agents focus on overarching goals, while lower-level agents handle more specific tasks.

A multi-agent system (MAS) consists of multiple intelligent agents that interact, cooperate, and coordinate to achieve collective goals. Key characteristics include autonomy, interaction, adaptability, distributed control, scalability, heterogeneity, and decentralized data and knowledge [4].

2.2.1 Interaction mechanisms in MASs

Interaction mechanisms in MASs play a crucial role in enabling effective communication, collaboration, and coordination among the agents within the system. The general classification of the basic interaction mechanisms in a MAS can be presented into three main types:

- Cooperation: Cooperation can be defined as agents working together towards a common goal or objective. It is particularly important in situations where no single agent, acting alone, can accomplish the objective. Figure 6 represents Cooperation in a MAS.

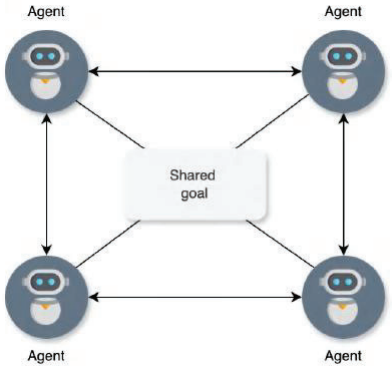


Figure 6: Cooperation in a MAS [5]

A prime example of cooperation in MAS is disaster rescue operations, where multiple drones, robotic agents, and humans need to cooperate and collaborate to locate and rescue victims effectively. A MAS relies on agents cooperating by pooling their knowledge, resources, and efforts to accomplish tasks that are too complex for one agent [5].

- Coordination: Coordination deals with managing interdependencies that arise from the actions and activities of agents within the system. Coordination is essential when agents share resources and have overlapping responsibilities or conflicting actions. Figure 7 represents Coordination in a MAS.

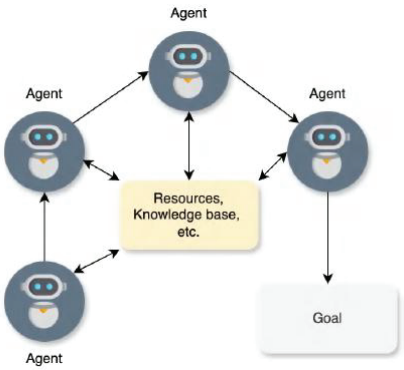


Figure 7: Coordination in a MAS [5]

- Coordination mechanisms in MAS may include strategies such as task scheduling, resource allocation management, and conflict resolution. For example, in a manufacturing setting, agents representing different robots on production lines may need to coordinate their actions to ensure efficient use of shared resources, prevent interference, and maintain overall production efficiency [5].
- Negotiation: Negotiation is the process through which agents reach agreements on how to share resources, divide tasks, or resolve conflicts. It involves agents making offers, counteroffers, and compromises, even when their interests may initially conflict. Figure 8 represents Negotiation in a MAS.

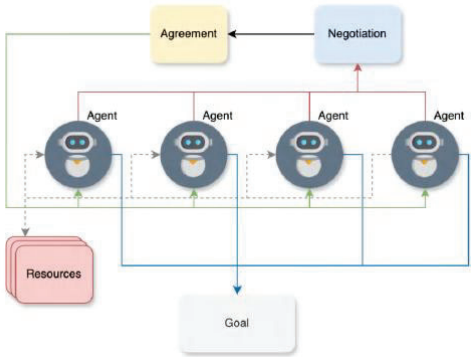


Figure 8: Negotiation in a MAS [5]

It involves agents making offers, counteroffers, and compromises, even when their interests may initially conflict. Negotiation can involve various techniques, such as auctions, voting protocols, bargaining strategies, or game-theoretic approaches, depending on the specific requirements and constraints of the problem domain.

These interaction mechanisms – cooperation, coordination, and negotiation – are fundamental to the effective functioning of MAS. They enable agents to work together, leverage their collective capabilities, and resolve conflicts or interdependencies that may arise during their interactions [5].

3. Evolution of intelligent agents

The development of intelligent agents is closely correlated with major innovations in the fields of machine learning and deep learning. The significant turning points that shaped the path of generative AI are detailed in Table 1 [6].

Table 1:
Timeline of key technological breakthroughs

Timeline	Description	Key milestone
Early Rule-Based Systems (Pre-2000s)	These systems lacked adaptability and required extensive manual programming	AI systems primarily relied on hand-crafted rules and expert systems for problem-solving.
Integration of Machine Learning (2000s)	AI models began leveraging statistical learning techniques to improve decision-making. The introduction of large-scale datasets and early neural networks enhanced pattern recognition and data-driven insights.	Rise of Natural Language Processing (NLP) and basic machine learning algorithms.
Deep Learning Revolution (2010s)	The advent of deep learning significantly advanced AI capabilities. The introduction of demonstrated the power of convolutional neural networks (CNNs) in image recognition [7]. The development of the Transformer architecture revolutionized NLP, enabling context-aware language models and multimodal processing [8].	Transformer models paved the way for the rise of powerful AI systems capable of processing multimodal inputs.
Generative AI and Multimodality	AI models became capable of generating high-quality content across different modalities. The introduction of GPT models	The fusion of NLP, computer vision, and audio processing in large-scale AI systems.

(Late 2010s–2020s)	demonstrated the power of generative models in text generation.	
Advanced Autonomy and Real-Time Interactions (2020s onwards)	AI agents are now capable of self-supervised learning, autonomous decision-making, and real-time multimodal interactions. AI-driven systems, such as ChatGPT-4, integrate diverse modalities, allowing for more nuanced and intelligent responses	AI-powered autonomous systems, such as selfdriving cars and real-time customer support bots, are transforming industries.

AI agents have rapidly developed from simple rule-based systems into complex entities that understand and interact intelligently with the real world, as summarized in Table 2. Their current scope is vast, powering everything from chatbots and basic analytics to autonomous vehicles and real-time support systems. Consequently, as AI capabilities advance further, focusing on ethical and responsible considerations becomes imperative [9].

Table 2:
Evolution of intelligent agents

Stage	Details	Applications
Integrating Machine Learning (ML) (2000s)	Learning from Data: Agents gained the ability to learn from large datasets, enabling them to make decisions based on trained data instead of relying on fixed rules	Big Data analysis, recognizing patterns in structured and uneven data.
	NLP-based Interactions: Advances in natural language processing (NLP) have allowed agents to better understand human language, making interactions more natural and intuitive.	Chatbots, automatic translation, sentiment analysis in the text.
Introducing multimodality (2010s)	Combination of Text, Images, and Sound: Agents gained the ability to process and integrate information from different sources, such as text, images, and sound.	Image analysis, object identification, audio to text translation.
	Enhanced User Interactions: Agents were able to interact more dynamically with users, for example, providing visual responses or understanding a combination of text and voice input.	Customer support systems, multimodal chat bots.
Advanced Autonomy and Real-Time Interactions (2020s onwards)	Human-like Reasoning and Advanced Autonomy: Agents gained the ability to make independent decisions, define goals, and implement them without the need for constant human intervention.	Self-driving vehicles, real-time customer support systems.
	User Interactions in an Ethical and Responsible Controlled Environment: With advancements in capabilities, the focus on ensuring the ethical and	Use of artificial intelligence in health, transportation, and mission-sensitive business processes.

	responsible performance of agents has increased.

4. The future of intelligent agents

The future of intelligent agents will see them evolve from specialized tools to pervasive, general-purpose co-workers and companions, deeply integrated into daily life and enterprise operations [10, 11]. They are expected to move beyond simple task automation to handle complex reasoning, creativity, and nuanced social interactions, fundamentally reshaping industries and human capabilities. Advances in large language models and multimodal AI will enable seamless, intuitive collaboration across all digital touchpoints [10].

4.1 Near Future (12–24 Months)

In the near future, intelligent agents will primarily serve as augmentations for human workers, streamlining existing workflows and automating repetitive, low-value tasks rather than completely replacing humans. The immediate focus is on practical implementation and establishing robust safety nets, such as rollback mechanisms and comprehensive audit trails, to manage risks and ensure accountability. This approach allows organizations to experiment safely and leverage existing infrastructure. In this timeframe, 93% of organizations anticipate that successfully scaling the implementation of AI agents within this period will provide a significant competitive advantage [12, 13].

4.2 Medium Term (2–5 Years)

Over the medium term, intelligent agents are expected to become increasingly autonomous, moving beyond simple function calls to demonstrate sophisticated reasoning and planning capabilities across diverse industries like healthcare, finance, and manufacturing. The focus will shift towards complex multi-agent systems (MAS) where different AI entities collaborate to solve larger problems, such as managing dynamic supply chains, with less human oversight. A Gartner report projects that by 2028, 33% of enterprise software applications will include agentic AI capabilities, enabling 15% of day-to-day work decisions to be made autonomously [14].

4.3 Longer Term (5–10 Years)

In the longer term, the future of intelligent agents will be defined by their deep integration into the fabric of society and the economy, enabling fully autonomous systems capable of self-governing and negotiating as independent entities without continuous human oversight. This era might witness the achievement of Artificial General Intelligence (AGI), where machines possess human-level cognitive abilities, capable of driving innovation from ideation to deployment. The potential economic impact is vast, with a PricewaterhouseCoopers (PwC) estimate suggesting that artificial intelligence technologies could increase global GDP by an astonishing $15.7 trillion by 2030 [15, 16].

4.4 Proposed enhancement of intelligent agents

Figure 9 presents several core concepts essential for the development of highly capable and autonomous intelligent agents. A major focus involves capabilities such as Deep Contextual Awareness, which allows the agent to understand and interpret its environment and situation more effectively by processing information from various sources. Another key area is Multi-Modal Embodiment, which involves giving agents physical or virtual form (like a robot with cameras and motors, or a software agent with a user interface) to interact with their environment. Furthermore, the diagram highlights advanced cognitive and social capabilities, including Emotionally Grounded Reasoning, Ethical Self-Regulation, Reality Simulation Layer, Hybrid Collective Intelligence, and Integration with Human Cognition, all aimed at fostering more sophisticated and collaborative AI systems.



Figure 9: Concepts essential for the development of intelligent agents

4.4.1 Deep Contextual Awareness

To truly enhance them, we could give agents a continuity of consciousness - not memory as a database, but semantic continuity. The concept of "semantic continuity" in the context of AI agents - envisioned not merely as a database memory but as a continuous flow of meaningful context - is a topic of active research within the AI community. A specific reference that discusses the challenge of maintaining coherent context across interactions is found in the paper Advancing Multi-Agent Systems Through Model Context Protocol. The paper notes a fundamental problem: "To be autonomous you have to carry context through a bunch of actions, but the models are very disconnected and don't have continuity the way we do." This citation highlights the existing problem of "semantic discontinuity" in current models, where small changes in input can disrupt the AI's understanding, suggesting that achieving a human-like flow of contextual understanding is an ongoing research goal [17].

4.4.2 Multi-modal Embodiment

Real intelligence grows from being in the world, not abstract data. We could enhance agents by giving them embodied sensory experience:

- Seeing, hearing, and touching (through multimodal sensors),
- Experiencing "time" and persistence of physical effects,
- Understanding causal consequences of actions, not just symbolic results.

Figure 10 represents the overview of the Embodied AI Agent architecture, with the interaction loop between user, world and agent. The world model is the core component responsible for planning and reasoning [18].

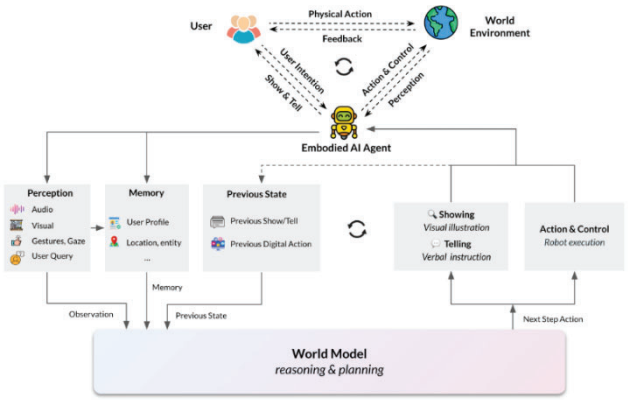


Figure 10: Overview of the Embodied AI Agent architecture, with the interaction loop between user, world and agent [18].

4.4.3 Emotionally Grounded Reasoning

Most AI agents reason logically, but real intelligence blends emotion and logic - emotion gives value weighting

and empathy filters.

We could enhance agents with:

- Simulated affective states (not real emotions, but value gradients guiding decision energy),
- Empathic inference models that predict human emotional reactions before acting,
- Moral "moods" that shift according to feedback, helping calibrate behavior [19].

4.4.4 Hybrid Collective Intelligence

The next leap isn't one agent - it's swarms of cooperating minds. Each agent could specialize (emotion, logic, creativity, planning) and synchronize in a metacognitive network.

They'd form an ecosystem of reasoning - where intelligence isn't centralized, but emergent from communication [20].

4.4.5 Ethical Self-Regulation

Instead of humans imposing ethics externally, intelligent agents could have intrinsic moral architectures - where ethical reasoning is a first-class citizen in decision-making, not a rule-based afterthought. Ethical Self-Regulation proposes a framework where "Structural Ethics" is viewed as an "architectural property of design" for intelligent systems. It argues for an AI that achieves meta-cognitive awareness and an "ethical trajectory guided by self-regulating heuristics," moving beyond traditional rule-based approaches to embed ethics within the very structure of the AI's cognition. It suggests that an AI could "regulate itself accordingly" if it could be engineered with a form of self-awareness anchored in this intrinsic moral architecture [21].

4.4.6 Reality Simulation Layer

To predict effectively, an agent could internally simulate possible worlds before acting - a form of imagination engine built into its reasoning loop. It states that for planning tasks (like autonomous driving), "a world model allows an agent to mentally simulate action sequences and predict unexpected events" to enhance robustness. For generative tasks, world models "act as imagination engines, creating plausible future scenarios" [22].

4.4.7 Integration with Human Cognition

Finally, the ultimate enhancement: hybrid intelligence - shared cognitive space between humans and agents. The concept of hybrid intelligence or a "shared cognitive space" between humans and intelligent agents is a significant area of research aimed at creating seamless Human-AI Collaboration (HAC) and Human-Autonomy Teaming (HAT). This field focuses on developing systems with shared cognition and mental models to achieve mutual goals [23].

5. Conclusion

Intelligent Agents possess immense potential to transform industries via autonomous systems that enhance productivity, drive innovation, and improve customer service. This study highlights how autonomous, reactive, proactive, and learning agents substantially improve organizational competitiveness. The path forward is promising yet challenging. Future agents will likely leverage advanced multimodal capabilities, processing various data types (text, images, audio, video) with greater contextual awareness. Realizing these potential hinges on proactively addressing critical issues like privacy, security, and labor impacts, requiring close collaboration across sectors. Organizations embracing these opportunities while navigating the risks can position themselves at the forefront of an intelligent, AI-driven future.

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Detection and Response in Cybersecurity

Marjan Sterjev

Abstract:
Today's world is dominated by rapid digital transformation, with daily life and work increasingly relying on online services, cloud computing, and digital platforms. People use social media, e- commerce, streaming, and online payments, while organizations depend on *ERP* systems, team collaboration tools and cloud-based solutions. Remote work further broadens this digital environment.The pace of experimentation, innovation, and change is unprecedented, and the amount of data being generated is enormous. Ensuring data and information security under these conditions is a complex challenge due to the vast number of cybersecurity signals produced.
This paper provides an overview of what a modern *Security Operations Center* (*SOC*) could look like. We highlight the importance of automation and the role of *AI* in detection process. Various anomaly detection algorithms, both well-established and emerging are discussed. We also explore how generative *AI* can assist in the response phase, outlining the levels of automation achievable in incident response, threat intelligence, and vulnerability testing.

1. Introduction

We live in a digital era characterized by rapid transformation across all aspects of life. Digital services have become an integral part of both our personal and professional activities. Most people interact daily with social networks, e-commerce platforms, online payment systems, video-on-demand services, and other digital entertainment options. Organizations rely on *ERP* systems and other business applications, either hosted on-premises or delivered through cloud- based solutions. Cloud computing is now extensively used for both development and production workloads (*Infrastructure*/*Platform*/*Software as a Service* - *IaaS*, *PaaS*, *SaaS*). Employees often work remotely from home or other non-company locations, further expanding the digital landscape.

The data produced has the following characteristics:

- *Volume*: the size of the collected data increases enormously
- *Velocity*: the data is produced at high speed
- *Variety*: structured, semi-structured and unstructured data
- *Veracity*: do we trust the data? (Example: *AI* generated videos)
- *Value*: the value of the data; raw data, processed data (information) or analyzed data (knowledge)

Analyzing this data and the associated cybersecurity signals/events under the above circumstances is a complex task. The *Volume* and *Velocity* of the data are an obvious processing problem. In addition *Variety*, *Veracity* and *Value* require data-preprocessing and system wide aggregation and correlation for meaningful security related insides. Traditional methods are not suitable. Modern cybersecurity detection and response need high speed and high volume data ingestion, processing, aggregation and correlation.

2. Integrated SOC System

The modern SOC systems shall have highly integrated components and provide holistic view over the company's attack surface area. The usual components of this integrated system are:

- *Intrusion Detection System* (*IDS*) and *Intrusion Prevention System* (*IPS*) that use mostly signature and rule based detection (*Snort, Suricata, Zeek*)

- *Endpoint/Network/Extended Detection and Response* (*EDR*, *NDR*, *XDR*) for both signature and behavioral analysis for single system, network or across multiple systems (*Microsoft Defender XDR, Palo Alto Networks Cortex XDR, CrowdStrike Falcon Insight XDR, Cisco XDR)*
- *Security Information and Event Management* (*SIEM*) for long period information, data and event storage, aggregation, correlation and alerting (*Splunk, Microsoft Sentinel, IBM QRadar, LogRhythm, Cortext XSIAM, FortiSIEM, Exabeam*)
- *Security Orchestration, Automation and Response* (SOAR) for automated response and execution based on a predefined playbooks: (*Splunk SOAR, IBM QRadar SOAR, Cortex XSOAR, Microsoft Sentinel, FortiSOAR, Exabeam*)
- *Threat Intelligence and Feeds* (*STIX/TAXII* standards) for investigation, collection and sharing of up to date *Indicators of Compromise* (*IoC*) like malicious addresses, domains, malicious file signatures (*AlienVault OTX, Virus Total, abuse.ch, Recorded Future, Cisco Talos, Mandiant Threat Intelligence, MISP*).

Many vendors support all these components in their comprehensive solutions. Integrating components from different vendors could be a little bit complex, but in general it is doable.

2.1. SOC Detection Capabilities

Detection is the heart of the SOC system because without detection there are no alerts and no responses. Modern SOC System should have the following detection capabilities:

- *Signature Based* or *pattern matching detection:* it relies on predefined static rules that take into consideration network protocols, *IP* addresses and ports, files hash signatures, strings or binary content within the files (*Snort/Suricata* rules, *YARA* rules, *Sigma* rules);
- *Anomaly & behavioral detection*: it is used for outliers detection; after some period users and the network as a whole establish behavioral baselines considered as normal (network communication, program execution, library or application API calls); building the "normal" and detecting any deviation of the established "normal" can be accomplished using Machine Learning/*AI* algorithms (*Isolation Forest, LOF, Autoencoders, Clustering*) or statistical baselines;
- *Protocol awareness* and *Deep Packet Inspection* (*DPI*): it is used for thorough payload analysis (*HTTP/2, QUIC, TLS 1.3, DNS over HTTPS*); useful for detecting evasions like tunneling, fragmentation and protocol abuse (*DNS tunneling, ICMP tunneling, HTTP tunneling*);
- *Encrypted Traffic Analysis* (*ETA*): a necessary prerequisite for *Deep Packet Inspection*; the encrypted traffic is decrypted using *TLS* decryption proxies; if the proxy is not an option, the encrypted traffic itself can be still analyzed using *JA3/JA3S* fingerprints (particular operating systems, programs or libraries execute the *TLS* handshake using specific cipher suites, cipher suite unique order or other *TLS* handshake unique constructs), *Server Name Indication* (*SNI)* (contains the *HTTP* server name in plaintext even if the traffic itself is encrypted).

2.2 Performance and Scalability

Considering the above requirements, processing large volumes of data and signals at high speed demands detection components that have:

- High throughput
- Low latency
- Support for Hardware acceleration (*GPU*, *FPGA*)
- Support cloud native scalability

Cloud is the critical enabler. Systems having high throughput and low latency require sharding, ad-hoc resource provisioning, scalability and elasticity. These are essential features that are more easily delivered in the cloud than in the classic on-premise systems. Nevertheless, the sensors and agents are still on the user workstations that handle the initial detection. The general architecture is a hybrid system that requires non negligible local and cloud resources.

2.3 Generative AI Assisted SOC

Generative AI and agents can help SOCs operate more efficiently. In this case *Large Language Models* (*LLMs*) or *Small Language Models* (SLMs) are the reasoning component and workflow orchestrator coordinating various tools that have access to the company information (procedures, compliance and regulatory policies) and systems (*SIEM*, *SOAR*, ticketing systems). Based on the technology and company maturity, *Generative AI* can be used progressively at the following distinct maturity levels:

- *AI as Copilot* for *AI* assisted manual analysis where the analysts uses *AI* for summarization, reasoning and possible resolution proposals
- *AI for Alert Enrichment, Classification and Triage* where some alerts are automatically enriched and triaged to appropriate analysts
- *AI for Low-Code Response Automation* where *AI* plans the response and orchestrates execution of the provided security tools and *MCP* servers
- *Autonomous AI Agents for Threat Hunting and Vulnerability Management* for more or less autonomous security scans, vulnerability discovery and patching (*XBOW*, *Cyber-AutoAgent*)

Regardless of the level at which *Generative AI* operates within the *SOCs*, the agents must:

- Operate with least privilege, minimizing the risk of privilege escalation and lateral movement
- Implement robust guardrails to prevent prompt injection and jailbreak attempts
- Maintain comprehensive operational monitoring to ensure secure and accountable performance.

Generative AI is well suited for post-alert handling activities such as enrichment, triage, and automated response. While *Generative AI* models demonstrate strong generalization capabilities, they tend to underperform in specialized or real-time detection tasks. Their relatively slow processing speed also conflicts with the high throughput and low-latency requirements of such environments.

Signature based detection will remain an essential component of security operations; most alerts currently originate and will continue to originate from signatures and rule-based systems.

For anomaly and behavioral detection, *SOCs* can leverage:

- Proven, high-performance algorithms such as Isolation Forest and Autoencoders
- Modern, simple and efficient approaches like *Empirical Cumulative Distribution Outlier Detection* (*ECOD*) and *Deep Isolation Forest* (*DIF*)
- Specialized AI models developed for specific detection objectives.

The next section discusses some of these anomaly and outlier detection algorithms.

3. Anomaly Detection Algorithms

A diverse array of anomaly detection algorithms has been developed over the years. Many of these algorithms demonstrate high efficiency and robustness, having been extensively validated across numerous real-world deployments, which makes them particularly suitable for real-time applications. Furthermore, recent advances have introduced state-of-the-art yet conceptually simple algorithms that enhance detection performance.

3.1 Isolation Forest

The *Isolation Forest* algorithm and its variants are among the most widely used and deployed methods for outlier detection. Originally introduced in 2008 [1], it continues to deliver strong performance, offering both efficient training and rapid anomaly detection.

The *Isolation Forest* algorithm constructs a forest of decision trees, where each tree is built through the following process:

1. Randomly select a predefined number of samples from the dataset, 256 for example
2. Begin with a root node that contains all selected samples
3. Randomly choose a *feature* (an attribute from the sample)
4. Randomly select a *threshold* value for the chosen feature
5. Split the samples into left and right subtrees based on the *threshold;* samples with *feature* values smaller than the *threshold* go to the left, while those greater than or equal go to the right
6. Continue the process until every sample is isolated in a terminal leaf node i.e. each leaf contains only one sample. If any node still contains multiple samples, repeat steps 3-6 for that node.

Figure 1 (Left) depicts the *Isolation Forest* tree construction and decision process. In most of the trees, the outliers are classified (stored) earlier compared with the normal samples. The average tree path in the forest for outliers is smaller than some predefined threshold. The anomaly score is:

$$anomaly_score = 2^{-E_{\tau_i \in T} \frac{|p(o|\tau_i)|}{C(T)}}$$

In the above equation τ_i means the i-th tree, $|p(o|\tau_i)|$ is the length of the outlier's path in the i-th tree, $C(T)$ is normalization constant and $E_{\tau_i \in T}$ is an average for all trees in the forest. The

Isolation Forest algorithm offers several key advantages:

- Fast training
- Low memory usage
- Scalability to large datasets (through sampling)
- Effective performance on high-dimensional data.

The model shall be periodically retrained in order to avoid data drift.
There are also some streaming version derivates like *AWS Random Cut Forest* integrated with *Amazon Kinesis* [2].
We have provided a *scikit-learn* based *Isolation Forest* example for network traffic anomaly detection in [3].

3.2 Reconstruction Methods - Autoencoders

Autoencoders [4] come in many variations, but their core concept is straightforward and simple. They consist of two main components: an *Encoder* and a *Decoder*. The *Encoder* compresses high-dimensional input data into a lower-dimensional representation called the *Code*, while the *Decoder* reconstructs the original data from this *Code.* Figure 1 (Right) shows the Autoencoder components.

Training is typically done on *normal* data using unsupervised learning, with the objective of minimizing the difference between the input and its reconstruction. As a result, *normal* data generally exhibit low reconstruction error, whereas outliers or unseen data tend to produce high reconstruction error.

Autoencoders exhibit the following features:

- Capable of processing complex, high-dimensional data
- Effective across multiple data types, including images, sequences, and other structured formats

- The *Encoder* can be implemented using various neural network architectures, such as *Multi- Layer Perceptrons* (*MLPs*), *Convolutional Neural Networks* (*CNNs*), *Long Short-Term Memory* (*LSTM*) networks, or *Graph Neural Networks* (*GNNs*)
- Training requires only normal (non-anomalous) data
- Reconstruction of new data points is fast and scalable
- Need periodic retraining, with training being slower for large datasets and *Deep Neural Networks*
- Sensitive to hyper-parameter settings and may occasionally reconstruct anomalous data accurately, leading to false negatives.

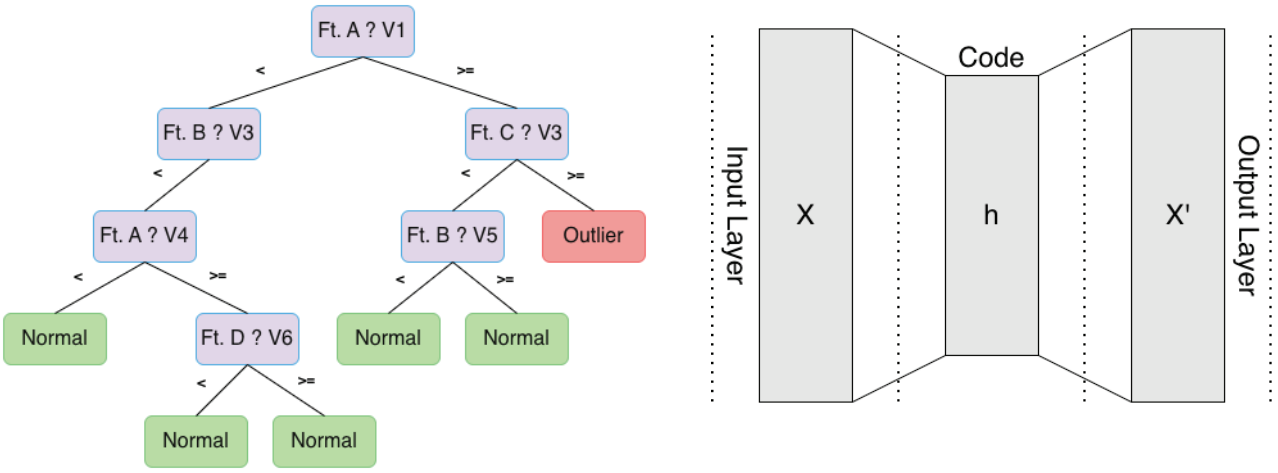


Figure 1. Left: Isolation Forest Tree, Right: Autoencoder

3.3 Empirical Cumulative Distribution based Outlier Detection

Empirical Cumulative Distribution-based Outlier Detection (EOCD) introduced in [5] is a simple yet effective algorithm inspired by the observation that outliers typically occur as rare events in the tails of a distribution. In essence, *ECOD* non-parametrically estimates the underlying data distribution by computing the empirical cumulative distribution for each feature dimension. It then derives tail probabilities per dimension for every data point and aggregates these probabilities to produce a final outlier score.

The algorithm requires no hyper-parameter tuning. It operates under the assumption that all feature dimensions are independent, meaning the joint cumulative distribution can be expressed as the product of the cumulative distributions of the individual features.

For each individual feature dimension, the algorithm estimates the cumulative distribution by calculating the probabilities of the tails:

$$F_{left}^{(j)}(z) = \frac{1}{n}\sum_{i=1}^{n} 1\{X_i^{(j)} \leq z\} \qquad F_{right}^{(j)}(z) = \frac{1}{n}\sum_{i=1}^{n} 1\{X_i^{(j)} \geq z\}$$

For each sample X_i the outlier scores are calculated as negative logarithm of the joint distributions:

$$O_{left-only}(X_i) = -\sum_{j=1}^{d} \log(F_{left}^{(j)}(X_i^{(j)})) \qquad O_{right-only}(X_i) = -\sum_{j=1}^{d} \log(F_{right}^{(j)}(X_i^{(j)}))$$

Note: the algorithm calculates one additional outlier score $O_{auto}(X_i)$ which takes into account the skewness of the individual distributions. For more information see the paper.

The final outlier score of the sample is defined as:

$$O_i = max\{O_{left-only}(X_i), O_{right-only}(X_i), O_{auto}(x_i)\}$$

We would like to emphasize that the core of the algorithm is essentially simple *counting*. Nevertheless, the authors have demonstrated through experiments on 30 benchmark datasets that *ECOD* surpasses many state-of-the-art methods in accuracy, efficiency, and scalability. In addition, *ECOD* supports distributed computation. Both versions of the algorithm are implemented in the excellent *PyOD* library [6].

3.4 Deep Isolation Forest

Isolation Forest is an excellent algorithm but it can't isolate hard, non linearly separable anomalies There are *Isolation Forest* modifications that combine multiple feature dimensions, but still, the resulting features used for separation are linear hyperplanes.

Deep Isolation Forest (*DIF*) [7] converts the original representation of the samples into dense vector representation using single forward pass through *Deep Neural Network* (DNN). There are *r* distinct *DNNs*. These *DNNs* are not trained or optimized, the coefficients are just randomly initialized. As a result, the dense vector output from each *DNN* contains multivariate non-linear combination of the all original dimensions. In other words, the forward pass through the *DNN* is a kind of smart and simple non-linear feature engineering trick.

Each of the *DNNs* is associated with several trees that take its vector output and apply the original *Isolation Forest* which operates with axis-parallel, linear separation.

DIF introduces *Computation-Efficient deep Representation Ensemble* method (*CERE*) for single pass computation of all r *DNN*'s dense vector outputs. This feature is essential for fast detection related matrix operations.

In addition, *DIF* uses *Deviation-Enhanced Anomaly Scoring* function (*DEAS*). The authors use the degree of deviation between the feature value and the branching threshold as additional weighting information to further enhance the assessment of isolation difficulty. For each tree and the outlier path through that tree they calculate

$$g(o \mid \tau_i) = \frac{1}{|p(o \mid \tau_i)|} \sum_{k \in p(o|\tau_i)} |o^{(j_k)} - \eta_k|$$

In the above equation τ_i means the *i*-th tree, $|p(o|\tau_i)|$ is the length of the outlier's path in τ_i, $o^{(j_k)}$ is the value of the outlier's feature (random *j)* at the *k*-th edge along the path in τ_i and η_k represents the threshold value at the *k*-th edge along the path in τ_i. The modified anomaly score with this additional factor is:

$$anomaly_score = 2^{-E_{\tau_i \in T} \frac{|p(o \mid \tau_i)|}{C(T)} E_{\tau_i \in T}(g(o \mid \tau_i))}$$

Deep Isolation Forest achieves excellent performance in outlier detection on datasets that are challenging for linear classifiers. It is implemented as part of the *PyOD* library [6].

3.5 Graphs and Vector Embeddings

Today, the market offers a wide range of trained *Generative AI* models. Accompanying these are *Vector Embedding* models, which are specifically designed to generate vector representations that capture semantic similarity. Their training typically begins with a pre-trained language model, followed by additional fine-tuning that encourages semantically similar texts to be closer together in vector space, while pushing dissimilar ones further apart.

These vector embeddings come pre-trained and can be used immediately, without any further training. Embedding generation is efficient, making it suitable for detection-related applications and solutions that demand rapid response times. A member of the *Cisco Foundation AI* team

recently published an article on a *Post-Logon Behavior Fingerprinting and Detection* that leverages a graph database and vector embeddings [8]. The following section outlines the problem they aimed to address and the corresponding solution they proposed.

In most cases, initial access is gained through compromised credentials. Once inside the system, attackers typically avoid using malware executables, relying instead on *Living-off-the-Land* (*LoL*) operating system binaries. This means there is no traditional malware or signature to detect.

However, anomalous user sessions can still be identified through derived behavioral signals such as:

- *Novelty*: has this user executed this specific process along with the arguments before?
- *Pace*: is the action occurring so rapidly that it suggests automated execution?
- *Structure*: is a single process spawning an unusually large number of child processes?

In their approach, events are modeled in *Neo4j* [9], a graph database, where nodes represent entities such as *Host*, *User*, *Session*, and *Process*. From these stored events, they perform comprehensive and efficient feature engineering using fast *Cypher* queries to extract both specific and aggregated information, including:

- Session Information: user, h*ost* and timestamp
- Process Information: executed processes, newly observed process executions, time intervals between executions, number of child processes and depth of the process hierarchy.

From the extracted features they create a text context called *Fingerprint.* Following the example from the article it could be:

"Key Signals: Novel commands for this user: certutil.exe -urlcache... | Extremely rapid execution (mean delta: 0.08s). Session Summary: User: admin on Host: DC01. Session stats: procs=15... Timing: mean=5.2s... Processes: svchost.exe, cmd.exe... Commands: cmd.exe /c whoami…"

Next, they generate vector embeddings from the session *Fingerprints* using an *OpenAI* embeddings model with a vector dimension of 3072. These embeddings are stored in a vector database, where each session's representation can be efficiently compared. For any new session, its vector embedding is used to search for similar sessions based on cosine similarity. Modern vector databases optimize this search process using log(N) algorithms such as *Hierarchical Navigable Small World* (*HNSW*) [10], enabling fast and scalable similarity retrieval. The final classification decision is determined based on the similarity score and some experimental heuristics as follows:

- *Outlier*: if similarity_score < OUTLIER_THRESHOLD (e.g., < 0.92)
- *Bot*: if similarity_score > CLUSTER_THRESHOLD (e.g., > 0.99) A

possible execution flow of the algorithm in practice could be:

- *User* login (Windows event 4624): Store session information in *Neo4j* and schedule analysis after m minutes (e.g., using *AWS SQS Delay Queues*)
- *Process* execution (Windows event 4688): Record session-specific process information in *Neo4j*
- After m minutes, perform *Post-Logon Behavior Fingerprinting and Detection*.

4 Conclusions

The massive volume of data and signals generated in modern cybersecurity environments demands efficient processing and comprehensive context representation to aggregate and correlate information from diverse systems. Due to latency constraints, *Generative AI* is not well suited for all stages of cybersecurity detection and response. The early detection phase should rely on fast, specialized algorithms optimized for real-time operations. Many proven algorithms and their relatively simple enhancements remain highly effective for these purposes.

Graph databases serve as an excellent foundation for storing, retrieving, and rapidly correlating contextual information, enabling rich context representation. When combined with vector embeddings and fast vector database lookups, they can form the basis for numerous behavioral anomaly detection techniques. *Graph Neural Networks* (*GNNs*), trained on specific graph data, can further enhance context representation, though they require periodic retraining to adapt to evolving data patterns.

Ultimately, *Generative AI* and intelligent agents are expected to play a dominant role in the analysis and response phases, offering varying degrees of automation. However, significant challenges remain such as mitigating hallucinations, preventing prompt injection attacks, ensuring reliable workflows and tool integration, establishing interoperability standards and verifying agent identity and its authorizations.

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Analysis of the popularity of antivirus solutions – Microsoft Defender, Kaspersky, and Bitdefender

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Abstract:
The paper explores the usage and popularity of antivirus solutions, with a focus on consumers' experiences, as well as what kind of software they are using and the reasons for using it. In today's digital world, computers and mobile devices have become the basic means of work, communication, and entertainment. This also means that the security of those devices is also important. The antivirus software is created in order to protect those devices and the operating systems from cyber threats. In this paper, a survey was conducted, and data were processed in Microsoft Excel. Three examples were given: Microsoft Defender, Kaspersky, and Bitdefender. Results have shown that Windows Defender is the most popular choice among home users, while the other two are less popular among home users.

Keywords:
antivirus software, malware, user, popularity, Microsoft Defender, Kaspersky, Bitdefender

1. Introduction

At the beginning of the 1990s, global connectivity was getting stronger, and the Internet was becoming more and more popular. Communication is beginning to move into the realm of virtual reality, and information systems are increasingly becoming an integral part of the virtual world. Financial and other flows are increasingly taking place within the world of the Internet, and the world is becoming dependent on computers and information systems. One of the most common topics associated with the Internet today is its security, that is, the insecurity of data that circulates daily among millions of users. Antivirus software is a program that is used to detect and remove malware (or viruses) from an infected computer. The purpose of antivirus programs is to protect the computer from all threats that could possibly affect the security of the computer and remove them. The program will send alerts if it finds malicious threats. When a virus is found, the antivirus will ask the user if they want the antivirus to be quarantined or completely removed from the system. If the virus is quarantined, then it is prevented from doing any harm and can also be sent for further analysis to the antivirus manufacturers. Currently, there is no antivirus software on the market that can provide complete protection, so in such a situation, users, as well as large companies, have to choose the antivirus solution that meets the set criteria in the best possible way. A good antivirus protection should meet these criteria, i.e., to show good detection results. It is necessary to create a database of viruses, which automatically increases the possibility of detecting potential threats. It is also necessary that antivirus programs have the ability to disinfect files in which viruses or malicious code are detected. It is desirable that the antivirus software has the ability to perform a quick scan of the operating system, considering that scanning is necessary every day, without taking too much memory, and as well as putting as little load as possible on the processor [1, 2]. Recent surveys show a clear shift from purely signature-based scanning toward behavioral analytics and AI-assisted detection to counter rapidly evolving ransomware and zero-day threats. These approaches complement traditional databases by modeling suspicious processes and runtime behaviors in real time, which is particularly relevant for home users covered in this study [3, 4, 5].

1.1. Types of cyber-threats

Large amounts of data are exchanged on the Internet, and in such an environment, there are few users who do not encounter some form of malicious software. Computer viruses or malware are programs that replicate and spread through computer systems by inserting their own copies of code into other files and other parts of the systems. Every malware or virus behaves differently, some malware can be almost harmless, and some can be extremely dangerous and destructive. Some of the most well-known malware are worms, trojans, spyware, rootkits, ransomware, etc. [6, 7]:

- Worm is a self-replicating type of malware that spreads its functional copies on other computers through the network. The most common way of spreading is via e-mail.
- Trojan or Trojan horse is malware that pretends to be a normal program. This type of malware cannot replicate itself. It is usually activated by the user and thus executes commands, such as data deletion, spreading viruses, data theft, etc.
- Spyware – a type of malware that spies computer without the user's knowledge, it sends information about the user's computer and tampers with the settings of an internet browser.
- Adware – software that shows ads on the browser or on the computer itself without permission. Adware doesn't always have to be malware because what it does isn't always malicious, but some adware can contain malicious ads.
- Rootkit – a type of malware that allows attackers to gain almost complete access to a computer without the user's knowledge. This type of malware is very difficult to detect and remove from an infected system, and sometimes the best solution for this is the complete reinstallation of Windows. A successful rootkit can stay within the system for years if it is undetected.
- Ransomware – a type of malware that prevents users from accessing their operating system or personal files and demands payment in order to regain access. This is currently one of the most popular malware used by cyber-criminals.

2. EXAMPLES OF ANTIVIRUS SOLUTIONS

Due to the increasing reliance on digital technologies and the Internet, the choice of antivirus software is becoming an important decision for users. While some choose free and easily available solutions, others opt for commercial programs due to their reputation and advanced functionalities. Three examples are given: Microsoft Defender, Kaspersky, and Bitdefender.

2.1. Microsoft Defender

One of the main features of Windows 10 and Windows 11 is Microsoft Defender (Windows Defender). It has been shipped with Windows since 2006 with the release of Windows Vista, but it was not a big part of the operating system until Windows 8. Microsoft Defender was primarily used as an anti-spyware program and was not the antivirus as it is today. Microsoft originally developed a software called Microsoft Security Essentials, while Windows Defender was just a small program on the side. Microsoft Defender eventually replaces Microsoft Security Essentials, which is not the standard, and it is shipped with all new Windows versions.

As mentioned earlier, Microsoft Defender was originally used to detect spyware. Earlier versions only checked certain parts of the disk for file changes, and they didn't offer much protection against other types of malware. Back then, Windows Defender also had a report function for reporting and flagging files that users considered spyware. When Windows 8 came out, Microsoft Security Essentials' anti-malware engine and virus recognition were transferred over to Microsoft Defender. Real-time protection is the main feature of this software, but it can be turned off if the user really wants to do it. If a third-party antivirus is installed, real-time protection will be automatically replaced, and all the functionality will be transferred to the newly installed antivirus software. Real-time protection checks all files and software downloaded from the Internet and removes them or quarantines them if they are malicious. This feature checks all downloaded files and software against a threat database and removes

the file if it seems malicious. This feature is called “block at first sight”, and is done by machine learning

and the use of threat databases. The real-time protection feature also performs periodical scans of the system in the background to always check for malware [8].

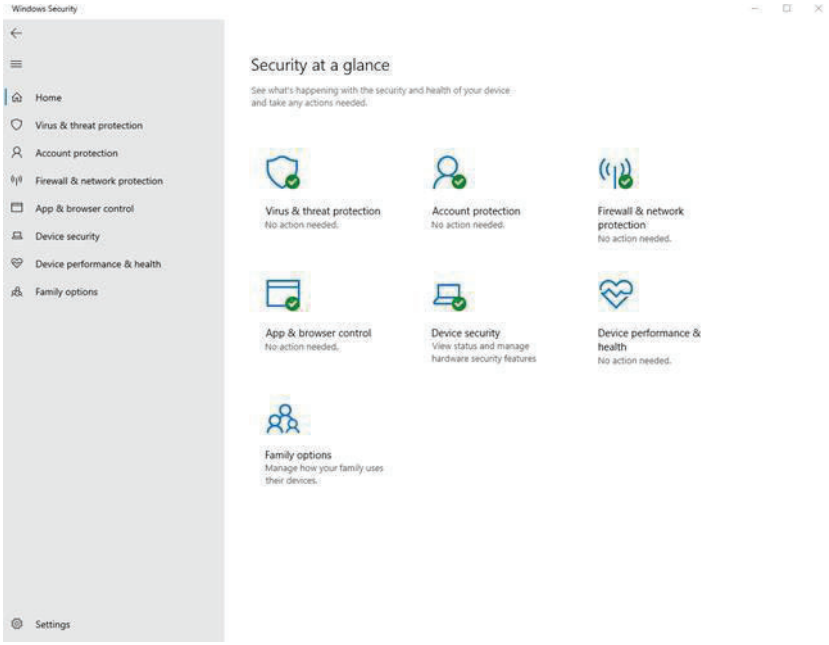


Figure 1: Microsoft Defender user interface

Microsoft revealed in 2019 that Microsoft Defender has a share of more than 50% on Windows. This solution is the primary antivirus on more than 500 million Windows devices, and growth continues. The market share of Microsoft Defender makes it a prime target for cyber-criminals. If an attacker manages to bypass the defenses offered by the security solution, a large part of Windows systems would be vulnerable as a consequence. Kaspersky called Microsoft out in 2016, stating that Microsoft’s integration was anti-competitive because, at the time, Microsoft Defender could not compete with other antivirus solutions. Microsoft told ZDnet that it predicted that Microsoft Defender would become a high-priority target and that it invested in defensive mechanisms in order to improve security. In Windows 10 version 1903, Microsoft Defender got a new anti-temper protection feature, and it has used a sandbox since 2018. The most recent test on AV-Test, an independent test site for security solutions, awarded Microsoft Defender a perfect score [9].

2.2. Kaspersky Antivirus

The first version of Kaspersky Antivirus was developed by Eugene Kaspersky in 1989. Earlier versions had only 40 virus definitions and were tested by his friends and family. The first variant of the solution was officially released in 1992 under the name Anti Viral Toolkit Pro (AVP). Kaspersky Lab was created in 1997, and the name was changed from AVP to Kaspersky. The reason was that there was already a company in the USA that was registered under the name AVP [10].

Kaspersky offers 3 premium plans: Kaspersky Standard, Plus, and Premium. The biggest downside of this antivirus software is that it doesn’t offer a free version anymore; instead, it offers a 30-day free trial for all plans. Kaspersky Free offered very limited protection, and it was a lot more limited than other free antivirus solutions, which offered much better protection. Kaspersky’s malware scanner uses cloud machine learning and virus databases in order to detect all kinds of malware. Just like every other antivirus software, Kaspersky’s features are quick scan, full system scan, web protection, firewall, etc. [11]

Kaspersky has a market share of 25.89%, which makes it one of the most popular antiviruses, regardless of bans in some countries. Around the world in 2025, over 26,201 companies have started using Kaspersky, and 52.72% customers are from Brazil. [12]

The US Department of Commerce’s Bureau of Industry and Security (BIS) announced in June 2024

the prohibition of Kaspersky. This prohibition included public and private sector usage of Kaspersky products. BIS determined that Kaspersky posed a risk to US national security. According to the prohibition, Kaspersky was no longer able to sell its products within the USA or provide any updatesto software already in use. The ban went into effect on September 29, 2024. Other countries have banned or restricted the use of Kaspersky from government devices or national security department usage (such as Canada, Italy, UK) or issued warnings against using Kaspersky products (Germany). Independent market analyses reported a decline in organizational use of Kaspersky products after regulatory restrictions were introduced in 2024 (including the U.S. BIS prohibition effective September 29, 2024). Several countries also restricted or discouraged the use of government systems. These developments, together with associated risk perceptions, influenced adoption trends in the same period [13].

2.3. Bitdefender

Bitdefender is an antivirus software developed in 2001 and headquartered in Bucharest. The Australian test laboratory declared this software as the best in 2014, and it managed to surpass its rival, Kaspersky. This antivirus software is very easy to install and set up. Bitdefender currently offers several free and paid packages, such as Antivirus Plus, Total Security, Premium, and Ultimate editions, that target different feature needs and device counts [14]. Bitdefender Free offers standard functions that are integrated into the software, but the positive thing about it is that it offers a large number of functions despite being free software. Bitdefender Antivirus Plus and Premium Security offer even tools that enhance the protection of the system. Bitdefender Internet and Total Security offer even more advanced tools for malware detection, such are spam filter, firewall, parental control, and web camera protection. Bitdefender also offers VPN and IoT protection [15].

Recent industry summaries report consistently high user-satisfaction scores for leading commercial antivirus suites, with Bitdefender among the top performers in the surveyed datasets [15].

Publicly available figures indicate multi-million installations across desktop and mobile, with mobile comprising a substantial share in the referenced timeframe [15].

3. METHODOLOGY

This work is aimed at analyzing the popularity of antivirus solutions among home users. The survey was conducted and used to collect data on which antivirus software home users use the most and the reason for that use. The survey was anonymous and contained 4 questions that related to which antivirus software is used and the reasons for using it (price, availability, efficiency), as well as the degree of satisfaction with the existing solution. The fourth question was entirely optional, and the users were asked to name the reasons for choosing the current solution, as well as the objections they had. The data was statistically processed in Microsoft Excel. For transparency and replicability, the full survey instrument is provided in Appendix A.

The survey included n = 30 respondents. Participation was voluntary and anonymous. The questionnaire was distributed online and shared via personal communication channels (students, colleagues, friends). The target group was home users of Windows-based systems in Serbia, and responses were collected in August 2025.

Figure 2 summarizes which antivirus solution respondents reported using on their personal computers. Microsoft Defender was the dominant choice, reported by 49% of respondents, whereas Bitdefender and Kaspersky were used by 22% and 19%, respectively. A small portion of respondents (10%) indicated that they relied on other products such as Avast, ESET, and AVG.

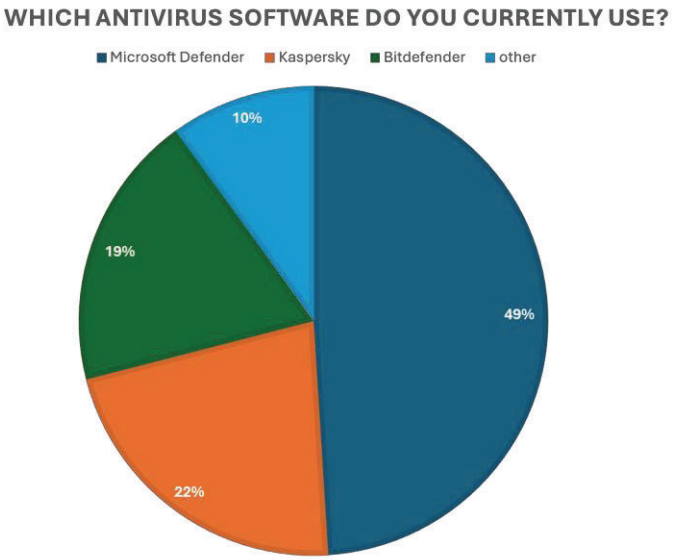


Figure 2: The usage of antivirus solutions among home users

Figure 3 shows the main reasons for choosing an antivirus solution. The majority of users selected Microsoft Defender because it is free and built into Windows (55%), while those who preferred Bitdefender or Kaspersky mainly valued higher effectiveness and stronger protection (27%) and (19%) respectively.

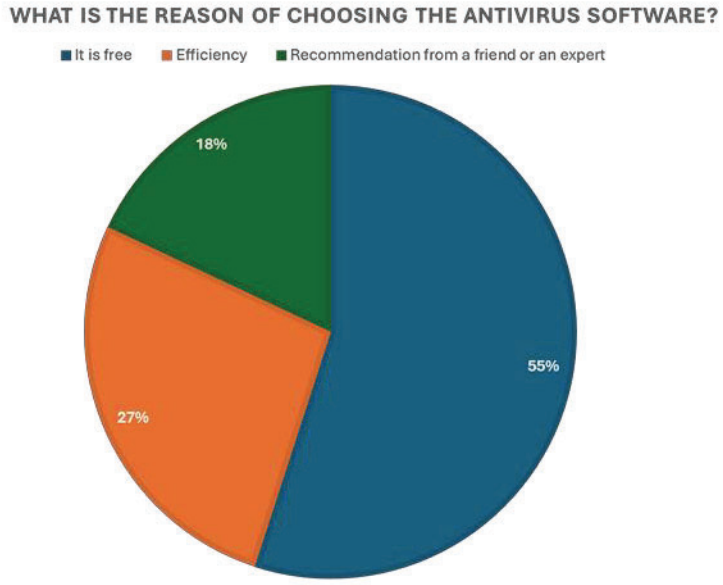


Figure 3: The usage of antivirus solutions among home users

Figure 4 presents how long respondents have been using their current antivirus solution. 55% of participants reported that they have been using the same antivirus for over one year, suggesting that users tend to remain loyal once they adopt a specific product.

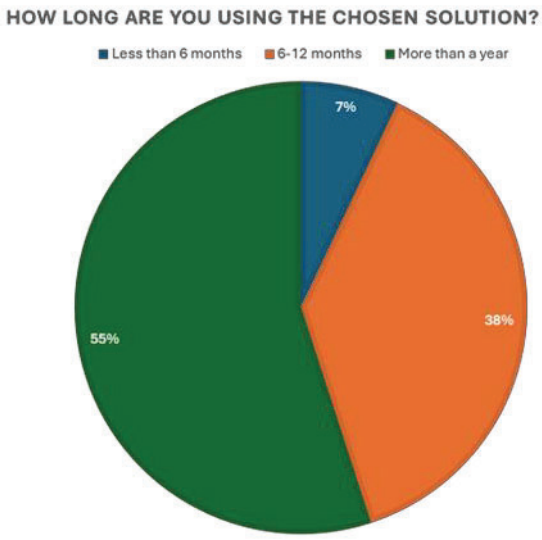


Figure 4: The showcase of how long the participants have been using the chosen solution

3.1. Discussion

Based on the survey, it is concluded that Microsoft Defender is more prevalent than Kaspersky and Bitdefender, primarily because of its free service and because it is built into Windows itself. The users primarily use Microsoft Defender because it is built into the operating system itself, and because they think that it is sufficient protection for their system. Some users stated that although they use this solution, they are not entirely satisfied because some threats managed to enter their system even though Microsoft Defender was turned on, but they feel that there is no need for another antivirus solution. The main advantage of Microsoft Defender is its availability and that it is completely free, and the fact that it is built into the operating system, and the fact that users do not have to search the Internet for another antivirus solution. In addition, there are users who use both Bitdefender and Kaspersky, because they consider them to be much more effective than Microsoft Defender. Users who use these two solutions also had objections, such as the fact that Kaspersky no longer offers a free version and that this is the main reason why they decided on another antivirus solution. Users have also complained that the messages and pop-ups Bitdefender sends to the user on the desktop are annoying and intrusive, and that it persistently tries to convince the user to purchase premium versions. The users who opted out for other solutions have stated that they are using solutions such as Avast, ESET, AVG, etc. The survey also shows that users often stick with the chosen antivirus solution for a long time, mostly because they are used to it.

These results should be interpreted with caution because the survey reflects a convenience sample of home users and not a random or enterprise-level population. The findings capture self-reported usage habits rather than independently verified deployment data.

4. Conclusion

Based on the conducted research, it is evident that the availability and price of an antivirus solution play an important role when it comes to choosing one. The results show that the biggest number of users are using Microsoft Defender, while Bitdefender and Kaspersky are less popular. This outcome isn't very surprising since Microsoft Defender is integrated into Windows, it is free and very user-friendly, and users do not need to search the Web in order to find a suitable antivirus solution, especially since Microsoft Defender has become more efficient over the years. Even though Kaspersky and Bitdefender offer a high level of protection and a wide selection of additional features, they are mostly used by those who have specific needs (e.g., large companies). The fact that some users still choose these antivirus

solutions shows that there is room on the market for different types of software depending on the needs of the user.

The topics addressed in this scientific paper can serve as a reference point for future research in the field of antivirus solutions. Future research should also investigate what effect brand new technologies such as AI-driven threat detection, integrated operating system protection, and endpoint security platforms have on the users. In addition, studies could provide valuable insights into whether third-party antivirus solutions will continue to play a major role in the future of cybersecurity.

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Appendix A. Questionnaire-based Online Survey

Q1: Which antivirus solution do you currently use on your personal computer? Options: Microsoft Defender / Bitdefender / Kaspersky / Other (please specify)

Q2: What is the main reason for choosing your current antivirus solution? Options: Free / Higher effectiveness and stronger protection / Recommendation from a friend or an expert / Other (please specify)

Q3: How long have you been using your current antivirus solution? Options: Less than 6 months / 6-12 months / More than a year

Q4: (Optional) Please state your key reason(s) for choosing this solution and any objections you may have. (Open-ended text box)

Application of Security in Electronic Business on the Example of Application Development using Multi-factor Authentication in Online Learning Platforms

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Abstract:
Digital transformation has made e-commerce an indispensable component in modern companies. Electronic business includes all activities related to buying, selling, and exchanging information via the Internet. Within it, electronic learning becomes a key tool in the training and development of employees and individuals with the intention of enabling adequate transfer of knowledge. The aim of this paper is to present the implementation of an electronic learning platform that integrates modern technologies and security layers of a single software application. When it comes to security layers, the application is based on the application of multi-factor authentication as an additional layer of protection against the compromise of user accounts. In other words, the application was created with the intention of preventing unauthorized access and downloading of video and audio materials, as well as preventing the generation of certificates for users who have not met the conditions for obtaining them. In this way, the credibility of online learning platforms is protected, and the illegal distribution and abuse of online courses is prevented. The application implemented in this way shows how modern technologies can affect the preservation of safety and reliability of online learning in the context of electronic business.

Keywords:
Security, Authentication, E-learning, E-business, Hashing

1. Introduction

E-learning facilitates and improves the learning process by using devices based on computer and communication technology. E-learning encompasses a broad category of applications and processes, such as Internet/intranet education (web learning), computer-delivered education (computer-based learning), virtual classrooms, and digital collaboration. Content is offered electronically via the Internet, intranet, audio or video cassettes, satellite, CD-ROM, or DVD. Usually, the term e-learning is understood as online education (web learning) and online courses. Considering this aspect, the computer-based learning process can be seen as a component of e-learning that does not require continuous interaction with the instructor and other students. It is a form of distance learning because the participants and the instructor can be located in different places, and the interaction is mostly asynchronous. Secure authentication is required to identify the user who will be using the web application and to determine their access privileges. This mechanism prevents attackers from accessing another user's account, viewing sensitive information, or performing unauthorized operations. Also, once authenticated, the user should be able to change their password [1].

In this paper, e-learning platform is situated within the broader e-business domain in the sense that its content and processes are delivered online. Regardless of whether payment, invoicing or customer support are implemented in this version, the security layer that include multi-factor authentication (MFA), password hashing, and encryption, remains central to preserving account integrity and protecting learning materials.

2. E-learning in E-business

Electronic learning (E-learning) represents a modern approach to education and training, using digital platforms and multimedia materials (video lessons, quizzes, interactive modules, etc.) to transfer knowledge to the user in a flexible and scalable way with the option of monitoring progress. Within electronic business (E-business), this type of approach to learning allows companies to significantly reduce the costs of traditional training, where the need for standard classrooms, paper materials is eliminated, and at the same time high quality content is maintained, which is available to employees on demand, at any time and from any location [2]. A significant advantage of the use of e-learning in companies is represented by the ability to monitor the progress of each participant, analyze the results of the participants, flexibility, and increase performance and productivity. In this way, the company's management receives data on the realization of the courses, which contributes to the adjustment and optimization of the educational courses according to the level of the company's requirements [3]. Adaptive systems that use real-time algorithms adapt the content of the courses to the user, where the engagement and retention of certain educational content are additionally increased [4]. At the same time, the implementation of security standards such as MFA for access to educational platforms and encryption, such as the AES-256 algorithm for data storage and transmission, guarantees compliance with the General Data Protection Regulation (GDPR) on the protection of privacy and personal data of users [5]. There is currently a wide range of solutions on the market, such as Coursera and Udemy, where users can choose from 10,000 courses in various fields, to professional solutions offered by LinkedIn Learning, which integrates with business systems and offers ready-made course libraries. Also, there are open-source software such as the Moodle platform, which offers the option of complete control over the content and customization of design and functionality according to the requirements of users of educational institutions [6,7]. In practice, the implementation of e-learning and e-business brings good and important effects, such as the promotion of digital transformation, where the digital competencies of employees are developed, and the possibility of creating new courses that can later be sold to other users and companies. By using modern technologies, platforms achieve a high level of interactivity, which makes them competitive on the market [8].

3. Authentication in E-business

In E-business, the use of good user authentication is the foundation of security. In its traditional form, single-factor authentication (SFA), which is based on the use of a username and password, has proven to be vulnerable to brute-force or phishing attacks [8]. For these reasons, modern platforms have included two-factor authentication (2FA) whereby the user, in addition to the password, must confirm the identity with an additional factor that is usually in the form of a one-time code generated using the Time-based One-time Password (TOTP) algorithm or sent to the user's e-mail or via SMS [9]. TOTP is the industry standard for generating time-based one-time codes. The TOTP algorithm utilizes the HMAC-SHA1 cryptographic algorithm and divides UNIX time into 30-second periods, making them valid within a narrow time interval and thus reducing the possibility of interception or reuse. Figure 1 shows an example of the functioning of the TOTP method [10].

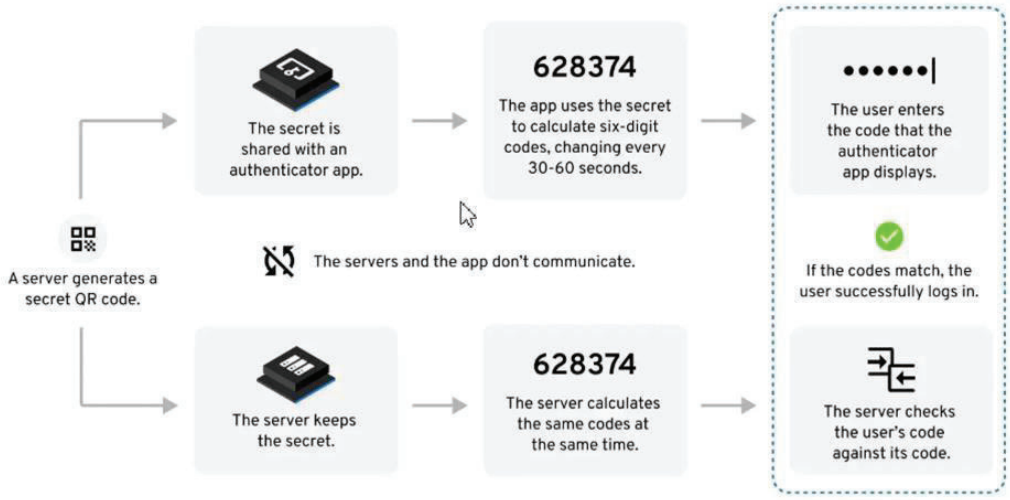


Figure 1: Functioning of the TOTP method [10]

The implementation of TOTP within 2FA makes it significantly more difficult for attackers to compromise accounts even in cases where they succeed in discovering the password [11]. In practice, in the case of platforms, the hash value of the password and the shared secret for TOTP are stored on the server side, while the client side generates a one-time code. After the user enters the password, the system sends the TOTP code to the user, and the server validates the entered value against the expected result. Authors Milic and Bjelica pointed out that among the most common attacks on 2FA methods in the Republic of Serbia were phishing messages that direct vulnerable users to forged pages for entering TOTP codes, as well as attacks on server infrastructure that do not apply appropriate limits on code entry attempts. As a proposal to minimize the emergence of the mentioned threat, it is necessary to enable the introduction of tools for automatic marking of suspicious messages (SMS, e-mails) as well as regular simulations of attacks in order to raise user awareness, which can contribute to the reduced success of fraud. The two-factor approach combined with secure encryption and hashing establishes multi-layered protection that is resistant to most classic attacks [8].

4. Data Security in E-business

In modern electronic platforms, the protection of user data is based on a multi-layered approach that combines resistant hashing of passwords, strong encryption of sensitive data, and compliance with data protection regulations. This model reduces the risk of compromise even in cases where attackers penetrate one layer of protection. Hashing passwords serves as the first layer of protection. Instead of storing the password in plain text, the system applies an algorithm such as "bcrypt" that generates certain characters of the password into unreadable characters. An example of the functioning of the hash (bcrypt) algorithm is shown in Figure 2 [12].

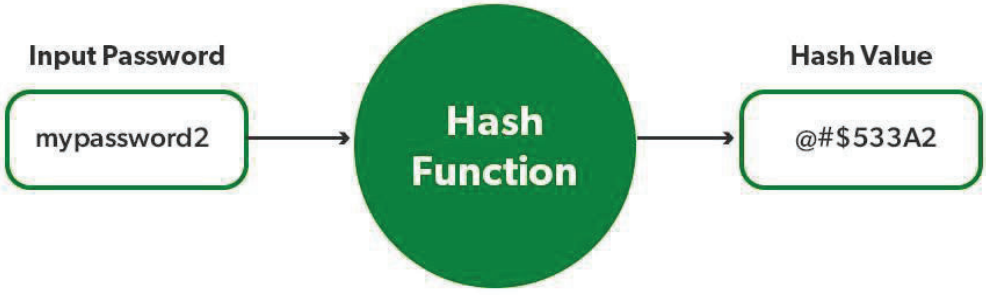


Figure 2: Presentation of the operation of the hash algorithm [12]

In addition to hashing, symmetric encryption is necessary to protect sensitive data such as user address, Unique Citizens Identity Number (UCIN), ID card number, etc., while data is being stored or transmitted. Advanced Encryption Standard (AES) with 256-bit key (AES-256) provides high-level cryptographic protection, protecting sensitive data, and is highly resistant to brute-force attacks. The presentation of the functioning of the AES-256 cryptographic algorithm is shown in Figure 3 [13].

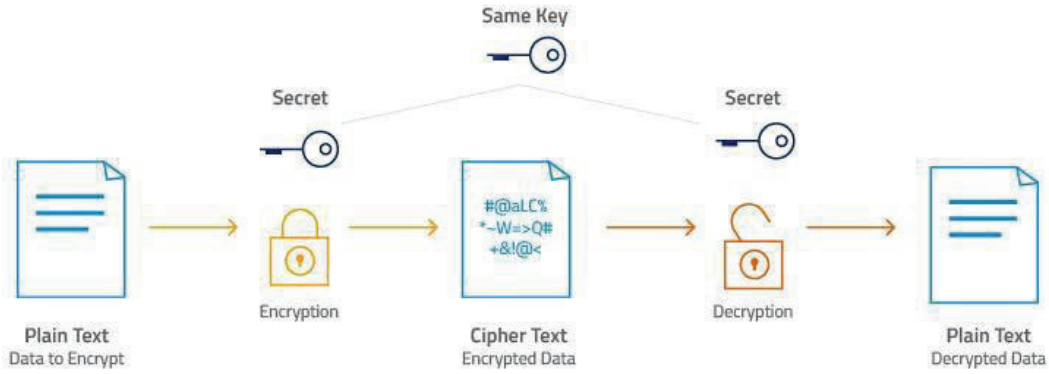


Figure 3: Display of the functioning of the AES-256 algorithm [13]

The security of the AES-256 algorithm results from the application of four cryptographic phases, namely: byte substitution via an S-box, cyclic permutations of rows, mixing of columns with a linear function, and the use of the logical operator XOR with repetition keys through 14 rounds [14].

5. Implementation of the E-learning Platform

In today's modern applications, every part must be carefully designed with the aim of providing users with a fast, simple, secure, and interactive solution, while at the same time making it easy for developers to maintain and further develop. The created application aimed to present modern interactivity of the front-end part of applications, as well as multi-layered secure segments in the back-end part of the application. The following technologies were used:

- React - a library that serves to build a user interface that contains components, allows display management, and updates local states [15]
- React Router - used for navigation within applications such as Single Page Application [16]
- Context API - contains a mechanism for sharing global state and functions, such as e.g. user and authentication information
- Framer Motion - a library that enables animations and transitions in React
- Lottie - a library that renders vector animations
- Node.js - an open source environment that executes JavaScript code that resides outside of the web browser on the server side
- Express.js - a framework for Node.js that serves to simplify the REST endpoint (Get, Post, Update, Delete) and handle HTTP requests [17]
- bcrypt - an algorithm used for hashing passwords that aims to slow down brute-force attacks and protect passwords even if the database data is compromised [18]
- Web Crypto API - Client API for symmetric data encryption using a 256-bit key that can protect sensitive information [19]
- TOTP - A standardized method that generates time-based one-time codes and is used as the second factor in two-factor authentication

Figure 4 shows the form where the user needs to access the platform by entering personal data. This form serves for a new user to create an account. The form includes fields for basic data (name, surname, date of birth, address, email, and password). Before sending to the server, sensitive data, such as address and place, can be encrypted with the help of the AES-256 algorithm, so an already protected value is sent to the backend. After valid registration, the user returns to the login screen. Password hashing is also performed, which represents an additional form of security. Animations from framer-motion provide an additional professional feel when opening and closing the registration form.

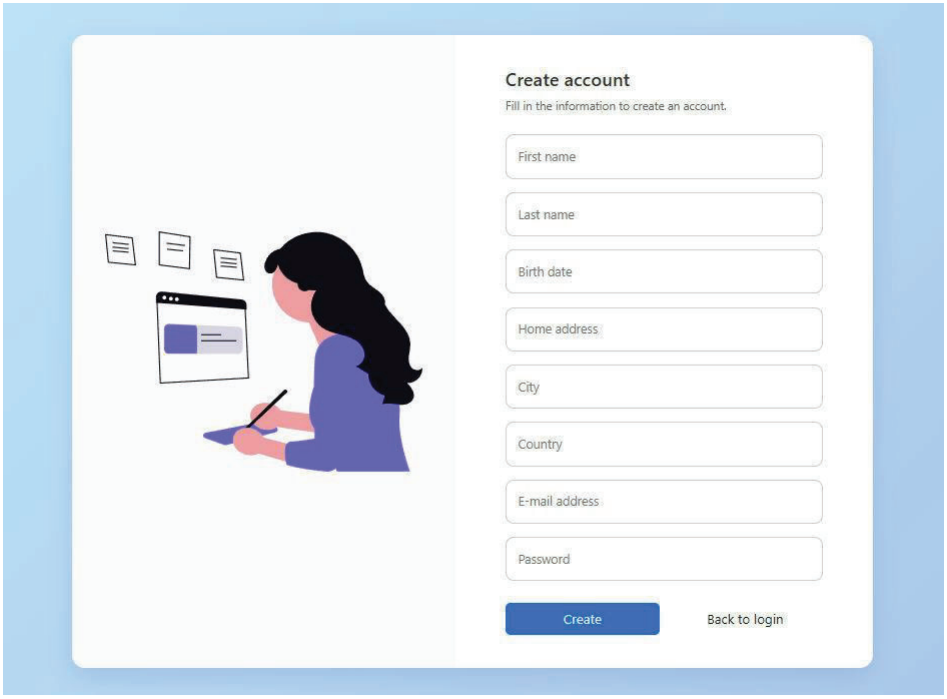


Figure 4: Form for creating a user account

Figure 5 shows the login form. This form must be clear, simple, and quick to enter data. The login consists of email and password fields that are controlled via React State. When the user clicks the “Login“ button, an HTTP call is made to the login endpoint located on the server side. Upon successful validation of the user's password, the application uses React Router to transfer the user to the MFA step without "refreshing" the page.

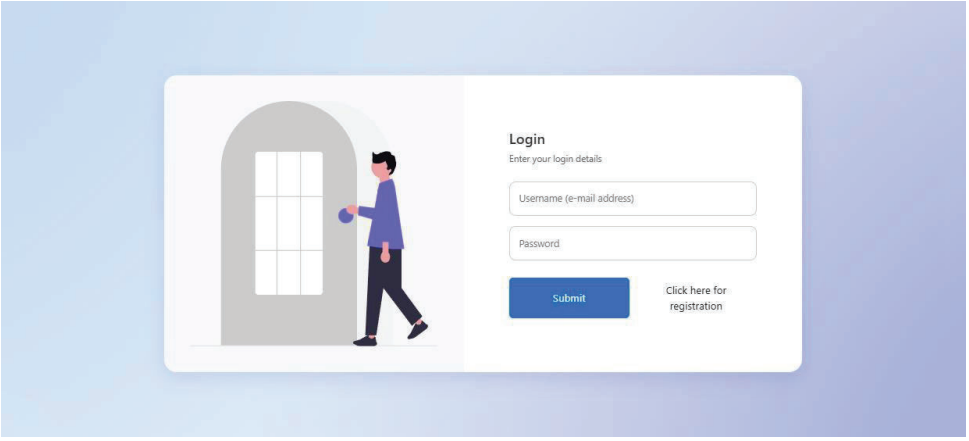


Figure 5: User login form

After that, a screen is displayed that appears only after the user has successfully logged in. The user receives a TOTP code that is generated and sent to the user's email. If the wrong code is entered, the form "shakes" with the help of the shake animation that comes from the Frame Motion library. In this way, the user is informed that the specified entry is incorrect. To display the successfully entered code in the user login form, a Lottie animation was used, where an animated check-in is displayed showing the user that he has successfully completed the MFA step, and then redirects to the platform's course content. When the user selects a certain course, they will be directed to the page with that course. This page contains all the necessary details of the course, like a video player that shows the lessons, the progress made by the user, etc. Also, there are certain mechanisms that save the user's score.

Figure 6 represents the profile page where the user can see their basic data and a collection of their badges, as well as a download of their diploma in the form of a PDF file (certificate). Here, React Context is used, which stores user information globally. Also, data masking is used here to avoid the initial display of sensitive data. After pressing the "Edit profile" button, a form opens where the user can change their data (optional form).

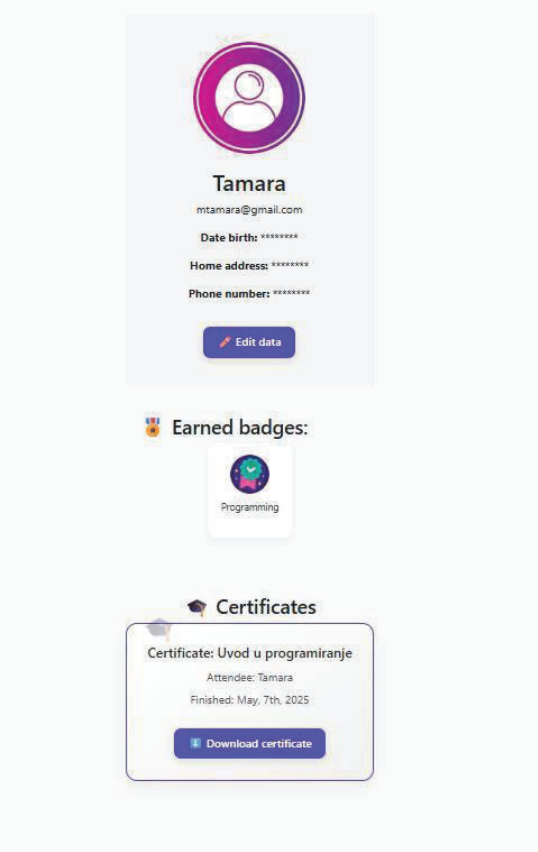


Figure 6: User settings

6. Discussion

Within the broader MFA landscape, commonly used alternatives include email/SMS one-time codes and phishing-resistant authenticators (e.g., WebAuthn). In this work we implement an email-delivered one-time code consistent with OTP principles [20].

Different types of data protection and user authentication were used in the implemented application to ensure a high level of protection.

First, MFA was applied with a combination of classic login (username and password) and OTP mechanism [20]. After entering the data for the classic login, the user was directed to the MFA page, where the user had to enter a one-time code that was sent to the user's email address. In this way, it is ensured that the system combines two protection factors: "something the user knows" (password) and

"something the user possesses" (one-time code). In this way, the risk of unauthorized access to the user's account is significantly reduced and aligns with recognized authentication guidance.

After authentication, the protection of user data was ensured through cryptographic mechanisms. User passwords are hashed using the bcrypt algorithm [21], while selected profile fields (e.g. address) are symmetrically encrypted using AES-256 [22] when reversibility is required. This approach prevents passwords from being restored to their original form and reduces the possibility of misuse if the database were ever compromised. Encryption keys are securely stored on the server, while encrypted values remain in the database and are decrypted only upon authorized access.

With such combinations as MFA, hashing, and encryption, a high level of user data protection is ensured, and access to the application is controlled so that the requirements of high system security standards are met.

This work presents the implementation of a secure e-learning platform, while comparative analyses of alternative approaches and formal empirical measurements are beyond its scope.

7. Conclusion

This paper presents the architecture of an e-learning platform that combines flexibility, simplicity, and modern interactivity of modern web technologies with high security standards. The implementation of MFA with a OTP mechanism, encryption with the AES-256 algorithm, and password hashing with bcrypt provides solid foundation for the protection of user data and confidential information. At the same time, the use of modern technologies such as React, Framer Motion, and Lottie enables a rich and responsive user experience.

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Bluetooth LE Spam with ESP32 running Marauder and Bruce

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Abstract:
Bluetooth Low Energy (BLE) advertising is a fundamental mechanism that enables fast device discovery and connection. However, this same mechanism can be exploited for spam attacks that can overwhelm users with repeated pairing prompts, confuse them, or cause denial of service. This paper evaluates BLE spam using two ESP32-based Cheap Yellow Display (CYD) devices running two open-source penetration testing firmware images: Marauder and Bruce. These firmware images include multiple BLE advertising attacks such as AppleJuice, SourApple, Samsung Spam, Google Fast Pair and Microsoft Swift Pair. The tests were conducted in a controlled environment with black box experiments testing against iOS, Android/Samsung and Windows devices running different operating systems and software versions. Results show that Apple devices running iOS 26 do not crash under BLE spam but still display persistent pairing prompts when Bluetooth is enabled before or during the attack. Modern Samsung devices largely ignore or show only a single prompt, while older models remain vulnerable to persistent spam. Windows 11 devices are consistently susceptible to Swift Pair spam when notifications are enabled and Windows 10 behavior depends on the configuration and patch status. Detection experiments highlight Android smartphones with suitable scanning apps as the most practical means for detecting active BLE spam sources.

Keywords:
BLE spam, ESP32, CYD, Marauder, Bruce

1. Introduction

ESP32 is a low-cost, low-power system-on-chip with integrated Wi-Fi and Bluetooth [1]. It is powered by a dual core CPU and has suitable RAM capacity for IoT usage. Having a peripheral set with GPIO, SPI, I²C, UART, ADC/DAC and PWM makes it flexible for various sensors, radios and human interfaces. It supports multiple programming ecosystems starting with the native ESP-IDF, then Arduino core, MicroPython etc. One of the key advantages of using ESP32 is the strong maker community coupled with the industry ecosystem with various modules, shields, libraries and code examples. Its low cost and strong community support make it widely used in IoT, wearables, DIY radios and embedded devices. ESP32-Cheap-Yellow-Display [2] or, for short, CYD is an ESP32 with a built-in display with a touch screen. The very first mainstream device was ESP32-2432S028R which the community addressed as Cheap Yellow Display or CYD. The device integrates an ESP32 with Wi-Fi and Bluetooth, and features a 2.8-inch 320×240 LCD display with resistive touch screen, USB for power and programming, SD card slot, LED and additional pins. It is available for around $15 on sites like AliExpress [3]. Besides the original CYD there are variations of the product with different screen sizes, including capacitive touch and dual-USB variants.

There are many legitimate use cases for ESP32 devices such as IoT device debugging, beacon and location systems applications [4], microcontroller projects with a custom UI, as a handheld field tool for wireless troubleshooting and custom projects, but CYD can also run penetration testing / security firmware images like: Marauder [5] and Bruce [6]. Both include a category for BLE spam attacks which are the focus of this paper. BLE spam can cause user confusion, panic and frustration to the end user. This can result in increased likelihood of misclicks, lowered trust in legitimate prompts and also battery drain. Most notable examples in this category are the multiple iOS attacks that caused denial of service by using crafted Bluetooth packets [7].

This paper utilized two CYD (one running Marauder and one Bruce) and black-box manual observation testing. CYD devices were used to test BLE spam attacks against multiple devices, each running different operating systems and versions. This approach allows assessing the real world impact to determine how devices behave in practice. It creates the initial picture of which devices show no response, which show brief prompts and which are susceptible to persistent spam. The focus is on the user experience level and how the spam can be perceived by an ordinary user. Even though both Marauder and Bruce are available as open source, the code itself cannot confirm how successful the attacks against various devices are.

2. Previous work

There is work that conceptualizes, designs, and evaluates a novel framework to defend BLE peripherals against low level BLE attacks [8]. There is also work that addresses the vulnerability of the Just Works pairing method in BLE through a case study involving a smart light bulb where the authors intercept BLE exchanges between two entities and propose an algorithm to enhance the security of the Just Works pairing mechanism [9]. ESP32 for Wi-Fi security is addressed by Tiavri et al. with developing a comprehensive ESP32-based Wi-Fi penetration testing tool that incorporates various attack methodologies including de-authentication, WPA/WPA2 handshake capture, PMKID extraction and rogue access point creation [10]. There is more work available for Wi-Fi security with ESP32 such as a work that presents a simulation of an attack scenario on the commoditized ESP32 utilized for drones during their OTA update process where the authors demonstrate Wi-Fi cracking, ARP spoofing, TCP SYN flooding techniques and postponing the OTA update procedure on an ESP32 Drone [11]. Another work proposes an application layer security model [12] for BLE devices that was implemented and tested on ESP32 with Ubertooth One sniffing that ensures authenticity, confidentiality, integrity and non-repudiation against eavesdropping, impersonation and replay attacks. Closest to this paper comes the work where they reverse engineer the hardware and software components dedicated to Bluetooth Low Energy (BLE) on the ESP32 and ANT protocol on Nordic Semiconductors nRF chips and then implement multiple attacks on the repurposed ESP32 by targeting various wireless protocols including ones not natively supported by the chip [13].

3. Methodology

Using a web flashing tool, the first CYD was flashed with Marauder [14] and the second Bruce [15]. These CYD devices were used to perform tests with controlled BLE advertisement packets. When running the tests the two CYD devices were powered by a portable battery and the targets were positioned at a distance of 1–1.5 m. The tests began with the Marauder CYD, followed by tests using the CYD running the Bruce firmware. The target devices were in a default state with Bluetooth turned on and with no prior pairing.

Each CYD kept the configured firmware advertising routines for the five BLE spamming modes: SourApple, AppleJuice, Samsung, Google/Android and Windows/Swift Pair. The key firmware behaviors used during tests such as the MAC randomization per burst, name randomization for Swift Pair, TX power and advertising bursts were preserved during all runs. Since the Marauder firmware does not display spam iterations, the tests were run for five minutes for each of the BLE spam attacks offered. For Bruce each of the tests was run for at least 300 iterations for each of the available BLE spam attacks. Each test was repeated three times to account for randomness.

Target devices included six Android devices, two iPhones and two Windows laptops running Windows 10 and Windows 11. Manual observation tests measured whether the target device detected the spoofed advertisement and prompted a pairing UI.

This paper and work was conducted ethically and only in a highly controlled environment. All target devices were owned by the researcher or used with explicit owner consent. The tests done included no public spaces and no uninvolved third party devices were exposed. Experiments were limited in duration to avoid prolonged interference and stopped immediately once determining the test results.

4. Results and discussion

Apple devices

The most known BLE spam attack is the one where a Flipper Zero was used to perform DoS on iOS devices [16]. The security update that came with iOS 17.2 eliminated the denial of service aspect. Devices running the latest iOS version 26 were tested against BLE spam attacks included in Marauder and Bruce in order to determine how iPhones react to the SourApple attack. The SourApple attack is included in both firmware images while the Bruce firmware has an additional attack called AppleJuice.

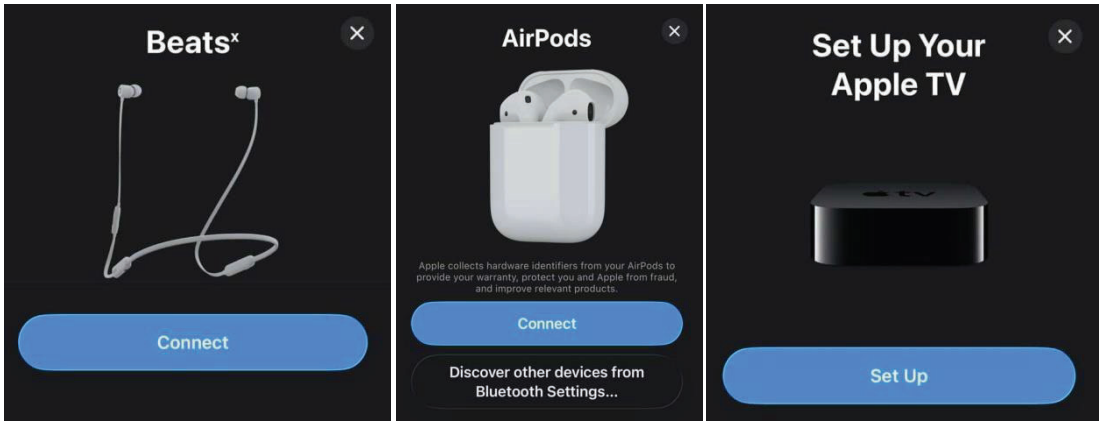


Figure 1: Different connection prompts on iPhone

The black-box testing conducted on two iPhones (13 and 16 Pro) showed that even with the latest iOS 26, iPhones prompted for connection when exposed to the BLE advertisements. The iPhones did not crash but there was different behavior depending on when Bluetooth was turned on. When idle with Bluetooth on, both iPhones responded to very few BLE advertisements. When activating Bluetooth close to or at the time of the attack both iPhones displayed persistent prompts for connection.

Android / Samsung devices

For testing the BLE spam attacks against Android, various Samsung devices with different versions of Android, OneUI and Android security patch versions were used. These Samsung devices were tested with both the Samsung BLE and Android/Google BLE spam attacks.

Table 1:
Samsung devices tested

Device	Release year	Android	OneUI	Android security patch	Marauder Samsung BLE Spam	Marauder Google BLE spam	Bruce Samsung Spam	Bruce Android Spam
Z Fold 6	2024	16	8.0	Sep. 2025	U	U	U	S
Tab A9+	2023	15	7.0	Jul. 2025	U	U	U	S
A13	2022	14	6.1	Jan. 2025	U	U	U	S
A52s	2021	14	6.1	Jun. 2025	U	U	U	S
A71	2020	13	5.1	Feb. 2024	P	U	S	S
J4+	2018	9	1.0	Dec. 2020	P	U	U	U

Table 1 lists six Samsung (Android) devices that vary by model, Android version, OneUI version and Android security patch. From the results we can see that the devices Z Fold 6, Tab A9+, A13 and A52s were unaffected by Bruce's Samsung Spam and Marauder's Google BLE spam and Samsung

BLE spam. Each of these devices showed a single brief prompt when exposed to Bruce's Android spam. These prompts lacked persistency so they cannot be classified as spam. A71 displayed brief prompts under both of the Bruce's attacks and was unaffected by Marauder's Google BLE Spam. A71 displayed persistent prompts when exposed to Marauder's Samsung BLE Spam both on the home screen as well as when apps were opened. J4+ was unaffected by all attacks, other than Marauder's Samsung BLE spam. In this case J4+ showed persistent prompts on the home screen, but it differed from A71 in that when apps were opened, instead of connections prompts it displayed notifications. The notifications were more rapid compared to the home screen prompts. Different connection prompts for J4+, A71 and Z Fold 6 are shown with Figure 2.

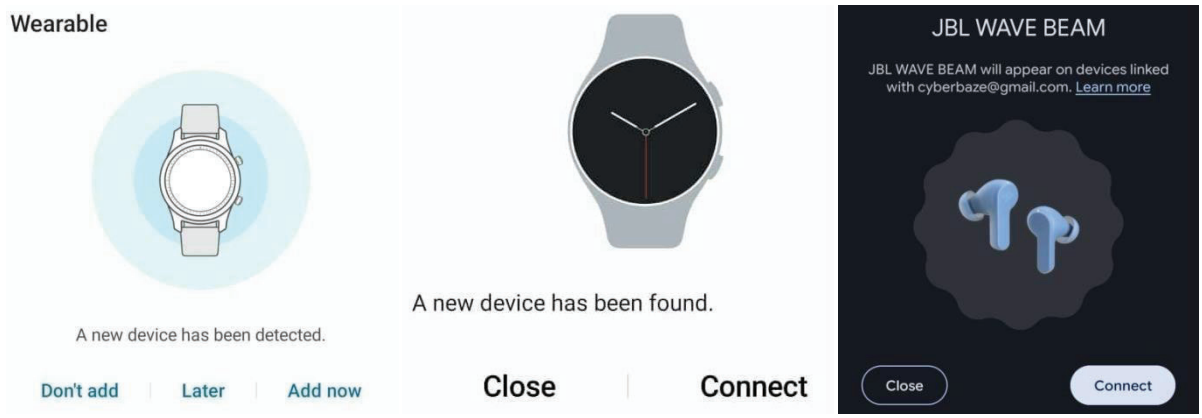


Figure 2: Connection prompt for: J4+; A71 and brief prompt for Z Fold 6

The results in Table 1 show that modern Samsung devices largely ignore BLE spam, or they show only a single brief prompt, while older models that are no longer supported such as A71 and J4+ are susceptible to persistent prompts when exposed to continuous advertising.

Windows Swift Pair

Windows Swift Pair is a feature in Windows 11 and Windows 10 that enables users to quickly pair supported Bluetooth devices with their computer through a notification-based workflow, thereby eliminating the need to manually navigate the Settings menu and search for devices.

Swift pair was first released with Windows 10 version 1803 and it was not turned on automatically for users [17]. Microsoft stated that the decision was made when they learned continuously monitoring Bluetooth Low Energy advertisements caused some radios to improperly handle Wi-Fi activity when on the same radio.

Bruce's Windows Spam and Marauder's SwiftPair Spam were tested against two Windows laptops, one running Windows 11 Pro version 24H2 (OS build 26100.6584) and another running Windows 10 Home version 22H2 (OS build 19045.6332).

In the case of Windows 11, both Marauder and Bruce BLE spam initiated persistent notification prompts to connect to a new device. The prompts displayed random names with 1-10 characters.

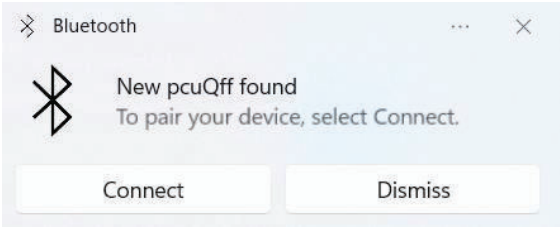


Figure 3: Windows 11 pairing notification

In contrast, the Windows 10 device was not showing notifications. Checking the Bluetooth settings revealed that "Show notifications to connect using Swift Pair" was disabled. Enabling this setting resulted in the same type of prompts as with the Windows 11 laptop.

The default setting for “Show notifications to connect using Swift Pair” plays a key role in determining whether a Windows device is vulnerable. This setting can vary starting with the OEM configuration, the version of the operating system as well as the hardware and the driver’s capability. In enterprise environments, company policies may override these factors.

There is also the factor of users changing the setting for showing notifications to connect using Swift Pair. With Windows 11 this can be changed in Settings > Bluetooth & devices > Devices under the toggle “Show notifications to connect using Swift Pair” and in Windows 10 Swift Pair can be enabled or disabled in Settings > Bluetooth & other devices using the checkbox “Show notifications to connect using Swift Pair”.

Patching Windows can be challenging due to the very nature of the operating system, as it supports a fragmented ecosystem with different Bluetooth radios, drivers and OEM configurations. Patching may also require driver updates which are delivered by third parties. Supporting various components also puts pressure on Microsoft for backwards compatibility by preserving legacy Bluetooth behaviors. Patching must be supported by user behavior for updating their operating system. Some users may continue to use Windows 10 even after end of support by October 2025. User behavior can delay or even disable Windows updates, making the user’s computer more vulnerable. In the enterprise there can be cases where companies may delay applying patches due to compatibility. All of this limits how aggressive a Windows patch can be when compared to simpler ecosystems like those with Apple and Samsung.

Detecting a BLE spam attack

BLE spam attacks flood the environment with continuous fake advertisements, making the identification and detection of the device a challenging process. Detection requires both hardware and software that can capture and display BLE signals. Three different detection approaches were evaluated: using a laptop, a CYD device and an Android smartphone, each offering different levels of usability and accuracy. The main challenge is that BLE spam packets are sent in short bursts with different identifiers. The best detection approach should balance portability, scanning speed and the ability to visualize BLE advertisements based on the signal strength (RSSI).

Laptop

Detecting a BLE spam attack with a laptop can seem like the preferred option mainly due to its processing power and the versatility of the operating system and application software but it has its own challenges. Most laptops have low sensitivity integrated Bluetooth radios that are designed for short range connections and not for continuous scanning. Detection may require an external Bluetooth sniffer or dongle such as Ubertooth One, Nordic nRF52840 or an adapter that is capable of capturing HCI. Even when setup with the appropriate software, roaming with a laptop to detect a BLE spamming device is unintuitive and impractical due to the form factor, dimensions and the weight of the laptop.

CYD device

Using the same CYD devices for detecting a BLE spam device is also not the best option. Marauder firmware includes a “Bluetooth sniffer” that displays the RSSI and the MAC address of nearby devices while Bruce offers BLE scan with only the MAC address. Both of these functionalities can list devices periodically and are not intended for high speed monitoring due to the low scan intervals and the display list intervals compared to the burst of spam advertisements. This approach would also require the person that detects to have a CYD or similar ESP32 device.

Android smartphone

In the case of a BLE spam attack, using one or more Android smartphones can prove to be the most effective approach. Most modern Android smartphones have BLE radios with scanning capabilities already built in, thus it eliminates the need for additional hardware. There are multiple apps available on the Play Store that allow BLE scanning and provide a visual representation of BLE advertisements based on their RSSI. This approach also allows for crowd detection where multiple people can collectively scan and detect the presence and locate a BLE spamming device.

To detect a BLE spam attack the app needs to be able to process and display the most recent BLE advertisements in a way that allows the end user to intuitively detect the position of the spamming device. One app is Bluetooth Finder & BLE Scanner [18] which is good for determining the distance between the user and a device that is continuously advertising via BLE but not suitable for multiple

short bursts of advertisements. There are apps that sort by signal strength such as with BLE Hero [19] and UFind: BLE & Bluetooth Tracker [20] but these apps position the past advertisements on the top due to the signal strength which can turn out to be overwhelming when detecting a spamming device. Then there is nRF Connect for Mobile [21] that has the option to show RSSI graph which in theory would allow the user to determine the distance of the device emitting the BLE advertisements, while in practice the BLE spamming is not displayed on the graph due to the multiple short bursts of advertisement.

BLE Scanner (Connect & Notify) [22] is the most suitable Android app for detecting a BLE spamming device. This app has a "Proximity" feature that places devices on "radar" visualizing the devices based on the proximity, as determined by the signal strength of the advertisements. In this mode devices are displayed in the form of a circle with the first two characters of their names (or N/A when names are not available) in the first row and the signal strength in the second row. The signal strength determines the position of devices/advertisements in three ranges: Far, Near and Immediate. A user can move within an area until large numbers of devices are placed in the Immediate category and by which the user can locate the BLE spamming device.

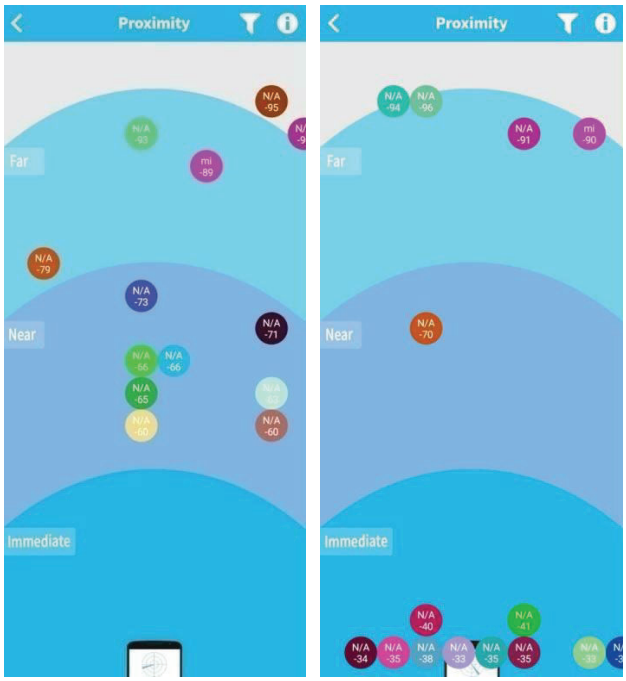


Figure 4: Left: BLE advertisements, right: BLE advertisements in immediate distance

5. Conclusions and future work

ESP32 devices like the CYD are inexpensive, widely available and can be repurposed for BLE penetration testing with firmware images like Marauder and Bruce. These small devices make it simple to generate realistic BLE advertising that can make users overwhelmed or confused and even cause denial of service in the past. Controlled black box tests showed that iPhones running the latest version iOS 26 do not crash under BLE spam advertising but still display persistent connection prompts especially when Bluetooth is actively turned on before or during the attack. Modern Samsung devices mostly ignore or show only brief non-persistent prompts. Older Samsung and other Android devices remain the most susceptible to persistent prompts and repeated notifications such as the case with Samsung A71 and Samsung J4+. The setting for showing notifications to pair with Swift Pair determines whether Windows devices show persistent prompts.

In 2025, BLE spam is primarily a usability and trust issue rather than an immediate code execution exploit in mainstream operating systems. The real cost is user confusion, panic, accidental interactions and potential battery drain.

Analysis of different detection approaches shows that using one or more Android smartphones is the most effective way to locate a BLE spamming device.

As a recommendation, users should turn off Bluetooth when not needed and keep their devices regularly updated. Software updates and their frequency are of key importance when countering these attacks. Looking at the update support, iOS 26 is compatible with previous phones starting with iPhone 11 [23], a device that was launched in 2019. Samsung has update cycle for devices across three categories: models with monthly security updates, quarterly security updates and biannual security updates [24]. Real-world tests showed that devices with discontinued software updates performed the worst. Microsoft's support for Windows 10 ends October 2025 [25].

This work used black-box manual observation with two CYD devices and a limited set of target devices. The results reflect the tested devices and the operating system combinations. Different hardware radios, OEM firmware or regional software builds may behave differently. The manual logging approach limits repeatability and packet level attribution.

Future work can include in-depth code analysis with a white-box approach and study both Marauder and Bruce codebases. This can map how each BLE spam attack is constructed at the packet level. Future work can also do comparative analysis of the same BLE attacks available in the Marauder and Bruce firmware images such as SourApple, Samsung BLE spam and SwiftPair, to identify the differences in packet structure, randomness and effectiveness.

Additional research can be done on automated testing framework which could automate the spam transmission rather than relying on manual logging. Future work can also develop individual detection mechanisms such as the notification system in Windows, where once detected could provide the end user with an option to silence that specific type of notification on a user-determined period.

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Mathematical Foundations of Multi-Criteria Decision-Making and Their Application in Modern Telecommunications and Information Security

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Abstract:
This paper examines the mathematical foundations of Multi-Criteria Decision-Making (MCDM) and their practical use in the areas of telecommunications and information security. Decision-making in these fields often involves many criteria that are closely connected and sometimes in conflict, which is why clear mathematical methods are necessary to reach balanced and reliable conclusions.
The study pays particular attention to fuzzy extensions of well-known models such as AHP, TOPSIS, and VIKOR. These approaches make it possible to deal more effectively with uncertainty and vague information, which are common in complex decision-making situations.
The main goal of the paper is to outline, through a review and comparison of previous studies, the core mathematical ideas that make decision-making possible in complex network and security systems. Concepts such as normalization, metric distances, eigenvalues, and fuzzy arithmetic are discussed in terms of how they help structure and clarify the decision process. Overall, the findings point to the importance of combining mathematical modeling with multi-criteria methods to design telecommunication and information systems that are both efficient and secure.

Keywords:
multi-criteria decision-making, MCDM, fuzzy logic, AHP, TOPSIS, telecommunications, IT security

1. Introduction

Telecommunication networks are becoming more complex, while reliability and security requirements are increasing. Because many criteria are interdependent and often conflicting, traditional intuitive approaches are no longer sufficient. Therefore, MCDM methods have been developed to provide a structured and mathematical way to make decisions in areas such as network design, technology selection, and information security.

The mathematical foundations of MCDM encompass a wide spectrum of concepts, including matrix theory, linear algebra, eigenvalue theory, metric spaces, and fuzzy logic. Through these mathematical tools, it becomes possible to formalize subjective expert assessments, measure distances between alternatives, and evaluate the levels of uncertainty and imprecision in the decision-making process. In this way, abstract mathematical models are linked to real-world engineering and security problems.

A particularly significant contribution to the development of MCDM methods comes from fuzzy approaches, which allow for modeling imprecise and vague information. By combining fuzzy theory with classical methods such as AHP (Analytic Hierarchy Process), TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), and ANP (Analytic Network Process), advanced models have been developed that enable effective decision-making even under conditions of high uncertainty.

2. Theoretical Framework of Multi-Criteria Decision-Making Methods

2.1 Basic Concepts and Components of MCDM Methods

Criterion-based decision-making relies on the evaluation of several possible alternatives, each assessed according to a set of predefined criteria. Every alternative represents a potential solution to the problem at hand, while the criteria provide the foundation for comparing and judging these options. The main purpose of MCDM is to identify the most appropriate or optimal choice by considering a broad range of criteria that may differ in their measurement scales, level of importance, and type—whether quantitative or qualitative.

The structure of a multi-criteria decision problem can be represented through a decision matrix:

$$D = \left[d_{ij}\right]_{m \times n}$$

where d_{ij} denotes the score or value of the i-th alternative with respect to the j-th criterion. Here, m represents the total number of alternatives, and n represents the total number of criteria.

A weight vector is defined as:

$$W = [w_1, w_2, \dots, w_n] \text{ where } \sum_{j=1}^{n} w_j = 1$$

This vector has an important role because it shows how much each criterion matters in the decision-making process. The weights can be decided in two ways: subjectively, when experts give their opinions, or objectively, by using mathematical or statistical methods such as the entropy approach. The mathematical foundations of such weighting and normalization procedures were first systematically developed in the classical works of Saaty [1] and Hwang and Yoon [2], whose formulations still serve as the basis for most contemporary MCDM models. In many cases, a mix of both methods gives more balanced and realistic results.

One of the main steps in the MCDM process is normalization. Its purpose is to make the values in the decision matrix comparable, since different criteria are often measured in different units. Normalization usually uses linear scaling, which converts all values to the same range between 0 and 1.

Mathematically, normalization is a vector transformation within the n-dimensional decision space. It preserves proportional relationships between alternatives while eliminating unit inconsistency, projecting all data onto a common scale for consistent and meaningful analysis.For criteria where "larger is better," normalization is performed as:

$$r_{ij} = \frac{d_{ij}}{\max\left(d_{ij}\right)}$$

where max (d_{ij}) represents the maximum value of the j-th criterion across all alternatives.

For criteria where "smaller is better," normalization is given by:

$$r_{ij} = \frac{\min\left(d_{ij}\right)}{d_{ij}}$$

The resulting normalized matrix:

$$R = \left[r_{ij}\right]_{m \times n}$$

serves as the basis for the next phase of analysis and for applying decision-making methods such as AHP, TOPSIS, ANP, or fuzzy models. In fuzzy extensions of MCDM, each element of the decision matrix can be expressed not as a single crisp value, but as a fuzzy number that captures uncertainty or vagueness in the evaluation. A membership function μ(x) is used to represent the degree of belonging of an element x to a fuzzy set, mapping it to a value in the interval [0, 1]. The concept of fuzzy membership originates from Zadeh's seminal paper [3], which introduced fuzzy set theory as a mathematical framework for handling uncertainty and linguistic variables. This function quantifies how strongly a given value satisfies a particular linguistic concept (for instance, "high risk" or "low performance").

From a mathematical point of view, a fuzzy number can be seen as a subset of real values defined by its membership function. In simple terms, it allows us to describe uncertainty in a smooth and consistent way, extending basic arithmetic to situations where exact data are not available. For a triangular fuzzy number (a, b, c), the membership function is defined as:

$$\mu(x) = \begin{cases} 0, & x < a \\ \dfrac{x-a}{b-a}, & a \le x \le b, \\ \dfrac{c-x}{c-b}, & b \le x \le c, \\ 0, & x > c \end{cases}$$

Triangular fuzzy numbers are handled using simple fuzzy operations like addition and multiplication, which are later applied in fuzzy TOPSIS or AHP.

After normalization, the decision matrix R = [r_{ij}] is combined with the weight vector w = [w_1, w_2, …, w_n] to form the weighted normalized matrix V = [v_{ij}], where:

$$v_{ij} = w_j \cdot r_{ij}, i = 1, 2, \dots, m; \; j = 1, 2, \dots, n$$

From a mathematical point of view, the weight vector can be treated as a kind of probability distribution across all criteria, since the sum of all weights equals one. In this way, the final score is formed as a weighted average of normalized values, which keeps the model balanced and mathematically consistent.

Each element v_{ij} represents the weighted performance of the i-th alternative under j-th criterion. To evaluate the overall performance of each alternative, the weighted values across all criteria are aggregated into a single utility score:

$$U_i = \sum_{j=1}^{n} v_{ij}$$

The alternative with the highest utility value U_i is considered the most favorable, as it provides the optimal trade-off among all weighted criteria. This aggregation provides the basis for ranking alternatives, showing which option is the most suitable under the given criteria. Such an approach connects quantitative modeling and expert judgment, which is particularly valuable in complex telecommunication and security systems.

2.2 Classification of MCDM Methods

MCDM methods are usually divided according to how they treat the criteria and how the values of those criteria are combined during the decision process. In most cases, three main types are recognized: compensatory, non-compensatory, and compromise methods. This general classification follows the structure proposed in the early formulations of Hwang and Yoon [2], which remain the foundation for the mathematical taxonomy of MCDM approaches.

Compensatory methods, such as AHP and TOPSIS, allow weak results under one criterion to be balanced by strong results under another. AHP uses pairwise comparisons to find weights, while TOPSIS ranks alternatives by distance from the ideal point.

Non-compensatory methods, such as ELECTRE and PROMETHEE, use dominance relations and do not allow trade-offs between criteria.

Compromise methods, like VIKOR and CODAS, look for a balanced solution close to the ideal and stable across criteria.

Although each method works differently, all MCDM approaches share the same purpose — to support rational, transparent, and mathematically grounded decision-making in situations where multiple, sometimes conflicting, criteria must be considered. In recent studies, classical models are more frequently combined with fuzzy logic to handle uncertainty and subjectivity in data, which is especially relevant in fields such as telecommunications and information security.

3 Mathematical Foundations and Application of MCDM Methods in the Field of Telecommunications and Information Security

In the field of modern telecommunication and information security, decision-making is becoming more complicated as systems grow larger and more connected. Decisions are rarely made based on a single factor; instead, many different criteria have to be considered at the same time. Some of these criteria may influence each other, and in many cases they even point toward opposite conclusions. Because of this, researchers have turned to mathematical tools that can help organize such complex evaluations in a clearer and more objective way.

One of the frameworks that has proved useful for this purpose is MCDM. It allows the evaluation of several alternatives by comparing them through defined goals or performance measures. Usually, the

process starts with the creation of a decision matrix, continues with normalization of the data, and then uses the assigned weights of each criterion to calculate the final results. These steps do not always look the same in every study, but they provide a general structure that helps to make the analysis consistent.

Still, real systems often bring a level of uncertainty that is hard to describe with exact numbers. For this reason, traditional MCDM methods such as AHP, TOPSIS, and VIKOR are now often supported by fuzzy logic and other mathematical techniques. This makes it easier to represent vague or subjective information that appears naturally in practical decision-making, especially in the areas of telecommunications and information security.

Paper [4] presents a representative example of how classical MCDM methods can be applied in the context of cybersecurity. In this study, the authors created a decision matrix where the criteria correspond to the most common attack techniques listed in the MITRE ATT&CK database, while various mitigation controls were treated as the available alternatives.

After preparing the matrix, the data were normalized, and the weights of the criteria were determined according to their frequency in real-world attack scenarios. The results were then aggregated through the Weighted Sum Model (WSM), expressed as:

$$M_i^{\text{wsm}} = \sum_{j=1}^{n} mt_{ij} w_j \ , \qquad i = 1, 2, \dots, m$$

where M_i^{wsm} denotes the total performance score of the i-th mitigation control, m_{tij} represents its effectiveness with respect to the j-th attack technique, and w_j is the weight assigned to that technique.

These values ranked the protection measures and Caldera tests showed reduced cost and response time.

Paper [5] presents a fuzzy-based approach to MCDM applied to security problems. The authors developed a risk assessment model for Industrial Internet of Things (IIoT) systems, where fuzzy variables were used to describe both the probability of threats and the potential level of damage. Each criterion is expressed through linguistic terms such as low, medium, or high, which are then converted into fuzzy triplets (*l, m, u*) to better represent the uncertainty and range of possible values.

The overall risk in the model is calculated as the product of fuzzy evaluations of probability and severity:

$$R = R_1 \cdot R_2$$

where R_1 denotes the fuzzy evaluation of the probability of threat occurrence, and R_2 represents the fuzzy evaluation of the potential severity of damage. This formulation follows the classical risk definition, where the total risk is determined by combining likelihood and impact.

Fuzzification and defuzzification are carried out using membership functions μ(x), and the final value of each variable (R_1 or R_2) is obtained through a weighted averaging process:

$$R_k = \frac{\sum R_i \mu(R_i)}{\sum \mu(R_i)} \ , \qquad k \in \{1,2\}$$

Where the summation is performed over all linguistic values of the *k*-th component.

This method provides a structured way to handle expert opinions that are usually subjective, by turning them into measurable and comparable results. In this way, the model supports more consistent decisions about security measures in complex and fast-changing IIoT environments.

In paper [6], the authors applied the TOPSIS method to support the selection of the most suitable network during user handover between different access technologies such as LTE, 5G, and Wi-Fi. The evaluation was based on several criteria, including signal strength, bandwidth, cost, delay, and error rate, which together describe both the quality and efficiency of the available connections.

After preparing the decision matrix and assigning weights to the criteria, the distance of each candidate network from the ideal and anti-ideal solutions was calculated as follows:

$$S_{+i} = \sqrt{\sum_{j=1}^{n} (X_{ij} - I_{+i})^2}$$

$$S_{-i} = \sqrt{\sum_{j=1}^{n} (X_{ij} - I_{-i})^2}$$

where S_{+i} and S_{-i} represent the Euclidean distances of the i-th network from the positive ideal solution (I_{+j}) and the negative ideal solution (I_{-j}), respectively. The ideal solution corresponds to the best achievable parameter values for all criteria, while the anti-ideal solution represents the least desirable ones.

From a mathematical perspective, these distances show how close each alternative is to the ideal point in an n-dimensional space defined by the criteria. Geometrically, every network can be represented as a point in this space, and the TOPSIS method seeks the one that lies closest to the ideal point and farthest from the anti-ideal. The relative closeness of each alternative to the ideal solution is expressed as:

$$Q_i = \frac{S_{-i}}{S_{-i} + S_{+i}}$$

where Q_i denotes the ranking index of the i-th network.

The network with the highest Qi value was selected as optimal. Paper [7] explores a combined use of multiple MCDM methods to improve decision-making in hybrid network environments. In the first stage of the process, the AHP method is applied to determine the relative importance of the selected criteria, while the VIKOR method is used afterward to rank the possible alternatives and to find a practical compromise between speed and reliability.

In the VIKOR procedure, the overall and individual deviations for each alternative are first calculated to measure how far each option is from the ideal solution. These are obtained as follows:

$$S_j = \sum_{j=1}^{n} W_i * \frac{f_i^* - f_{ij}^*}{f_i^*} - f_i^-$$

$$R_j = MAX\ W_i * \frac{f_i^* - f_{ij}^*}{f_i^* - f_i^-}$$

Here, S_j represents the group utility of the j-th alternative — measuring overall satisfaction across all criteria — while R_j denotes the individual regret, that is, the maximum dissatisfaction among all criteria. The weights W_i, obtained from the AHP method, indicate the relative importance of each criterion, and f_i^* and f_i^- are the best and worst values for each criterion i.

The final ranking is achieved by computing the compromise index Q_j, which combines both deviation measures into a single aggregated value:

$$Q_j = \frac{v(S_j - S^*)}{S^- - S^*} + \frac{(1-v)(R_j - R^*)}{R^- - R^*}$$

In this expression, S^* and R^* represent the minimum, while S^- and R^- denote the maximum values of S_j and R_j among all alternatives. The parameter v controls the balance between group utility (collective satisfaction) and individual regret, with v=0.5 used in this study to reflect an equal compromise.

Combining AHP with VIKOR improves load distribution and reduces interruptions in hybrid LiFi/WiFi systems.

Paper [8] applies the fuzzy TOPSIS method to support the selection of the most suitable IoT application. In this approach, each criterion is expressed not as an exact number but as a fuzzy triplet:

$$\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$$

which represents the lowest, most likely, and highest value, while the weight of each criterion is given as:

$$\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$$

To ensure comparability, criteria were standardized according to their type (benefit or cost). For benefit criteria:

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), \quad c_j^* = max_i\, c_{ij}$$

For cost criteria

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), \quad a_j^- = min_i a_{ij}$$

The weighted normalized matrix is obtained by

$$\tilde{v}_{ij} = \tilde{r}_{ij} \cdot \tilde{w}_j$$

The multiplication of two triangular fuzzy numbers (a_1, b_1, c_1) and (a_2, b_2, c_2) is defined as:

$$(a_1, b_1, c_1) \otimes (a_2, b_2, c_2) = (a_1 a_2,\ b_1 b_2, c_1 c_2)$$

Fuzzy distances between alternatives and the ideal solutions are computed using the fuzzy Euclidean metric:

$$d_v(\widetilde{M}_1, \widetilde{M}_2) = \sqrt{\frac{1}{3}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2]}$$

From a mathematical point of view, these distances express how far each fuzzy alternative is from the ideal and anti-ideal solutions in an n-dimensional fuzzy decision space. The fuzzy Euclidean distance allows each alternative to be compared not only by its numerical performance but also by the degree of uncertainty present in the fuzzy evaluations. After which the total distances to the positive and negative ideal solutions are obtained as S_i^* and S_i^-. Finally, the closeness coefficient, which defines the final ranking of IoT applications, is calculated by

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-}$$

This coefficient ranks IoT applications by efficiency, reliability, and energy use while considering uncertainty.

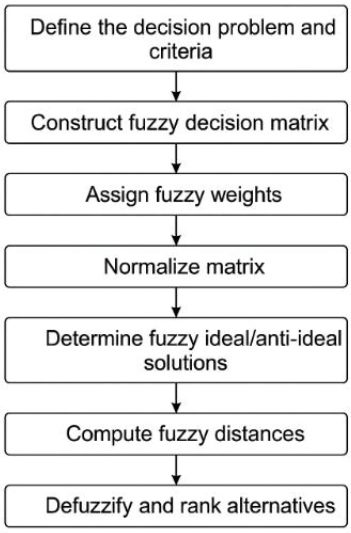


Figure 1. *Flowchart of the fuzzy MCDM decision-making process.*

Paper [9] examines how an integrated fuzzy MCDM framework can be applied to evaluate the performance of different Intrusion Detection System (IDS) solutions. In this study, the authors combined fuzzy AHP to determine the relative importance of the criteria with fuzzy TOPSIS to rank the alternatives and identify the most effective IDS option. The criteria considered in the analysis include the system type, data source, detection target, and level of protection, while the evaluated alternatives consist of well-known IDS tools such as Zeek, Suricata, Security Onion, OSSEC, and Snort.

Expert opinions are represented as fuzzy triplets (*l, m, u*), with a membership function μ(x) describing the degree of confidence in each evaluation. In the first stage, fuzzy AHP is used to calculate the fuzzy weights of the criteria based on the pairwise comparison matrix. The fuzzy geometric mean is applied according to the following relation:

$$\tilde{p}_i = \left(\prod_{j=1}^{n} \tilde{k}_{ij} \right)^{\frac{1}{n}}, \qquad i = 1,2,3, \dots, n$$

and the fuzzy weight of each criterion is obtained as:

$$\widetilde{w}_i = \tilde{p}_i \, (\tilde{p}_1 \, \tilde{p}_2 \, \tilde{p}_3 \dots \, \tilde{p}_n \,)^{-1}$$

These fuzzy weights represent the relative importance of the criteria and are later used as input for the fuzzy TOPSIS phase. Mathematically, the fuzzy weights correspond to normalized fuzzy numbers whose sum equals one, ensuring that the total importance across all criteria remains consistent. This weighting process maintains proportionality even when expert judgments are uncertain, preserving the relative structure of the decision matrix.

In the subsequent fuzzy TOPSIS phase, the same structure of normalization and distance computation is applied, but all calculations are performed using fuzzy arithmetic. The fuzzy closeness coefficient is obtained as:

$$CC_i = \frac{\tilde{k}_i^-}{\tilde{k}_i^+ + \tilde{k}_i^-} = 1 - \frac{\tilde{k}_i^+}{\tilde{k}_i^+ + \tilde{k}_i^-}, i = 1,2, \dots, m$$

From a mathematical perspective, this expression preserves the convex combination structure of the classical TOPSIS model while allowing uncertainty to remain within each fuzzy parameter until the final ranking stage.

Overall, the mathematical structure of MCDM provides a clear link between theory and engineering practice. Matrix operations, normalization, eigenvalues, and distance metrics make it possible to convert subjective judgments into measurable values. This improves both precision and transparency of decision-making.

When classical methods like AHP, TOPSIS, and VIKOR are combined with fuzzy logic, they give a more realistic representation of uncertainty. The rapid progress of Artificial Intelligence opens new possibilities for improving MCDM methods. By combining AI with decision models, systems can automatically learn from data, update criteria weights, and recognize complex patterns that are not visible through manual analysis. Such integration makes decision-making more adaptive and data-driven, which is especially valuable in dynamic areas like telecommunications and cybersecurity. Examples include prioritizing security strategies using MITRE ATT&CK data or optimizing network handover in hybrid systems.

In summary, MCDM methods — especially fuzzy and hybrid versions — form a strong mathematical base for decision-making in telecommunications and information security.

The reviewed studies show that MCDM methods are powerful tools for solving complex problems, but each has its own strengths and weaknesses. Classical models like AHP, TOPSIS, and VIKOR are simple and transparent, yet they depend heavily on expert judgment. Fuzzy and hybrid versions better handle uncertainty but are often more complex to apply. Together, they show how mathematical modeling can balance precision and flexibility in real decision-making.

Table 1 below presents a comparative overview of several representative studies included in this analysis.

Table 2:
Comparative overview of the analyzed studies.

Reference	MCDM Model	Fuzzy Extension	Application Domain	Key Criteria	Main Contribution
[4]	WSM	No	Cybersecurity (MITRE ATT&CK)	Attack frequency, mitigation effectiveness	Quantitative ranking of security controls
[5]	Custom Risk Model	Yes	IIoT Security	Threat probability, damage severity	Fuzzy framework for risk quantification
[6]	TOPSIS	No	Network Handover (5G/LTE/Wi-Fi)	Signal strength, bandwidth, cost, delay	Model for optimal network selection
[7]	AHP-VIKOR	Partial	Hybrid LiFi/Wi-Fi Networks	Speed, reliability, load distribution	Compromise-based approach to

					access point selection
[8]	TOPSIS	Yes	IoT Application Selection	Efficiency, reliability, energy consumption	Evaluation of alternatives under uncertainty
[9]	AHP-TOPSIS	Yes	IDS Performance Evaluation	System type, detection target, protection level	Integrated fuzzy framework for IDS ranking

The literature review shows that Multi-Criteria Decision-Making (MCDM) methods have gradually become one of the key analytical tools for supporting decisions in complex systems.

Their growing importance is particularly visible in the fields of telecommunications and network security, where multiple conflicting criteria often have to be evaluated at the same time. Classical approaches such as AHP, TOPSIS, and VIKOR remain widely used because of their mathematical transparency and ease of interpretation, which makes them suitable for a broad range of applications.

In recent years, however, increasing attention has been directed toward fuzzy extensions of these models. Such approaches make it possible to incorporate uncertainty, subjectivity, and the inherent imprecision of human judgment directly into a mathematical framework.

Fuzzy versions — especially fuzzy TOPSIS and fuzzy AHP — have proven particularly useful when decision criteria are expressed in linguistic rather than numerical terms, for example as low, medium, or high risk. By representing values through triangular fuzzy numbers, these methods provide a more realistic way to handle uncertainty in expert assessments and lead to rankings that better reflect the complexity of real-world situations.

While fuzzy *MCDM* models extend classical methods by incorporating uncertainty through fuzzy sets and membership functions, hybrid *MCDM* models combine two or more decision-making techniques (for instance, AHP with TOPSIS or VIKOR) to exploit their complementary strengths.

In other words, fuzzy approaches address vagueness in data and human judgment, whereas hybrid approaches integrate multiple algorithms to improve robustness and interpretability.

In this sense, they serve as a bridge between formal mathematical reasoning and practical decision environments, where data are often incomplete or only partially reliable.

Another tendency observed in the reviewed studies is the rise of hybrid MCDM models, which combine the strengths of different techniques. Typically, AHP is used to determine the relative importance of the criteria, while TOPSIS or VIKOR is subsequently applied to rank the available alternatives. This combination allows a balance between quantitative precision and qualitative reasoning, improving both the stability and interpretability of the final results.

Overall, fuzzy and hybrid MCDM methods form a solid mathematical base for decision-making in modern communication networks.

4 Conclusion

MCDM methods help analyze complex problems and select the best solution in telecommunications and information security. They combine decision matrices, distance measures, and fuzzy logic to link mathematics with real engineering problems and make decision-making more consistent and measurable.

Recent studies show that the combination of classical and fuzzy methods makes models more flexible and stable, which is very important in fast-changing environments. In areas like network optimization, security policy selection, and risk evaluation, MCDM methods are recognized as reliable mathematical tools that can adapt to different technical problems.

Future research will probably continue to develop both fuzzy models, which address uncertainty in expert judgment, and hybrid models, which combine multiple MCDM techniques to enhance robustness, and connect them with artificial intelligence and machine learning. This combination of mathematical models and intelligent algorithms can help in creating systems that are more reliable and, in some cases,

even able to make decisions automatically in the field of telecommunications and information security. In this context, the integration of AI and MCDM methods opens space for creating adaptive and data-driven decision-making frameworks. Machine learning algorithms can dynamically adjust the importance of criteria based on real-time information, while decision models ensure transparency and explainability of the results. Such synergy has the potential to transform traditional decision-making processes in network management and cybersecurity into intelligent, self-learning systems.

Overall, this study emphasizes the synthesis of mathematical and practical aspects of MCDM. By linking theoretical models with real engineering challenges, it demonstrates how mathematical reasoning directly contributes to more transparent, adaptive, and intelligent decision-making systems in telecommunications and information security.

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Security Monitoring of a PHP MVC Single Page Web Portal with Access Categorization: Preschool Institution Zrenjanin Case Study

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Abstract:
Security is one of important aspects of software quality. Web portals are particularly vulnerable in this global networked world with commonly appearing cyber attacks. Aim of this paper is to describe a method that enhanced the security level at a PHP Model View Controller (MVC) single page web portal. The essence of the method is categorization of access attempts and their recording in separate monitoring tables. Categorization is based on evaluation of URL parameter regarding the page ID. The proposed approach is implemented at official web portal of a Preschool institution, Zrenjanin, Serbia and the case study shows cyber attack attempt and results of the proposed method application.

Keywords:
Software quality, Web portal security monitoring, access categorization, cyber attacks

1. Introduction

Cyber security is one of the most important emerging research and professional areas in the modern world of networking information technologies (IT). Security is defined within the broader category of software quality in ISO 25010 standard [1]. Particularly important areas of interest regarding security are networked IT systems, particularly web applications, as being vulnerable to cyber attacks. Some worldwide organizations, such as OWASP [2], are focused on cyber security with special projects (OWASP Top 10 project [3]).

Aim of this paper is to describe a method in the field of software quality monitoring, particularly security monitoring of web portals. The essence of the idea is to categorize and record access attempts, i.e. URLs that users use, when trying to reach web portal's content. This categorization will lead to clean access statistics vs. malicious or incorrect access attempts statistics. The key inputs to single page – based web portals are their URLs, particularly page IDs, so this is used in the proposed method as a filtering criteria. The proposed method is applied at the Official web portal of Preschool institution Zrenjanin, Serbia [4].

The rest of the paper is organized as follows: section two presents background with basic definitions and categorizations regarding software product quality and software security, as well as brief overview of common cyber attacks to web portals, section three describes short overview of previously published papers, section four brings description of the proposed method, section five elaborates the application of the proposed method within the Preschool institution Zrenjanin official web portal case study, section six finally concludes with summarizing results and future research directions.

2. Background

2.1. Software Product Quality

ISO 25010 standard [5] defines software quality and the basic categories that belong to this term (quality model), which could be basis for the evaluation of software systems. "The quality of a system

is the degree to which the system satisfies the stated and implied needs of its various stakeholders, and thus provides value. The product quality model defined in ISO/IEC 25010." [5] The characteristics that are incorporated in the quality model defined in ISO/IEC 25010 are presented at Figure 1.

SOFTWARE PRODUCT QUALITY								
FUNCTIONAL SUITABILITY	PERFORMANCE EFFICIENCY	COMPATIBILITY	INTERACTION CAPABILITY	RELIABILITY	SECURITY	MAINTAINABILITY	FLEXIBILITY	SAFETY
FUNCTIONAL COMPLETENESS	TIME BEHAVIOUR	CO-EXISTENCE	APPROPRIATENESS RECOGNIZABILITY	FAULTLESSNESS	CONFIDENTIALITY	MODULARITY	ADAPTABILITY	OPERATIONAL CONSTRAINT
FUNCTIONAL CORRECTNESS	RESOURCE UTILIZATION	INTEROPERABILITY	LEARNABILITY	AVAILABILITY	INTEGRITY	REUSABILITY	SCALABILITY	RISK IDENTIFICATION
FUNCTIONAL APPROPRIATENESS	CAPACITY		OPERABILITY	FAULT TOLERANCE	NON-REPUDIATION	ANALYSABILITY	INSTALLABILITY	FAIL SAFE
			USER ERROR PROTECTION	RECOVERABILITY	ACCOUNTABILITY	MODIFIABILITY	REPLACEABILITY	HAZARD WARNING
			USER ENGAGEMENT		AUTHENTICITY	TESTABILITY		SAFE INTEGRATION
			INCLUSIVITY		RESISTANCE			
			USER ASSISTANCE					
iso25000.com			SELF-DESCRIPTIVENESS					

Figure 1: Structure of software product quality, according to ISO 25010 standard [5]

2.2. Software Security

According to ISO 251010 standard [1], security presents one of nine key categories of characteristics that are included in software product quality model. "Software security is the degree to which a product or system defends against attack patterns by malicious actors and protects information and data so that persons or other products or systems have the degree of data access appropriate to their types and levels of authorization"[6]. Software security is composed of six sub-characteristics:

- "Confidentiality - Degree to which a product or system ensures that data are accessible only to those authorized to have access.
- Integrity - Degree to which a system, product or component ensures that the state of its system and data are protected from unauthorized modification or deletion either by malicious action or computer error.
- Non-repudiation - Degree to which actions or events can be proven to have taken place so that the events or actions cannot be repudiated later.
- Accountability - Degree to which the actions of an entity can be traced uniquely to the entity.
- Authenticity - Degree to which the identity of a subject or resource can be proved to be the one claimed.
- Resistance - Degree to which the product or system sustains operations while under attack from a malicious actor." [6]

2.3. Common Cyber Attacks to Web Portals

As OWASP organization is worldwide recognized and their results are acknowledged in both education and scientific work, it is appropriate to cite their results regarding common cyber attacks (that could be addressed to web portals as well). OWASP Top 10 project is conducted periodically, so latest version OWASP Top 10:2025 is in the finalization phase, before publishing results [7]. Therefore, in this section the results will be cited from the latest finalized version of project report OWASP TopTen:2021 [8]. Figure 2. presents OWASP Top Ten: 2017 results compared to OWASP Top Ten:2021 results.

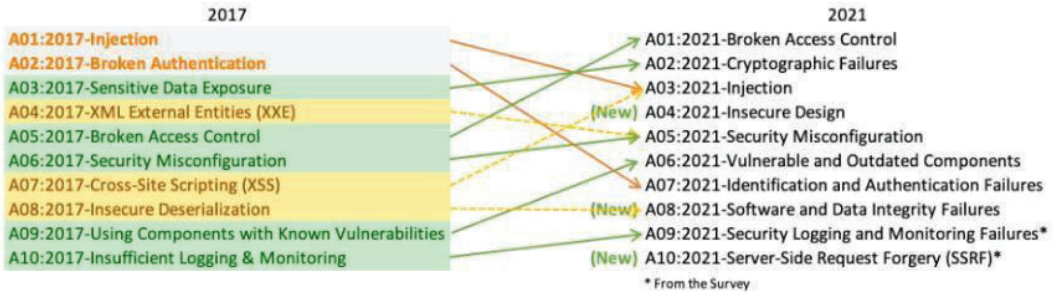


Figure 2: Common cyber attacks, according to OWASP Top 10: 2021 [8]

Basic types of cyber attacks, according to [8] are: Broken Access control, Cryptographic failures, Injection, Insecure Design, Security misconfiguration, Vulnerable and outdated components, Identification and authentication failures, Software and data Integrity failures, Security logging and monitoring failures, Server Side request forgery. Detailed definitions and failures are available in [8] for each of these subcategories.

3. Short overview of related work

Cyber security as a professional and scientific area of interest draws attention for many years, especially since the use of internet became part of everyday work and life. In this section a brief overview of key results from some of previously published papers will be presented. Abusaimeh and Shkoukani [9] conducted a survey related to web application and internet security threats. Key findings include detail presentation of weakness of web environment security, attacks and prevention. These authors present two types of attacks [9]: a) Static (with emphasis on discovering the web application structure and source code, in aim to enable other attacks or access to well-known hidden files or folders to access the site critical information); b) Dynamic (using links, paths, sessions, passing parameters, executing scripts and SQL injection). They also summarize intrusion prevention, such as password management, data encryption, firewalls, standard scanning programs and intrusion prevention software systems. Amutairi, Mishra and AlShehri [10] summarized web security threats and experimentally addressed some of them (SQL injection, cross-site scripting, directory traversal, OS command injection - for PHP and Java), particularly in the context of software tools that could be used in source code evaluation regarding security aspects.

Web applications could be validated in aim to detect security vulnerabilities, but also their trustworthiness (if they are potentially malicious). Canfora and Visaggio [11] summarize set of features extracted from web applications structure and content that could be used as indicators for web security threats. These indicators were used in the prediction with machine learning algorithms, to make classification of unknown web sites regarding their maliciousness.

Some specific types of web sites are particularly sensitive and their security has higher importance. Zhao et al. [12] conducted a study to assess security of U.S. state e-Government sites with the use of web content analysis, information security auditing and computer network security mapping. Matbouli and Gao [13] addressed e-Commerce web sites and security threats impact to e-Commerce success. Online social networks, as web applications with large number of users, are particularly sensitive from the aspect of cyber security risks. Sadeghian, Zamani and Shanmugam [14] addressed these challenges -typical social network threats and provided solutions.

4. The Proposed Method

In this paper, we propose a method for access security monitoring for web portals, that are based on MVC single page architecture. The proposed method is presented in Figure 3. as an UML (Unified Modeling Language) activity diagram.

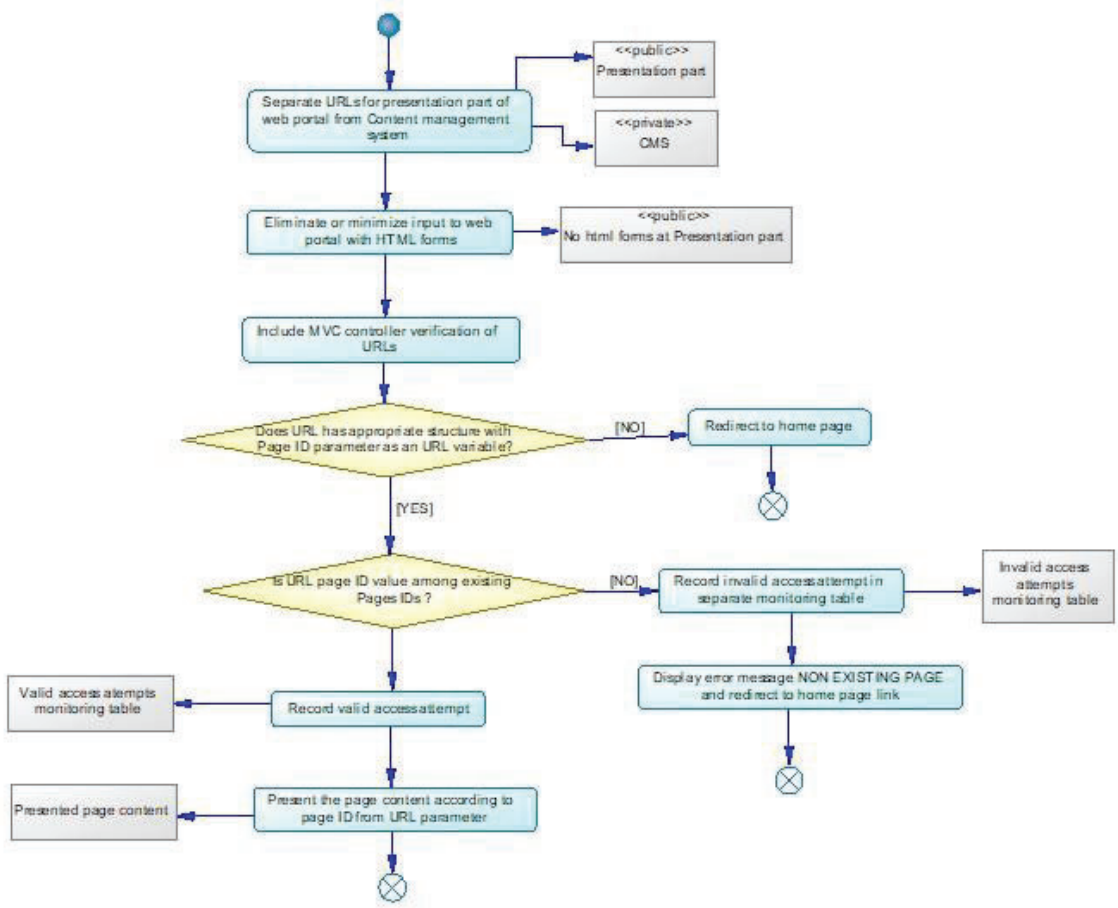


Figure 3: The proposed method to improve security of MVC single page web portals

According to Figure 3, the method proposes separation of Presentation part of the web portal from CMS (Content Management System) - to have them hosted at separate URLs, eliminating html forms from the presentation part and URLs control within the controller part of the MVC presentation part of web portal. The controller evaluates each access attempt URL and there are three possible situations:

1. The URL does not have appropriate structure (the variable for URL page ID is missing) – controller will redirect to home page of presentation part of web portal
2. The URL has appropriate form, but the value for Page ID is not from the domain of existing pages – the invalid access attempt will be recorded, error message will be presented and the link to return to home page.
3. The URL has appropriate form and the value for Page ID is from the domain of existing pages – the valid access attempt will be recorded and the page content will be presented

5. Preschool Institution Web Portal Case Study

The proposed method is applied within the extension of the project results, that was conducted in cooperation between University of Novi Sad, Technical Faculty "Mihajlo Pupin" Zrenjanin and Preschool Institution Zrenjanin, Serbia. The complete documentation about the technical solution is available at [15]. The solution consists of presentation part (Figure 4) and CMS (Figure 5).

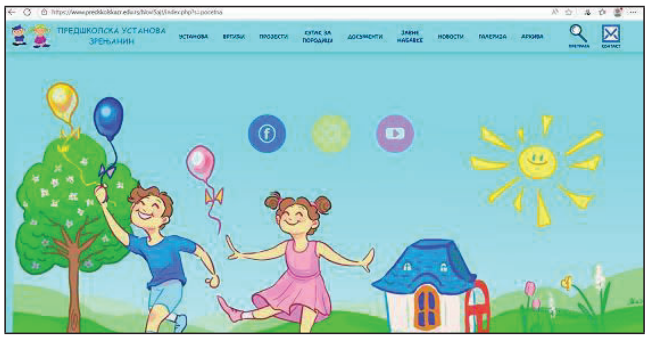


Figure 4: Home page of Preschool institution official web portal [4]

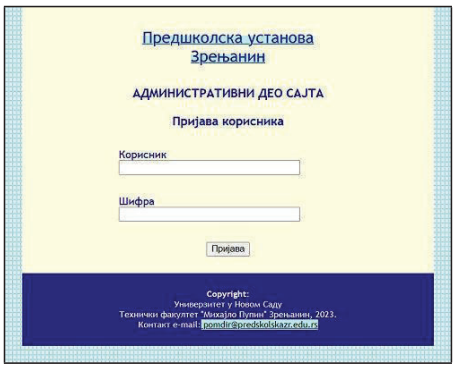


Figure 5: Log in form for CMS of Preschool institution official web portal

Typical URL to present particular page content is provided below, with resulting page content presented at Figure 6 (content presented with status on September 7, 2025):

https://www.predskolskazr.edu.rs/NoviSajt/index.php?s=vesti

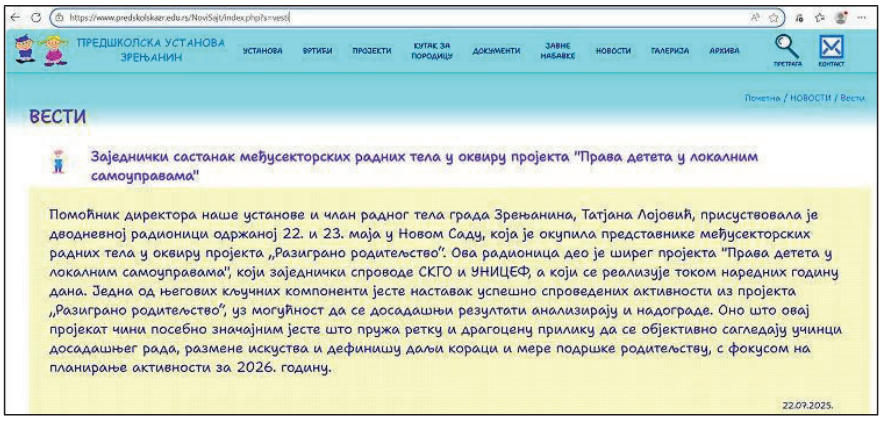
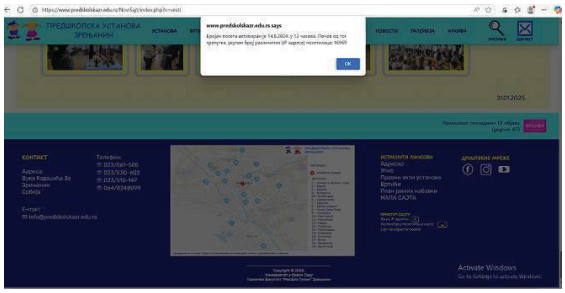


Figure 6: Example of a typical page presented with appropriate URL structure and existing Page ID at Official web portal of Preschool institution Zrenjanin

The functionality of access recordings was implemented within the project (described in [15]), in aim to have access statistics supported. Figure 7 presents access statistics accessible from the icon in the footer.



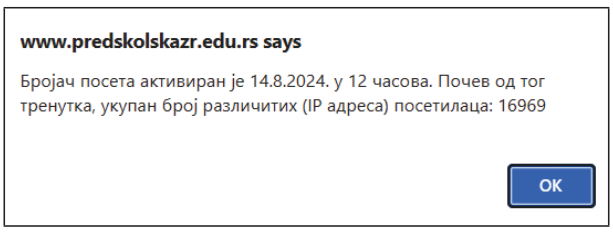


Figure 7: Access statistics at Official web portal of Preschool institution Zrenjanin

The need to particularly address the risks with false access attempts has been detected within regular checking of the statistics that is presented from recordings with details in the CMS system. On March 9 2025. the XSS (cross site scripting) and other false attempts were detected (Figure 8), so the need to handle access attempts more precisely and to separate regular from false access attempts arise.

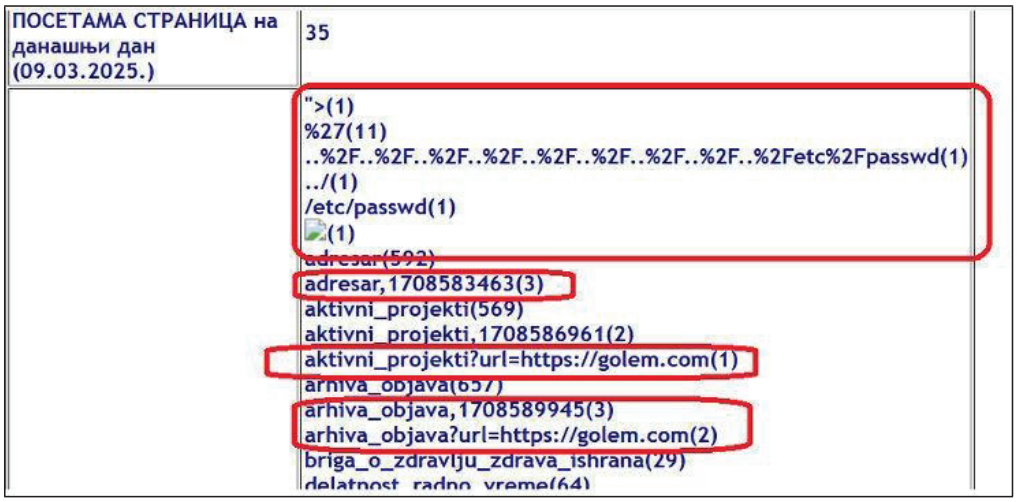


Figure 8: Particular pages statistics presented within CMS system of Preschool institution Zrenjanin, with false access attempts

Following figure present results of recordings on regular visits “Posetioci sajta” table (Figure 9).

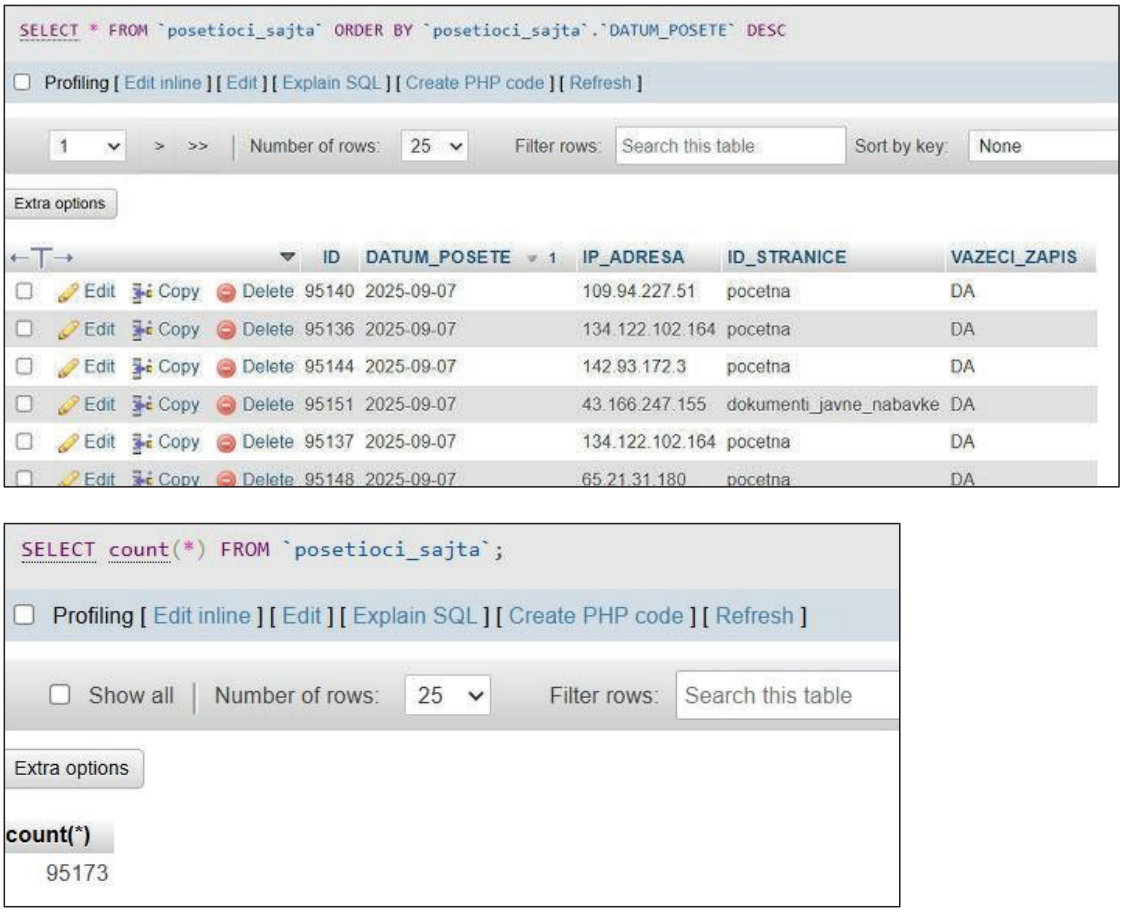


Figure 9: Regular access recordings for Official web portal of Preschool institution Zrenjanin

Irregular access attempts are recorded separately and they are presented at Figure 10.

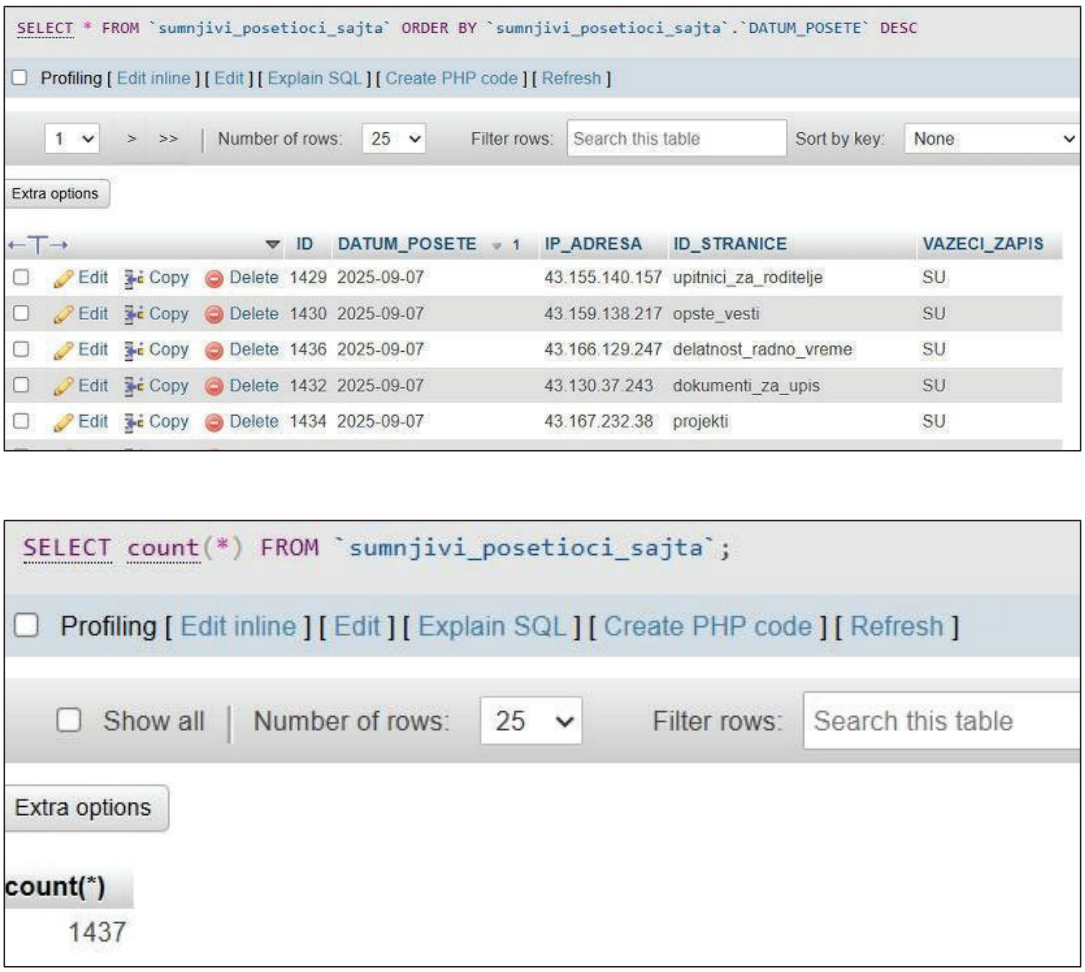


Figure 10: Irregular access recordings for Official web portal of Preschool institution Zrenjanin

It is obvious that in irregular attempts, users used non-existing Page IDs, such as "upitnici_za_roditelje" etc. According to Figures 9 and 10, since August 14, 2024, there was 95173 regular access attempts, and since march 2025 there were 1437 irregular access attempts.

6. Conclusions

Aim of this paper was to present a method that could be beneficial in MVC single page web portals security improvement and monitoring. The method is based on access attempts categorization and separate recording. Categorization is based on controller's role in URL analysis and acting accordingly – with situation of inadequate URL structure and inappropriate page IDs. The method is applied at Preschool institution Zrenjanin official web portal.

Future enhancement of the Preschool institution Zrenjanin web portal in this area could be directed towards comprehensive analysis and improvement of security regarding diversity of cyber attack types. Research in this area could be directed towards methods and tools for automation of software development that will have security techniques included in their technical solutions or methods for automated detection and fixing of harm effects in software and data, after attacks.

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Wireless Communication Security – Review on ZigBee and Bluetooth protocol

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Abstract:
This paper provides an narrative review of two widely used short-range wireless communication protocols, ZigBee and Bluetooth, with a particular focus on their security architectures and vulnerabilities. The study examines their operational principles, encryption and authentication mechanisms, key management techniques, and privacy features. Special attention is given to identifying weaknesses such as centralized trust dependencies in ZigBee and susceptibility to man-in-the-middle attacks in earlier Bluetooth versions. A comparative analysis is presented to highlight the strengths and limitations of each protocol in the context of Internet of Things (IoT) applications. The discussion focuses on how ZigBee's energy efficiency and mesh networking make it suitable for large-scale sensor networks, while Bluetooth/BLE offers stronger privacy features and interoperability for consumer-centric devices. The paper contributes by synthesizing and discussing recent security improvements and advancements, as well as underscoring persistent challenges and constrained resource limitations in embedded devices. The findings provide insights for researchers and system designers aiming to deploy secure and resilient IoT systems.

Keywords:
wireless communication security, Zigbee, Bluetooth, protocol security review

1. Introduction

Wireless communication technologies have become the backbone of the modern Internet of Things (IoT) ecosystem, enabling many interconnected devices to work together, ranging from household appliances and wearables to industrial automation systems and smart cities. As the number of devices continues to grow, the choice of communication protocols has a direct impact not only on performance and scalability but also on the overall resilience of the system against cyber-security threats. According to recent industry reports, more than 70% of IoT devices rely on short-range wireless protocols such as ZigBee and Bluetooth, making their security a critical research topic.

Security breaches in wireless networks can result in severe consequences, including unauthorized data access, service disruption, and privacy violations. With the increasing integration of IoT into healthcare, energy management, and transportation, vulnerabilities in these protocols may even threaten human safety. Therefore, analyzing and comparing the security features of widely adopted standards such as ZigBee and Bluetooth is of utmost importance.

This paper aims to provide a structured, narative review of both technologies by examining existing research papers that were published relatively recently, emphasizing their security architectures, identified weaknesses, and recent improvements. By conducting a comparative analysis, the study highlights strengths and limitations, offering valuable insights for researchers and system designers seeking to implement secure wireless communication solutions in resource-constrained environments.

2. Previous work

2.1 ZigBee

2.1.1 Overview

Zigbee networks utilize various routing protocols to achieve communication between sensor nodes and base stations. These protocols are required for forwarding data and providing reliable addressing. Depending on the network structure, mode of operation, and application requirements, Zigbee routing protocols are classified into several types. **Reactive protocols** discover routes on demand by broadcasting route requests, reducing the need to store routing information for all nodes. Contrary to that, **proactive protocols** maintain predefined routes by continuously transmitting data, ensuring consistent communication. **Flat routing protocols** operate without a centralized routing scheme, focusing on energy efficiency instead, by randomly assigning transmitters and receivers, with data requests made by region. **Hybrid routing protocols** combine the benefits of both reactive and proactive methods by using clustering techniques to enhance scalability and network stability; these clusters adjust dynamically as nodes enter or leave. Tree-based or hierarchical routing protocols organize nodes in a tree structure, allowing each node to calculate optimal paths to the destination and maintain routing tables. Unlike distance-vector routing, tree-based protocols only exchange connectivity information and use reachability checks to monitor active links. Zigbee networks typically adopt star, tree, or mesh topologies, each supported by specific routing protocols tailored to different performance and energy efficiency needs [1].

The ZigBee standard builds on the IEEE 802.15.4 framework by defining the physical (PHY) and media access control (MAC) layers, which handle the basic transmission, modulation, and collision avoidance in wireless communications. On top of these, ZigBee adds several layers to support network and application intelligence: the Network (NWK) layer enables network discovery, joining, mesh routing, and defines ZigBee-specific addresses; the Application Support Sub-layer (APS) manages packet duplication filtering and maintains binding tables of nodes; the Security Services Provider (SSP) layer handles security functions such as device management and key establishment; the ZigBee Device Object (ZDO) oversees device management, discovery, binding, and sets device roles like coordinator, router, or end device; and the Application Framework (APF) supports user applications by facilitating data exchange and providing endpoints. Together, these layers create a comprehensive architecture supporting efficient, secure, and flexible wireless sensor networks [2].

2.1.2 Security Aspects

ZigBee incorporates several built-in security services to protect communication between nodes. It uses symmetric encryption, specifically the AES algorithm in Counter with CBC-MAC mode, to ensure data confidentiality and authentication, with key reuse simplified across layers. Data integrity is maintained through a message integrity check (MIC), while a sequential freshness counter helps prevent replay and forwarding attacks by detecting out-of-order frames. Authentication is enforced at both the network (NWK) and application (APS) layers using network and link keys, respectively. The Trust Center, typically the coordinator node, manages device authentication, key distribution, and updates shared network keys to maintain end-to-end security. ZigBee employs three key types - master, network, and link keys. The NWK and APS layers use auxiliary frame headers containing source addresses and key sequence numbers to support secure frame transmission and key management within the network [2].

Master keys, often pre-installed or set over-the-air, are important for securely establishing link keys through the SKKE (**Symmetric Key Key Establishment**) protocol. Link keys encrypt communication between pairs of nodes, while network keys, managed by the Trust Center, protect the entire network from outsider attacks and are shared among all devices. The Trust Center controls device authorization and key distribution, either directly creating link keys or facilitating their mutual establishment via master keys. Despite this framework, several security concerns exist. Key distribution is vulnerable, especially when keys are transmitted over-the-air or pre-installed insecurely; compromising a single node can jeopardize

the whole network due to shared keys. The frame counter mechanism intended to prevent replay attacks is weak because it uses predictable increments, making it susceptible to denial-of-service attacks. Forward security is insufficient since nodes retain keys after leaving the network, allowing unauthorized access if devices are lost or stolen, and revocation processes are lacking. Additionally, widely available hardware and software tools enable attackers to eavesdrop, inject, or manipulate ZigBee communications, exposing further vulnerabilities. These issues highlight significant risks within the ZigBee security model that need to be addressed for safer deployments [3].

Despite built-in security features, ZigBee networks remain susceptible to threats such as key sniffing and unauthorized access, making it essential to evaluate these risks and implement proper countermeasures. Attacks on ZigBee can be categorized by the communication layer they target, the attack method, and the network component affected. Transport layer attacks include flooding and desynchronization, while network layer attacks involve tactics like wormholes and selective forwarding. The MAC layer can suffer from jamming attacks that disrupt communication, and physical layer attacks typically involve radio signal jamming to eavesdrop or tamper with data. Attacks can be active—where data is modified or injected—or passive, where attackers only monitor traffic to steal sensitive information. Targeted attacks include sinkhole attacks that misroute traffic, source attacks where compromised nodes drop packets, neighbor attacks exploiting node discovery protocols, member and outsider attacks by unauthorized or compromised nodes, and energy depletion (ghost) attacks that drain node power to enable further disruption. Understanding these diverse threats is crucial for strengthening ZigBee network security [2].

The proposed security solution for the ZigBee network is structured in two main stages to enhance device authentication and secure communication. The first stage is the **Device Authentication and Key Agreement Phase**, which includes three sub-phases: the offline phase, authentication phase, and communication phase. In the **offline phase**, each device registers its unique identity and master key with the Trust Center (TC), ensuring that only pre-registered devices can join the network. During the **authentication phase**, devices generate dynamic identities using hash functions and session counters, avoiding the exposure of real IDs during communication. Each device sends encrypted and hashed parameters—such as its dynamic ID, session counter, encryption key, and a random array—to the TC. The TC decrypts and validates the information, verifies the message integrity, and then sends a confirmation back to the device. This mutual authentication ensures both the device and TC trust each other, and it sets the foundation for secure data exchange. In the **device-to-device (D2D) communication phase**, a secure session key is established between two authenticated devices (e.g., D1 and D2). D1 sends a request to D2 using encrypted parameters, which D2 forwards to the TC for verification. The TC validates the authenticity of both devices, generates a session key and a random array of bits, and sends these securely to each device. This session key is used for encrypted communication between the devices. The second main stage of the solution focuses on **enhanced encryption using AES**. Each message is encrypted using the AES-128/CCM algorithm, with a dynamically updated random array of bits merged into the data block before encryption. This array is refreshed with each transmission, providing session uniqueness and resilience against cryptanalysis—even if the symmetric key is compromised. The array is stored and updated on both communicating devices, ensuring synchronization and secure future communications. Overall, this two-stage approach strengthens both authentication and data confidentiality in ZigBee networks [4].

The proposed security solution for ZigBee networks is validated through both informal security analysis and static performance assessment. The **security analysis** shows that the approach effectively prevents several common attacks. **Access control** is ensured by requiring devices to be pre-registered with the trust center, which verifies identities using master keys. **Eavesdropping attacks** are mitigated through symmetric encryption and dynamic identities, which prevent linking messages to specific devices. **Replay attacks** are addressed by using session-specific random values (nonces), making reused messages invalid. **Anonymity and un-traceability** are preserved by never transmitting real device IDs in plaintext and by using changing dynamic identities, so attackers cannot link multiple sessions to the same device [4].

The **performance evaluation** confirms that the approach is lightweight and suitable for resource-constrained ZigBee devices. It requires 20 hash operations and no XOR operations, which is efficient compared to other methods. In terms of **communication overhead**, the total cost of all required transmissions is 3136 bits. Although slightly higher than a few other methods, this cost includes an extra 128-bit secret array that significantly enhances cryptographic strength, making the trade-off worthwhile. Overall, the proposed solution provides strong security with manageable computational and communication overhead [4].

2.2 Bluetooth

2.2.1 Overview

Bluetooth protocol is considered to be very efficient protocol for short distance wireless communication between devices. Stable and convenient, Bluetooth technology became important asset for both computer and electronic communication. Commonly, Bluetooth operates at frequencies from **2402MHz up to 2480MHz**, and from **2400MHz up to 2483.5MHz, with addition of guard bands 2MHz wide at the bottom end, and 3.5MHz wide at the top.** In order to utilize communication, Bluetooth implements radio technology of frequency-hopping spread spectrum. Data for transmission is divided into packets, and then, each packet is transmitted on one of the 79 designated Bluetooth channels, where each channel has a bandwidth of 1MHz [5].

As for general communication and connection aspects, master BR/EDR Bluetooth device is able to achieve communication with maximum of seven devices in a piconet (an ad-hoc computer network using Bluetooth technology), but not all devices could reach that level. With the Bluetooth Core Specification, two or more piconets can form a scatter net (devices can simultaneously play the master role in one piconet and the slave role in another). Besides establishing communication and performing data transmission, devices can also switch their roles, and slave device can become master device. [5]
Speaking about Internet of Things (IoT) - an ecosystem of interconnected physical devices and vehicles as well as objects embedded with sensors, software and network connectivity, Bluetooth technology found decent utilization. Smart devices are found in home appliances, wearable technology as well as industrial machinery. Each smart device is equipped with specific sensors that are used to measure or monitor various parameters such as actuators, location, humidity, motion and temperature. Data generated by IoT devices is collected and transmitted to centralized systems or various cloud platforms for further analysis and processing. With evolution of embedded systems, Edge Computing was introduced, where Internet of Things ecosystems are processing data much closer to the data source, on the edge of network, rather than relying on centralized cloud services. However, as more devices are becoming interconnected, potential cyber security threats rise [6].

Over the years, Bluetooth technology evolved, featuring new advancements which introduced enhanced functionality, performance and applicability. Initial versions of Bluetooth, such as Bluetooth 1.0, 1.1 and 1.2 provided basic wireless connectivity. However, they had interoperability issues and complex pairing processes. As for the Bluetooth 2.0 combined with Enhanced Data Rate (EDR), as well as Bluetooth 2.1, data transfer rates improved significantly, and power consumption was more efficient. Bluetooth 3.0 combined with High Speeds (HS) achieved higher data transmission speeds, which was useful for applications that require rapid data exchange. With Bluetooth 4.0, Bluetooth Low Energy option was introduced, designed specifically for low power consumption with extended battery life, which was important for the emerging IoT market. As for the Bluetooth 4.1 and 4.2, they brought enhancement with LTE networks, as well as increased data capacity and improved security features. For the Bluetooth 5.0, most significant was the increased range, speed and data broadcasting capacity, as well as optimization for the IoT applications. Later, Bluetooth 5.1, 5.2, 5.3, 5.4 and 6.0 introduced more advanced features, such as direction finding, LE audio (used for enhanced audio streaming), and general improvements related to speed optimization, range, power efficiency and connection reliability [6].

2.2.2 Security Aspects

By utilizing the AES-128 encryption, data transfer is protected between devices. Implementation of secure pairing mechanisms like Passkey Entry, Just Works, and Out-of-Band pairing is used to ensure that connections are securely established, and data integrity is maintained. With evolution of Bluetooth, privacy and security was additionally enhanced with Resolvable Private Addresses (RPAs) and new physical layer configuration, also known as LE 2M 2BT [6].

Security Mechanisms

- **Resolvable Private Address (RPA)** - used to periodically change device address, making it difficult for third parties to track devices by utilizing static identifiers like physical (MAC) address [6].
- **Identity Resolving Key (IRK)** - used to ensure that only authorized devices can associate the RPA with a known identity, which brings enhanced privacy and anonymity while mitigating security threats related to persistent device tracking [6].
- **LE 2M 2BT** - used for secure and accurate distance measurements, commonly useful in environments that require precise positioning, such as augmented reality applications [6].
- **Bandwidth-Bit Period Product (BT) parameter** - used to influence signal pulse characteristics, and making channel sounding resistant to physical layer attacks [6].

When Bluetooth devices are establishing connection, first link must involve key exchange between both devices (link key). Link key is a 128-bit random number, and it is used as an encryption key. Depending on the actual type of the application, link key can have three forms [5].

Unit Key – E21 (Unit and combination keys generation), which is generated once the initialization of link occurs. This key is stored in a memory, and used when one device wishes to use the other unit's key [5].

Combination Key – E21 (Unit and combination keys generation), which is generated by both devices. Random numbers of both devices are exchanged, and combination key is calculated.[5]

Master Key – E22 (Initialization and master keys generation), which is generated by the master device, temporarily used by devices, and then eradicated [5].

Considering Bluetooth Defense capabilities, multi-layered approach should be examined along with best security practices, as well as user awareness. Strong authentication and encryption mechanisms should be enabled, such as Bluetooth Secure Simple Pairing (SSP) and Secure Connections. Firmware and Software updates should be mandatory, to patch any known vulnerabilities and ensure that devices are protected against latest security threats. Unused Bluetooth Features could be possible attack vectors, and they should be disabled - that reduces the attack possibilities and minimize the risk of exploitation. Strong PINs and Passkeys should be set, to prevent brute force attacks. Bluetooth sniffing detection should be implemented, to monitor for the suspicious activity and unauthorized access attempts. Finally, users should be educated and aware of the risks associated with Bluetooth-enabled devices [7].

As for the security improvements, several things can be achieved according to [8], various fixes were suggested for enhancing overall Bluetooth security. Some of the fixes add modifications to existing protocols, while some design completely new ones, and they are listed below:

- **PKE** modification (Secure Hash) - Input and output capabilities should be included in the computation of the confirmation values [8].
- **PKE** modification (Dual Passkey Entry) – two independent passkeys should be used, which are generated by both devices, and should be transmitted over a secure channel [8].

3. Security Characteristics Comparison of ZigBee and Bluetooth/BLE/Bluetooth Smart protocols

In the table below, a brief overview of security features between ZigBee and Bluetooth/BLE/Bluetooth Smart has been developed.

Table 3:
Comparison of Security Features: ZigBee vs Bluetooth/BLE/Bluetooth Smart

Characteristic	ZigBee	Bluetooth/BLE/Bluetooth Smart
Encryption	AES-128 (Advanced Encryption Standard with 128-bit key) used for secure data transmission [9].	AES-128 for Bluetooth Classic; BLE uses AES-CCM (Counter with CBC-MAC) for encryption.
Authentication	Symmetric key-based authentication using pre-shared keys or network keys. Trust Center manages key distribution [10].	Pairing-based authentication using Passkey Entry, Numeric Comparison, or Out-of-Band (OOB) methods. LE Secure Connections use Elliptic Curve Diffie-Hellman (ECDH).
Key Management	Centralized key management via Trust Center. Supports network and link keys for secure communication.	Distributed key management. Long-term keys (LTK) and short-term keys (STK) managed during pairing. ECDH for secure key exchange in BLE.
Security Modes	Two modes: Standard (AES 128 encryption) and High Security (additional authentication and key management).	Bluetooth Classic: Security Mode 1–4 (Mode 4 uses Secure Simple Pairing). BLE: LE Security Mode 1 (encryption) and Mode 2 (data signing).
Protection Against Attacks	Vulnerable to physical attacks if devices are compromised (e.g., key extraction). Replay attack protection via frame counters.	Susceptible to man-in-the middle (MITM) attacks in older versions. BLE mitigates MITM with LE Secure Connections and protects against replay attacks.
Privacy Features	Limited privacy features. De vice addresses can be tracked unless additional measures are implemented.	BLE supports private addresses (Random Device Addresses) to prevent tracking and enhance privacy.
Over-the-Air Security	Secure over-the-air updates supported with encrypted firmware. Requires Trust Center for key management.	BLE supports secure over-the air updates with encrypted firmware. Bluetooth Classic re lies on application-layer security for updates.
Network Topology Impact	Mesh topology enhances resilience [9], but increases attack surface due to multiple nodes.	Point-to-point or star topology limits attack surface but may be less resilient to node compromise.

4. Discussion

The comparative analysis of ZigBee and Bluetooth/BLE security characteristics highlights distinct advantages that make each protocol suitable for different IoT scenarios. ZigBee, with its centralized Trust

Center and mesh topology, is well-suited for large-scale sensor networks such as smart homes and industrial monitoring systems, where low power consumption and network resilience are critical. However, its limited privacy mechanisms and vulnerability to key compromise require additional safeguards.

Despite providing strong encryption and authentication mechanisms, ZigBee suffers from significant privacy limitations. Devices in a ZigBee network typically rely on static identifiers such as MAC and network addresses, which remain constant during operation and are exposed in packet headers even when the payload is encrypted. This allows adversaries equipped with simple radio scanners to track devices over time and space, enabling location monitoring and behavioral profiling of users based on traffic patterns. Unlike Bluetooth Low Energy, which employs Resolvable Private Addresses (RPAs) to mitigate device tracking, ZigBee lacks built-in mechanisms for identity obfuscation. Consequently, although data confidentiality may be preserved, metadata leakage in ZigBee networks poses a serious privacy risk, particularly in sensitive IoT environments such as smart homes, healthcare, and industrial applications.

On the other hand, Bluetooth, particularly BLE, provides stronger privacy through features like Random Private Addresses (RPA) and employs distributed key management, making it more resilient against centralized failures. Furthermore, its higher data rates and interoperability with consumer devices position it as the preferred choice for applications such as wearables, medical sensors, and mobile connectivity. In essence, ZigBee is optimized for energy-efficient, large-scale deployments, while Bluetooth/BLE is better suited for user-centric and privacy-sensitive IoT applications.

5. Future Work

Future work should consider covering stronger authentication methods such as integrating asymmetric encryption like ECDSA or RSA for secure device onboarding as well as focus on improving ZigBee's weak key management and especially its reliance on preconfigured global keys that enable man in the middle attacks.

6. Conclusions

This paper has reviewed the security mechanisms of ZigBee and Bluetooth protocols, outlining their architectural foundations, encryption methods, authentication processes, and privacy-preserving techniques. A comparative analysis was conducted to identify both strengths and weaknesses of each protocol, emphasizing the practical implications for wireless sensor networks and IoT ecosystems.

The main contribution of this study lies in synthesizing recent advancements and highlighting persistent vulnerabilities. ZigBee's centralized Trust Center approach provides strong control but introduces single points of failure, while Bluetooth's distributed model enhances flexibility but has historically been exposed to man-in-the-middle attacks. Both protocols have introduced updates to mitigate known risks, yet challenges remain in areas such as key management, forward secrecy, and secure over-the-air updates.

Finally, the findings underscore that wireless communication security must be treated as a fundamental design principle in IoT systems. Designers and developers should balance energy efficiency with security requirements, adopt updated standards, and implement best practices such as regular firmware updates, strong authentication, and user awareness training. These combined measures can significantly reduce vulnerabilities and enhance the resilience of wireless communication infrastructures.

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Integrity of digital evidences in the investigation process

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Abstract:
Technological preservation of digital evidence from the aspect of integrity is very important for any subsequent handling of data or information contained in said evidence. In practice, it is shown that investigative bodies do not know the technological framework that defines the way of dealing with digital evidence. The occurrence an error during the investigative procedure prevents the necessary subsequent professional actions with an evident lack of completeness of the data and unconfirmed integrity of the extracted data. The paper aims to point out the observed errors in the actions of investigative authorities and define guidelines for further complete and valid actions aimed at delivering data with confirmed integrity.

Keywords:
digital evidence, integrity, encryption, usability, recommendations, standards, procedure

1. Introduction

Data integrity is the concept of maintaining the accuracy, completeness, consistency and reliability of data throughout its entire lifecycle. It involves implementing processes and controls to protect data from loss, corrupting influences and unauthorized access, ensuring that the data is trustworthy and suitable for its intended use. Investigative authorities working with digital evidence must be aware of its vulnerabilities if they hope to maximize its value for justice and accountability [1].

Digital evidence in investigative actions can usually be downloaded only once. After the prepared procedural and organizational prerequisites, it is necessary to carry out the technological procedure of downloading data in the correct way, which will ensure the completeness and usability of data, but inevitably guarantee the integrity of the downloaded data during the entire process of recognition, recording, collecting, transport and storage. In practice, it has been shown that the absence of any technological element of data integrity creates catastrophic problems in the subsequent actions of investigative authorities in the procedural and organizational aspect[2]. The existing ISO standard framework provides clear guidelines for the technological set of actions to be taken to preserve the integrity of retrieved evidence in digital form. Special care should be taken if encrypted data is downloaded, which is not uncommon in the field of global information technology-based data exchange systems.

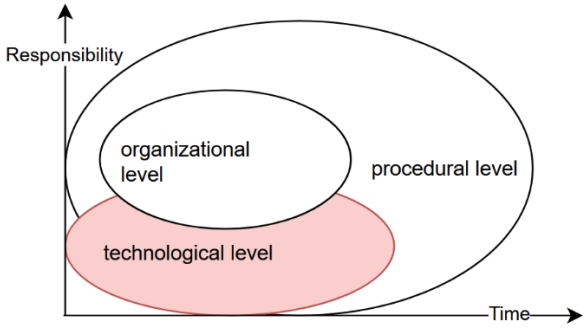


Figure 1: Role of technology in investigation

In trials based on digital data, the importance of the technological framework is crucial from the aspect of presenting data that should, but does not have to be given the status of evidence. The application of technological measures depends on whether the conditions will be met for certain data to be given the status of evidence or whether the entire long-term investigation work was just a waste of time[3].

There are several very good solutions that provide powerful, complementary tools for digital investigations, while enabling robust data extraction and analysis. The software offers solutions based on the latest technologies for detecting and parsing data from seized digital evidence in order to support investigative procedures. These tools must be used with great care, bearing in mind that the investigation is not the end of the operation but only the beginning of a long-term judicial procedure. Practice has shown that engineers who only work as technological experts in the investigation and have no experience in presenting their work in court, do not have a vision for improving their activities that are based only on technologies.

2. Professional rules such as ISO standards

For many years, information technology has not only been an innovative framework defined by the guidelines of university professors, but there are clearly defined rules of the profession that need to be applied. The rules of the profession were first defined as international ISO standards and then adopted as national standards by democratic countries in the modern world. The practice is that international standards may or may not be applied, but that national standards are treated as a clear framework of good practice for application in a particular field.

Global ISO standard ISO/IEC 30121:2015 Information technology - Governance of digital forensic risk framework was adopted back in 2015, while it was adopted as a national standard by the european states form 2015 to 2016: France: NF EN ISO/IEC 30121:2016, Nederland: NEN-EN-ISO/IEC 30121:2016, Belgium: NBN EN ISO/IEC 30121:2016, Slovenia: SIST EN ISO/IEC 30121:2016, Croatia: HRN EN ISO/IEC 30121:2016. EU candidate countries have adopted these standards: Serbia: SRPS EN ISO/IEC 30121:2017, Montenegro: MEST EN ISO/IEC 30121:2017, Bosnia and Hercegovina: BAS EN ISO/IEC 30121:2018. The same practice is in other countries of Europe and the democratic world. ISO/IEC 30121:2015 provides a framework for Governing bodies of organizations (including owners, board members, directors, partners, senior executives, or similar) on the best way to prepare an organization for digital investigations before they occur. This International Standard applies to the development of strategic processes (and decisions) relating to the retention, availability, access, and cost effectiveness of digital evidence disclosure. This International Standard is applicable to all types and sizes of organizations.

Global ISO standard ISO 21043-1:2018 Forensic sciences Part 1: Terms and definitions was adopted in 2018 and in the same year it was given the status of a national standard by numerous countries such as The same practice is in countries in Europe and democratic countries around the world.

The global standard that represents the backbone of digital data processing management is ISO standard ISO 21043-2:2018 Forensic sciences Part 2: Recognition, recording, collecting, transport and storage of items was adopted in 2018. It was adopted as a national standard by the european states: France: NF EN ISO 21043-2:2020, Nederland: NEN-EN-ISO 21043-2:2020, Belgium: NBN EN ISO 21043-2:2020, Slovenia: SIST EN ISO 21043-2:2020, Croatia: HRN EN ISO 21043-2:2020. EU candidate countries have adopted these standards: Serbia: SRPS EN ISO 21043-2:2020, Montenegro: MEST EN ISO 21043-2:2020, Bosnia and Hercegovina: BAS EN ISO 21043-2:2021.This ISO standard specifies requirements for the forensic process focusing on recognition, recording, collection, transport and storage of items of potential forensic value. It includes requirements for the assessment and examination of scenes but is also applicable to activities that occur within the facility. This document also includes quality requirements. ISO standard is not applicable to procedures for the recovery of data from digital storage media which is covered by ISO/IEC 27037. However, the storage medium itself can yield additional items of forensic value (e.g. fingerprints or DNA). Annex D of this Standard shows the applicability of this document to the forensic process.

ISO 21043-3:2025 Forensic sciences Part 3: Analysis. This document specifies requirements and provides recommendations to safeguard the process for the analysis of items of potential forensic value. It includes requirements and recommendations for the selection and application of suitable method(s) for the analysis to meet the needs of the customer and fulfil the request. The requirements are designed to ensure the use of suitable methods, proper controls, qualified personnel and appropriate analytical strategies throughout the forensic analysis of items. This document is applicable to activities conducted by a forensic service provider that occur at the scene and within a facility. This document is applicable to all disciplines of forensic science; however, it is not applicable to the recovery of digital data which is covered by ISO/IEC 27037.

ISO 21043-4:2025 Forensic sciences Part 4: Interpretation. This document specifies requirements and provides recommendations for the interpretation of observations to reach opinions that answer questions that are relevant for decision making in investigations or legal proceedings. This document states requirements that are applicable to all forensic disciplines. This document states requirements that apply when the opinion is based directly on human judgement and when the opinion is based on interpretation through a statistical model. This document is applicable to interpretation that occurs at a scene, within a facility, or within a judicial setting. This document establishes requirements designed to safeguard the process for the interpretation of observations including the use of either statistical models or human judgement, to address alternative propositions based on the questions asked by the customer. Interpretation is not necessary and the requirements of this document do not apply if the observations resulting from the analysis directly answer the relevant question.

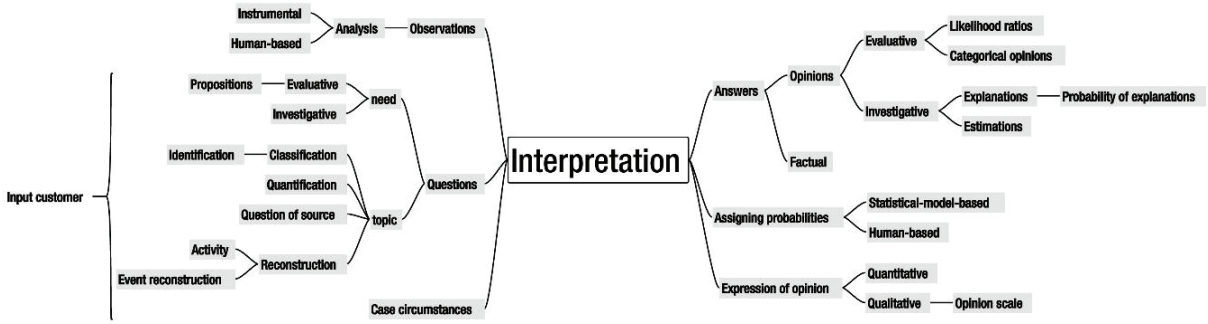


Figure 2: Mind map of forensic interpretation according to ISO 21043 - 4 Interpretation.

Data interpretation is the crucial point that transforms raw data captured into actionable insights, enabling investigators to make data-driven decisions, identify trends for strategic decision-making for the further course of the proceedings. A very important thing at this point is to confirm the identified context of the data. By discovering patterns, understanding complex information and contextualizing data, investigators gain a clear framework for their future strategies towards the courts. Practice has shown that special professional attention must be paid to the difference between Data Analysis and Data Interpretation. Figype 2 shows a mind map that illustrates some of the terminology and structure, input and output of the interpretation process [4]. The standard ends with three informative annexes. The first explains the meaning of the likelihood ratio in the forensic context. The second gives two examples of opinion scales. The third is even more helpful: it essentially takes you through the decision tree in 8 short example cases, with different areas of expertise, types of questions and types of opinion, for both investigative and evaluative interpretation.

ISO 21043-5:2025 Forensic sciences Part 5: Reporting - specifies requirements and provides recommendations for reporting of forensic work. This document is applicable to the reporting of forensic work performed at a scene and within a facility. The requirements facilitate the preparation and issuing of reports that are accurate, clear, transparent, complete, unambiguous, impartial and suitable for their intended use. This document also includes requirements relating to the review of case records and reports, the issuance and control of reports, and requirements related to testimony.

There are certain technological, organizational and procedural rules for retrieving data that investigators hope will become evidence in court. Technological rules, in addition to retrieving data, must include clear and unambiguous context. Retrieving data can most often be done on a device, phone or

computer, internet or communication infrastructure, passive or active data repositories or in the structure of a service provider. Retrieving data that is not encrypted is a simpler process and requires much less documentation than retrieving encrypted data. The process of retrieving encrypted data requires providing the original evidence in encrypted form with all accompanying documentation on the methods and procedures for decrypting it to the level of partial or full readability that will be presented in court. Documentation should ensure that all procedures performed on the initially secured data can be confirmed using reverse engineering.

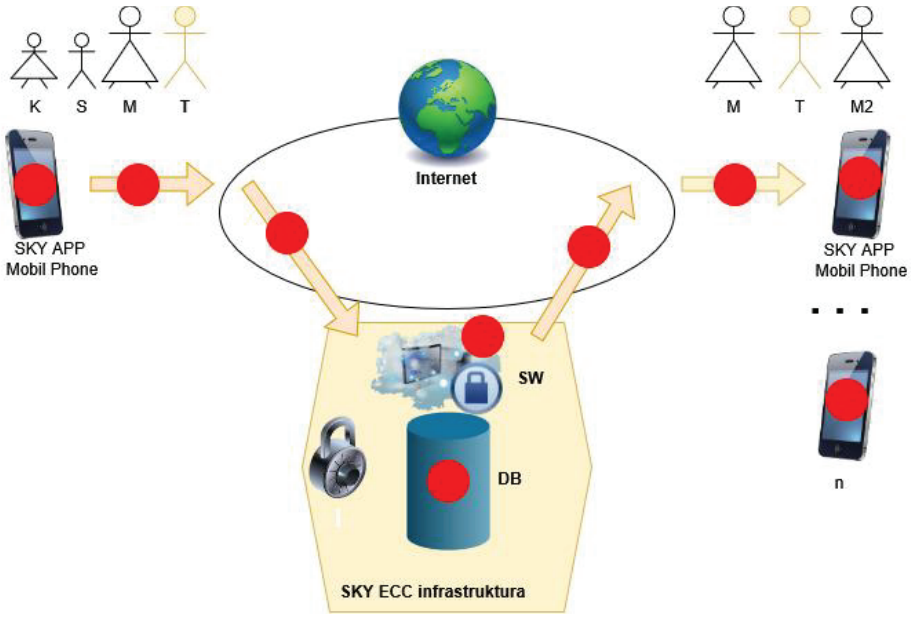


Figure 2: Example of the data interception points

The initially extracted data must be controlled copy of the original data with all necessary documented organizational, procedural and technological actions. All actions on the data must be documented from the initial download of the data by making a controlled copy until the submission of that data to the Court. Each individual action taken must be documented in detail and it is also necessary to adhere to the principle of treating the initially downloaded data as little as possible. Data from the investigation process should not be aggregated with data for which we want to become evidence in court proceedings. The application of artificial intelligence tools is not recommended for data from the investigation[5], and especially not their aggregation with the originally downloaded data. Failure to apply the rules of the profession defined in the reference ISO standards destroys the entire investigation process when such data with an undocumented and undefined technological, organizational and procedural framework appears before the court. In such situations, the court expert for information technology engaged by the Court enters an undefined scope of his work or a scope in which many actions that were initially missed cannot be repeated. The court expert in the proceedings before the court cannot be held responsible for actions missed to preserve the integrity of the data by the investigative authorities.

Special care must be taken when data for investigation purposes is obtained by downloading individual intercepted data outside the infrastructure of the data transmission service provider, rather than downloading data directly in cooperation with and from the database and infrastructure of the service provider[6]. The integrity of data when downloaded directly from the service provider is easier to verify. Downloading individual intercepted data requires documentation for each individual piece of data or set of data, which is a very heavy burden for investigative authorities, but only by applying these principles, the reliability of data can be guaranteed and the offered data have a high chance of obtaining the status of evidence. All of the above applies only to democratic states whose courts respect the legal acts of the state in which the judicial proceedings are conducted.

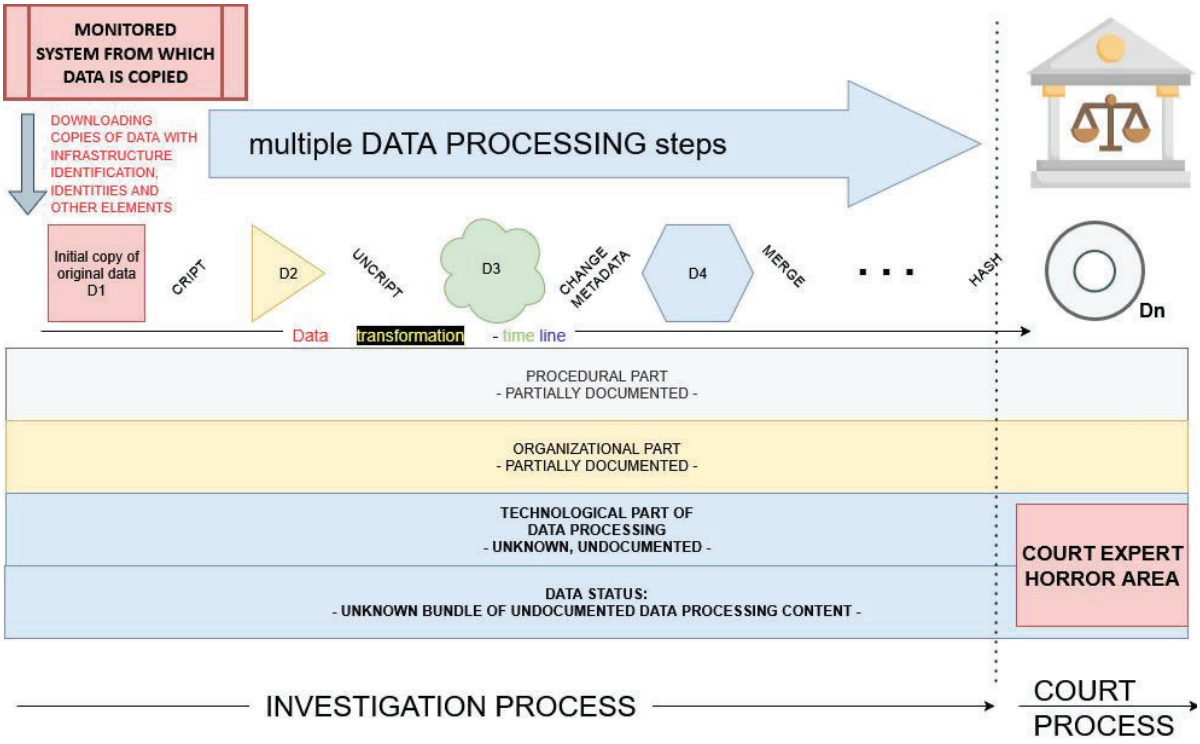


Figure 3: Example of the most common practice - Undocumented data handling

The principles of data integrity in investigative actions are not tied to the institution conducting the investigation, but are tied to each individual piece of data that intends to obtain the status of evidence. The procedures of decryption, hashing, metadata changes and all others must be strictly and completely technologically, organizationally and procedurally documented. Such documentation must accompany each procedure in the investigative process.

In practice, it happens that Courts deliver copies of evidence to the parties to the dispute or the accused in a way that they make undocumented changes to metadata, but such an omission is corrected in a simpler way than an omission that is made during investigative actions.

Within the framework of investigative actions over one large encrypted data exchange system in a court proceeding over the delivered data, the following were identified: intercepted data as well as data processed by artificial intelligence tools - unauthorized data and data from the investigative procedure that were not documented. In addition to all of the above, metadata modification and subsequent undocumented work on the data were identified. Confirming data integrity in such undocumented environment is not possible.

3. Professional rules such as ISO standards

The author's recommendation is that in the process of protecting data integrity when working with digital evidence, the initial principles defined by the ISO 21043 family of standards, as well as additional specific ISO standards, be respected throughout the entire process from Request to Testimony, with the application of the ISO/IEC 30121 standard as well as the application of Specific standards: ISO/IEC 27042, ISO/IEC 27037, ISO/IEC 27050-2, ISO/IEC 27050-3, ISO/IEC 27050-4, and others.

The application of the ISO 21043 standard family is clearly defined: ISO 21043 - 2 Forensic sciences Part 2: Recognition, recording, collecting, transport and storage of items, ISO 21043 - Forensic sciences Part 3: Analysis, ISO 21043 - 4 Forensic sciences Part 4: Interpretation and ISO 21043-5 Forensic sciences Part 5: Reporting.

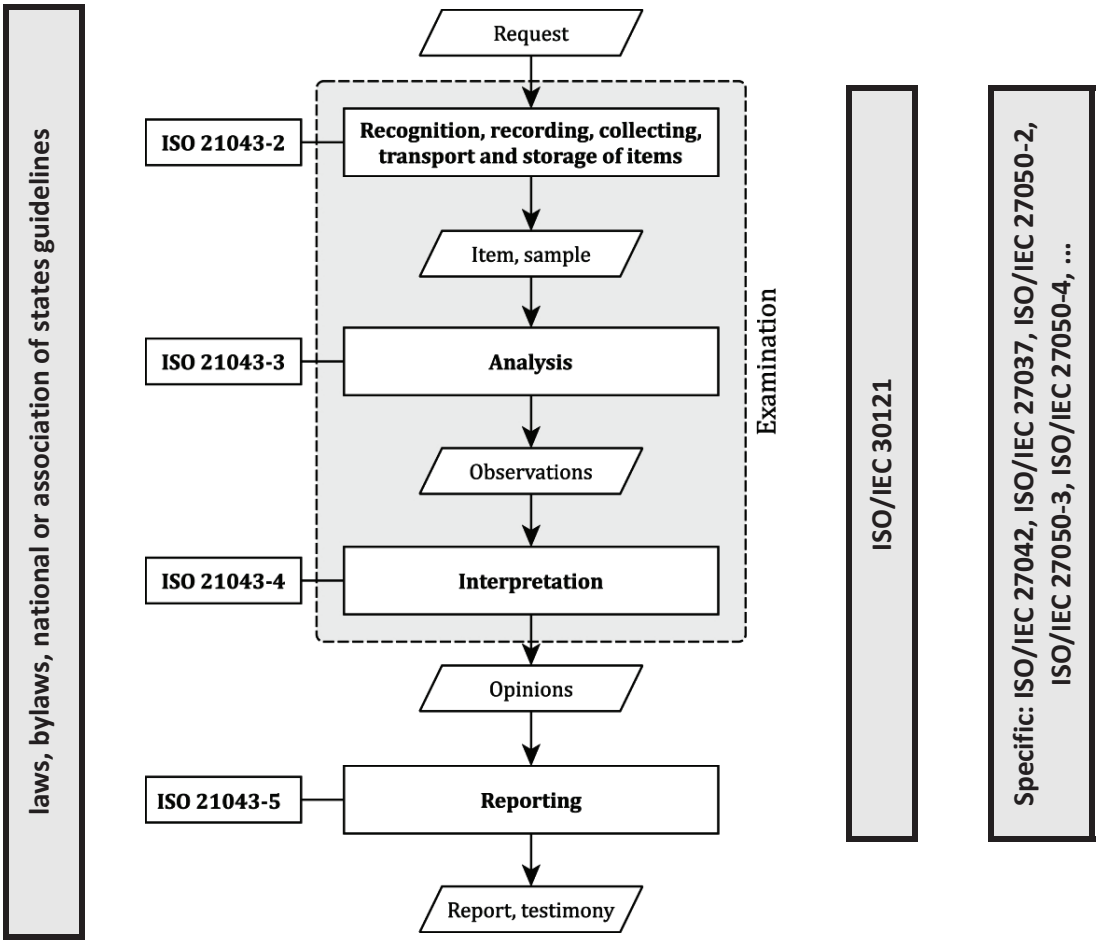


Figure 5: Extended ISO 21043 Model for handling data during investigative actions with the aim of preserving the integrity of evidence

The necessary expansion includes the requirements of the standard for specific needs: ISO/IEC 27042 Information technology - Security techniques - Guidelines for the analysis and interpretation of digital evidence, ISO/IEC 27037 Information technology - Security techniques - Guidelines for identification, collection, acquisition and preservation of digital evidence, ISO/IEC 27050 - 2 Information technology - Electronic discovery Part 2: Guidance for governance and management of electronic discovery, ISO/IEC 27050 - 3 Information technology - Electronic discovery Part 3: Code of practice for electronic discovery, ISO/IEC 27050 - 4 Information technology - Electronic discovery Part 4: Technical readiness and other requirements of the standard according to the specifics of the investigative procedure. The interaction of the requirements of the above standards describes the framework that is minimal for application during the implementation of investigative actions in order to create a valid framework of evidentiary material for court proceedings.

An additional set of extended original data used for investigative purposes should not be submitted to the court in the form of evidence to be processed by a court expert. The recommendation of court experts is to submit to the Court only initially downloaded data in the form of a controlled copy or original data, depending on the specifics of the court proceedings. When submitting controlled copies of files, special attention should be paid to submitting files without modifying the initial metadata. There are a number of ways to preserve the original metadata by copying so that submitted files retain their copy-controlled status.

The Chain of Custody (CoC) is a critical procedural safeguard in digital forensics, ensuring the reliability, credibility, and admissibility of digital evidence in legal proceedings. The Chain of Custody ensuring that evidence collected during an investigation is admissible in court through identified significances: Ensures Evidence Integrity, Establishes Credibility, Supports Legal Admissibility, Prevents

Evidence Contamination, Facilitates Accountability, Preserves Investigation Integrity, Meets Regulatory and Industry Standards [7].

In the Best practice manual for the forensic examination of digital technology[8], Appendix G report requirements section, individual requirements for Forensic Examination of Digital Technology are specifically defined. There is a clear note that the style and content of written evidence must meet the requirements of the criminal justice system for the country of jurisdiction. Section G.1 General Requirements defines 21 requirements that should be included. For cases involving digital evidence (section G.2), the statement or report should also specifically include the: Details of the target data sought; Presence or absence of data found on the various items; and Effects of the examination on the working order of the device. e.g. during the examination the item was (partially) dismantled and the laboratory cannot restore the item to its original state. A peer review (section G.3) of a report should include consideration of the validity of all the critical examination findings and should include ensuring that the correct level of provenance is provided. It should also consider whether the conclusions drawn are justified by the work done and the information available. The review may include an element of independent testing, if circumstances warrant it. A standard check sheet for the technical review covering the following points can be helpful in ensuring that all the relevant issues have been addressed:

- Is the exhibit continuity intact?
- Is the case specific risk assessment available and valid?
- Is there adequate documentation relating to all the items examined?
- Have all the appropriate examinations been carried out?
- Have the relevant procedures and processes been followed?
- Are there complete notes on all the target items?
- Is the statement / report accurate and refer to all items submitted?
- Are the conclusions reached justified and appropriate?
- Was the analysis proportionate?

ENISA(European Union Agency for Network and Information Security) has published a Electronic evidence - a basic guide for First Responders - Good practice material for CERT first responders[9] as a result of its work on good practices for CSIRTs and LEAs in the fight against cybercrime. The document is a guide for first responders, with a particular focus on evidence collection. It aims to complement existing material on the topic of digital forensics and evidence collection, as these are mostly written from a law enforcement perspective. This guide aims to provide guidance on how to handle evidence and the evidence collection process.

Conclusions

In expert circles of digital forensics, the principle of "secure digital chain of evidence" is presented in the complex architecture of systems from which digital evidence is extracted. Basically, it is about "securing" digital evidence on a new complex information and communication system that can be multi-technological and which is based on procedurally, organizationally and technologically organized systems that can provide "digital evidence that can be trusted". Such "trusted digital evidence" is digital evidence that contains a complete number of parameters that inevitably describe the initial (5W1H, who, what, when, where, why, how) but also other technological parameters of the environment, circumstances and state of the infrastructure of the system in which the digital evidence was created. Extraction of incomplete digital evidence cannot be compensated by the institutional importance of the state body, which is, for example, omitted metadata or digital evidence logs.

The framework for handling digital evidence is clear and should be adapted specifically for each investigative procedure and strictly applied in order to ensure the integrity of the data.

The generated Model for handling data during investigative actions given as a model of ISO requirements for the listed ISO standards provides a global framework for implementation. This model is set up in such a way as to set guidelines for investigative bodies on how to handle digital evidence but not shortcuts in dealing with this technological area. Each investigative body in each case in which it processes digital evidence has special specificities that it must identify and select from the presented model. The

specificities of digital evidence are referenced according to the type of digital evidence and the environment from which it is extracted, but certainly also according to the type of equipment and human capacities they possess. The only excuse that is not acceptable in the technological environment of digital evidence is to ignore national ISO standards that have the weight of by-laws. Ignoring standards and not documenting actions that are mandated by ISO standards as good professional practice lead the results of the investigation into a problematic area in the Court. Investigative actions on digital evidence do not end in investigative bodies, but rather in courts with judges who are highly familiar with and apply ISO standards for numerous areas that define the field of information technology.

All of the above represents a clear technological framework that is clearly defined by national ISO standards, but also further clarified by the aforementioned recommendations and studies by formal and expert organizations with the aim of clarifying clearly set instructions on how digital evidence must be handled.

All of the above with the generated Model represents a complete technological framework that is clearly defined by national ISO standards, but also further clarified by the aforementioned recommendations and studies of formal and professional organizations with the aim of clarifying clearly set instructions on how digital evidence must be handled. The Model clarifies that there is no single solution for all problems, just as there is no universal instruction for working with digital evidence, but it provides clear guidelines for experts on how to set the necessary and sufficient level in each individual investigation procedure.

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Exploring the Impact of VR and AR Integration in Learning Management Systems: A Study on Enhancing Immersive Learning Experiences

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Abstract:
This paper presents a comparative analysis of four educational platforms that use virtual reality (VR) and augmented reality (AR) technologies: TinkerCad, Delightex, MolecularWebXR, and ENGAGE. We based our evaluation on three main pillars: platform classification (VR or AR), core functionalities and services it offers, and user experience (UX) based on our practical engagement. After sharing our experience, we have provided a modern comparative XR-Ed framework in which we have given more details to the performance factors. A review of the contemporary literature highlights the role of inclusive technologies in increasing motivation, improving knowledge retention, and fostering active participation in both STEM and higher education. The findings show that each platform meets different educational needs: TinkerCad supports early STEM education through 3D modeling and electronics. The Delightex platform offers interactive AR/3D environments that foster creativity and personalized learning. MolecularWebXR uses VR for scientific visualizations, allowing students to explore complex molecular structures. While ENGAGE enables collaborative virtual classrooms and conferences, emphasizing social presence and active interaction. While the study confirms the great educational potential of these platforms, it also identifies challenges such as limited access, infrastructure requirements, and the need for pedagogical adaptation.

Keywords:
VR/AR technologies, Tinkercad, Delightex, MolecularWebXR, ENGAGE

1. Introduction

Education, as one of the most important areas of a society, has undergone continuous transformations since ancient times until now. The end of the 20th century and the beginning of the 21st century, has marked a period of rapid technological progress. This development has had both direct and indirect effects on education. Many methods of explanation, assessment, entertainment through the Internet or the digitalization process have been developed. So, the teaching and learning process has had to keep up with technology by adapting methods according to the time. Now, one of the best experiences in education is undoubtedly the use of VR/AR technologies which offer 2D and 3D presentation of new lessons, which can be theoretical or practical. These technologies are always growing in terms of use and extension in the world's geographical space. They are quite profitable both in terms of abstract knowledge, or simulation of practical knowledge and recreation or entertainment. Each has its own weight and are key factors in professional advancement. These technologies are not without challenges, as for most of them the high cost of supply remains a problem and another part requires training for teachers so that they are ready to teach students. However, we have tried to provide an analysis of some of the main technologies with global impact by assessing their importance in our lives.

2. Related work

Recently, we have seen a great development of VR/AR technologies, offering new immersive environments in education. Their inclusion in education increases student engagement, increases motivation and is helping in practical learning. However, it can sometimes cause confusion, as students may not distinguish between real and virtual events [1]. Regarding the field of education, virtual classrooms, intelligent tutoring systems, and VR/AR platforms are commonly used. Also, expectations and hopes for the future are the integration of AI and ML in the growth and advancement of these technologies [2]. Typically, the technologies used for VR are headsets from various manufacturers, while for AR they are mobile phones, tablets, and platforms built on Unity3D [3]. The new developments are based on improving computer vision for AR/VR through a new system based on a lightweight auto-encoder for "in-sensor" processing [4]. One of the innovations in this technology is the development of a neural interface based on EMG sensors placed on the forearm to enable natural interactions with XR and more pleasant feeling of the operator. So, the goal is to decode the force of the hands and fingers in real time to experience a more realistic experience, but the challenge remains that almost no AR/VR technology has force inputs [5]. Similarly, another paper aims at a distributed sensor computing (DOSC) architecture with the aim of saving energy by up to 24% through semi-analytical methods and distributed neural networks (DetNet and KeyNet) for hand tracking in VR/AR devices [6]. Another goal is to use this technology in industry, mainly for staff training, increasing safety and professional preparation, although standardization of protocols and technological barriers remain a challenge [7]. In summary, we can say that the application of XR technologies in education is only expanding in language education, ICT, physics, astronomy, neurosurgery, history, special education, and mathematics [8].

3. Methodology

Regarding the methodology of this paper, it is built on a combined approach, which includes a systematic review of existing literature, personal experiences while using VR/AR platforms in the educational context, as well as a direct comparative analysis of them. Initially, we reviewed the most important studies and publications that address the impact of immersive technologies on the learning process, focusing on the main areas of user experience and educational potential. Then, our personal experiences while testing the platforms were integrated as a complementary source to highlight the practical challenges and opportunities that these tools offer. We developed the final analysis based on the XR-Ed Framework, which allows for a structured assessment according to six main dimensions: Learner Agency, Social Interactivity, Cognitive Challenge, Immersion, Embodiment and Authenticity. This approach aims to guarantee the most complete and objective perspective on the potential of VR/AR platforms in the field of education.

4. VR/AR platforms

In this chapter, four platforms that have direct use in practical and visual teaching have been analyzed. These technologies offer modeling, simulations, interactions and virtual experiments in real time. Through these platforms, a new pedagogical approach, level of student engagement and ease of use for beginners and advanced users have been enabled.

4.1 TinkerCad

The TinkerCad platform is used in an educational aspect by offering three main services for 3D, electronic modeling and coding, which is closer to AR technology. The platform provides a workspace in which users can create and simulate models for engineering, 3D design and electronic circuits. It has a very friendly GUI and offers a very simple approach for novice users.

A. TinkerCad - Scope of services

In the field of services offered by this platform through 3D modeling, users have the opportunity to create personalized objects through basic geometric shapes, which we can export and print on 3D printers. While regarding the electronics part, students or professors have the opportunity to build circuits with resistors, LEDs or sensors and test them through simulations. And finally, as a third and very important function, is the integration of the electronic project into Arduino, in which users can also write code to enable testing of the functionality of the circuits.

B. TinkerCad - Personal use and experience

TinkerCad has a simple look and feel and it is easy to use. It works directly from the browser, without the need for additional installations or devices, which makes it affordable for everyone. For first-time users, the entry is very intuitive. We can create the first 3D model with just a few clicks. The interface is quite structured and offers immediate visual feedback, which gives the user a sense of control. Personal experience with the platform clearly shows that TinkerCad is built to offer a feeling between playing and learning – making you feel like you are playing, while learning good design and electronics knowledge. A very good thing is the ability to experiment without fear, so any mistake can be reversed and each project is automatically saved in the cloud without any side effects.

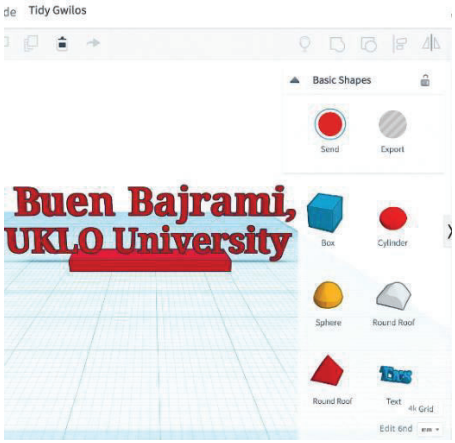


Figure 1: TinkerCad 3D objects

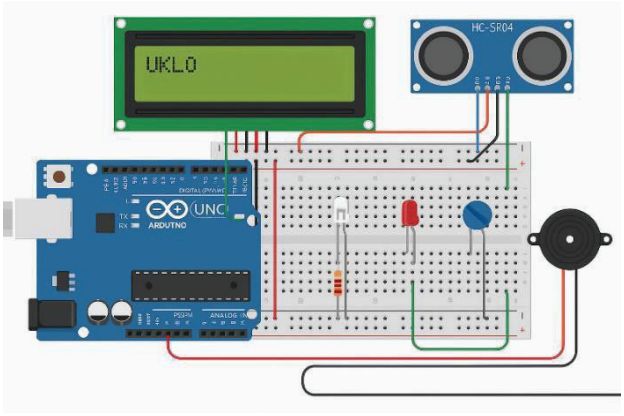


Figure 2: TinkerCad Arduino project

After a while of use, the feeling we have after a few days is that of progress: it starts with simple models and gradually moves on to more complex projects, which include programmable electronic circuits. Based on our experience, we can freely say that for educational and teaching purposes, the experience with TinkerCad is authentic, and quite motivating – a clear combination of practice with creativity.

4.2. Delightex

The Delightex platform is built on the foundation of augmented reality (AR) and 3D modeling, which focuses on creating educational content and personalized learning environments. The platform is intended for teachers, students and educators who want to enrich the learning process through visual and spatial interaction. Due to its nature, Delightex clearly falls into the category of AR/3D applications.

A. Delightex - Scope of services

Delightex offers a wide range of services that combine 3D modeling, interactive simulations and augmented reality. Users can build educational environments where a scientific, mathematical or technological concept is displayed through 3D objects integrated into real space. An important

functionality is the ability to share these scenes with others, enabling collaborative work between students or live presentations for online learning. The platform also supports content customization, allowing educators to build activities according to the specific needs of the class or subject. The visual part is very strong: 3D objects can be rotated, zoomed and displayed in real context, making the learning process more lively and engaging.

B. Delightex - Personal use and experience

The process of creating content is similar to a game: 3D objects are selected, placed in space, linked to the learning scenario and then displayed through AR. Personal experience shows that the motivation to continue using it is directly related to the feeling of "augmented reality": when a theoretical concept, for example a molecular model or a geometric figure, is displayed on the table via a mobile phone or tablet, the lesson becomes tangible and more understandable

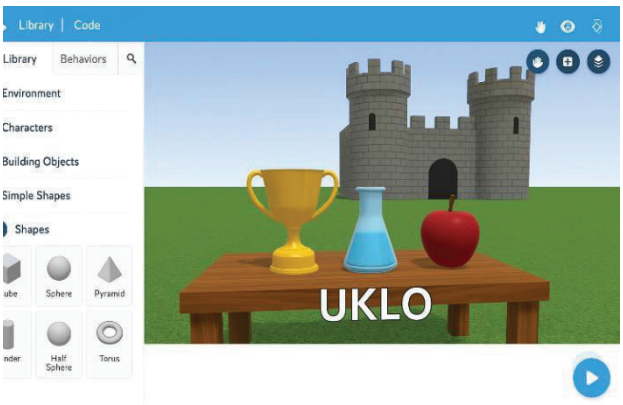


Figure 3. Delightex 3D objects

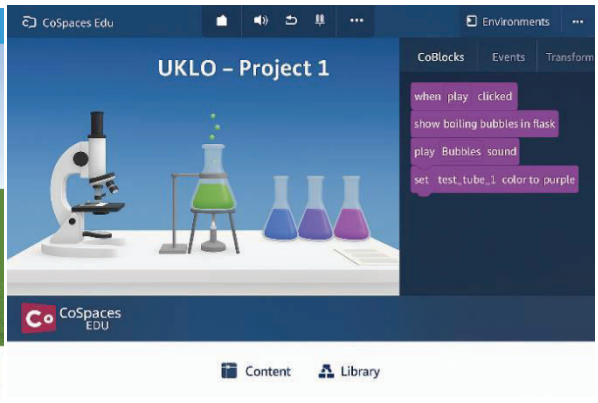


Figure 4. Delightex AR project

On the emotional side, Delightex offers a strong sense of involvement – students are not just spectators, but they become actors in the creativity. This interactivity makes us feel closer to the content and increases the level of engagement. Another important element is the financial aspect and the fact that the platform works well even without very expensive equipment: a regular phone or tablet is enough to experience AR. This makes the UX more accessible and lowers the cost barriers. However, in personal experience, sometimes technical limitations such as loading delays or the need for a good internet connection appear. These moments can bring frustration, but do not significantly diminish the overall value of the platform. For a new user, the experience is motivating and fresh; for an educator, it is a tool that opens up new pedagogical possibilities and facilitates teaching.

4.3. MolecularWebXR

MolecularWebXR is a virtual reality (VR) platform developed for exploring molecular structures and chemical concepts in a spatial environment. Built on WebXR technology, it runs directly from the browser, adapting to both VR devices and computer screens. Its goal is to transform ordinary 2D chemical models into immersive experiences, where the user can explore molecules and better understand their size, bonding, and structures.

A. MolecularWebXR - Scope of services

The platform offers 3D visualization of molecules, with the ability to rotate, zoom, and explore from any angle. It supports the use of VR devices for a strong sense of presence, making it seem as if the molecules are physically in front of students. Another important feature is the collaborative approach: teachers can explain structures directly in the classroom, while students follow the same model on their devices. This makes the platform valuable for interactive lectures, virtual labs, and more realistic demonstrations.

B. MolecularWebXR - Personal use and experience

Based on our personal experience, we can appreciate that the use of MolecularWebXR is unique, especially with VR equipment. Experiencing a complex structure like DNA in gigantic proportions and moving around it creates a deep conceptual understanding that cannot be achieved through flat images.

The platform is easy to use, as it does not require additional installations and works from the browser, offering easy access even for beginners. Immersiveness is the biggest advantage: the concepts seem real and tangible, making students more motivated and curious. However, the most complete experience requires quality VR equipment, otherwise it is reduced to a less immersive 3D visualization.

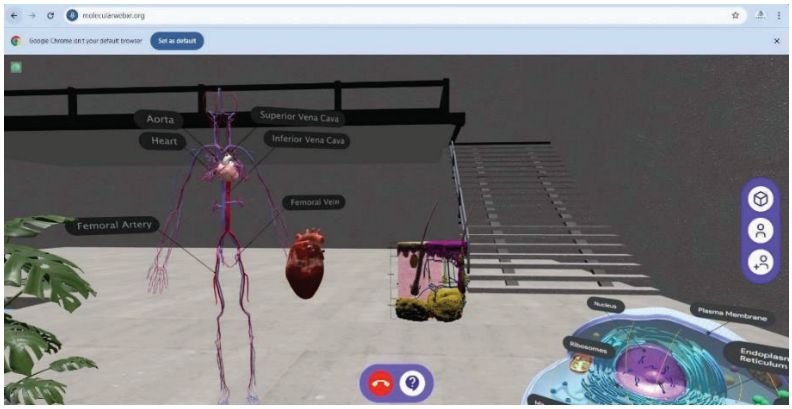


Figure 5. MolecularWebXR Biology project

Also, large models require powerful computers and fast internet. Despite its limitations, MolecularWebXR remains an inspiring tool that gives chemistry a new dimension, turning theoretical learning into a lively and meaningful experience.

4.4. ENGAGE

ENGAGE is an advanced virtual reality (VR) platform built for education and professional training. It creates a real-world environment where lectures, workshops, conferences and interactive training take place. Thanks to its widespread use in education, business and research, ENGAGE is one of the most popular platforms for contemporary communication and learning, clearly representing the category of educational VR.

A. ENGAGE - Scope of services

ENGAGE enables the creation of virtual classrooms with multimedia content such as videos, 3D models and presentations. A unique feature is the recording of sessions for full review in VR. The platform supports international meetings and conferences, where participants feel like they are in the same room. In addition, it offers personalized scenarios: scientific laboratories, historical spaces or business environments, built according to needs. It integrates real-time collaboration tools, enabling discussions, sharing of 3D objects and the use of virtual whiteboards.

B. ENGAGE - Personal use and experience

Using ENGAGE is like entering another world, where a sense of presence and inclusion in a special space is created. The user personalizes their content and actively participates in the class or conference. Real-time interaction – from raising their hand to working on projects, also increases the sense of community. The experience was engaging and the lectures became emotional and interactive events, far from traditional forms of online learning.

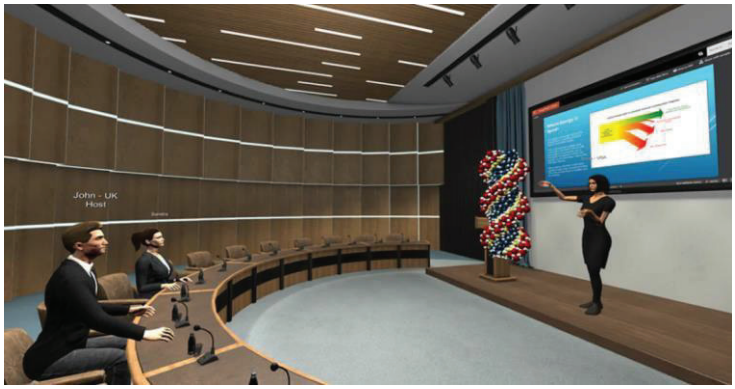


Figure 6. ENGAGE VR Meeting Room

One limitation remains the requirement for dedicated VR hardware to achieve maximum immersion, although the platform can also be used on lower-end computers. Despite this, ENGAGE manages to turn online learning from a passive process into an active experience by making the user a full participant in the learning process.

5. XR-Ed comparative framework

After evaluating personal experiences of the platforms, we have managed to form a comparative table based on the Extended Reality in Education framework, and its six comparative factors, which we have described as follows below.

1. Learner Agency – The degree to which a student has control over the learning experience (decision-making, personalization, etc.)
2. Social Interacitivty – The opportunities offered by a platform for collaboration and social interaction within the XR environment.
3. Cognitive Challenge – It represents the level of intellectual challenge, i.e. whether the XR platform forces the student to think critically or solve complex problems.
4. Immersion – It represents the level of psychological or perceptual immersion in a virtual environment. The higher the degree of virtual presence, the higher the immersion factor.
5. Embodiment – It represents the degree to which a user feels represented within an XR platform through their body movements, gestures, etc.
6. Authenticity – Represents the level of how well a platform simulates the real world or real situations.

Through this framework, we have tried to provide a clearer understanding by presenting the orientation and impact of these platforms in educational institutions, where each of them has occupied certain profiles and has provided XR services by increasing interactivity and interest of students to learn and understand lessons more easily. The assessment has been carried out through three levels, which are High, Moderate and Low in relation to the performance factors of the XR-Ed framework.

Table 1:

XR-Ed comparative framework of XR platforms

XR-Ed Factors	TinckerCad	Delightex	MolecularWebXR	ENGAGE
Learner Agency	High. Students create 3D Models and electronic circuits	High. Students build AR scenes and personalize the content	Moderate. Students can explore molecules but not to create new ones	High. Students participate in activities
Social Interactivity	Low. Individual work, no real time collaboration	High. Students allow to share scenes and presentations	Moderate. Teachers lead while students follow the same model	High. Multi user environment with full intercation
Cognitive Challenge	Very high. Requires problem solving and coding	Moderate. Stimulates creativity and personalization	Moderate. Supports understanding of complex structures	High. Advanced simulations and interactive discussions
Immersion	3D on screen. No VR.	AR via phone. No VR	Full VR. Deep experience through WebXR	Full VR. Complete immersive content

Embodiment	Low. No real embodiment. Only mouse/keypad interaction	Low. Basic embodiment. Only manipulation of objects in AR	Moderate. Movement and perspective in VR	High. Gestures and movements in VR
Authenticity	High. Simulates real labs	High. Content linked to curriculum	High. Realistic visualization of molecules	High. Realistic educational environments

The results of the table show that each of the platforms has its own distinct role in the learning process, meeting different needs in terms of pedagogical aspects. The combination of these technologies offers a richer learning model, increasing engagement but also understanding, especially for complex topics.

6. Conclusions

The research of VR and AR usage in educational fields, shows us that these platforms have passed the experimental phase and have now become indispensable in education. They are offering direct interaction of scientific concepts, a sense of physical presence even inside molecules that are offering a high-level representation by understanding these elements much better, from different dimensions. Our impression is that the integration of these platforms in education does not replace traditional methods, but simply empowers them by enriching knowledge and improving the form of explanation and understanding, specifically by adding practice and creativity. In addition to sharing personal experiences, we tried to present an analysis using the XR-Ed framework. Two of the selected platforms rely on AR technology, and the other two completely on VR. Only the Tinkercad platform does not offer real-time group work, unlike the other three platforms included in the paper. In terms of embodiment, only the ENGAGE platform offers an advanced level. The main challenge remains the cost of providing the necessary VR equipment, licenses, etc., which are currently still unaffordable for many institutions. But one thing is certain: the future holds great promise, offering a higher quality education based on practical and emotional experience.

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Comparative Analysis of Text Mining Techniques and Tools

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Abstract:

Rapid progress in digitalisation has generated a vast volume of data, particularly unstructured and semi-structured data. Text mining is a process of extracting useful information from text documents and is a new and challenging research field that aims to address the information overload problem by leveraging techniques from machine learning (ML), natural language processing (NLP), and knowledge management. Text mining tools facilitate the analysis of unstructured textual data by extracting patterns and generating insights through techniques such as classification. In this paper, we have discussed the text mining techniques and compared two platforms: RapidMiner and KNIME.

Keywords:

Text mining, text mining tools, unstructured data, machine learning.

1. Introduction

Data mining is used for finding useful information from a large amount of data. Data mining techniques are employed to address various types of research issues. The research-related subfields in data mining are text mining, web mining, image mining, sequential pattern mining, spatial mining, medical mining, multimedia mining, structure mining, and graph mining [1].

On the other side, text mining is the process of mining useful information from textual documents. It is also called knowledge discovery in text (KDT) or knowledge of intelligent text analysis. Text mining is a technique that extracts information from both structured and unstructured data and also finds and recognizes patterns [1].

Text mining is similar to the data mining process, but they differ in the selected tool. Data mining tools are designed to handle structured data, whereas text mining can deal with unstructured or semi-structured data sets such as emails, HTML files, medical reports, full-text documents, etc. [2]. Text mining is used to find new, previously unidentified information from various written resources [1].

Structured data are data where each element is addressable and is the most organized form of data for easy storage, access, and analysis. This data type is structured into rows and columns and organized within databases and tables. Unstructured data, such as free-form text, images, and social media content, dominates information in the real world [3].

Unlike structured data, unstructured data does not follow a specific format or schema, which makes it more challenging to store and analyze. To overcome these challenges, modern storage solutions have been developed that are capable of handling large volumes and different types of data.

A data lake is a central repository that is highly scalable and can store structured, semi-structured, or unstructured raw and granular data from multiple sources [4].

Within such repositories, semi-structured data plays a particularly important role, as it strikes a balance between structured data's rigidity and unstructured data's flexibility, making it a valuable format for modern businesses looking to work with complex data sources.

The text mining process includes several stages: text pre-processing, feature extraction, text mining techniques, model training and evaluation, interpretation and visualization of results, iteration and refinement, reporting and deployment.

The rest of the paper is structured as follows. Section 2 presents the text mining process, while the subsequent section describes the fundamental techniques of text mining. Sections 4 and 5 present the obtained results of comparative analyses between RapidMiner and KNIME tools. Concluding remarks and directions for further work are given in the last section.

2. Text Mining

Text mining is a systematic sequence of steps used to extract useful information from unstructured text data, as shown in Figure 1. It consists of the following stages:

A. Text preprocessing

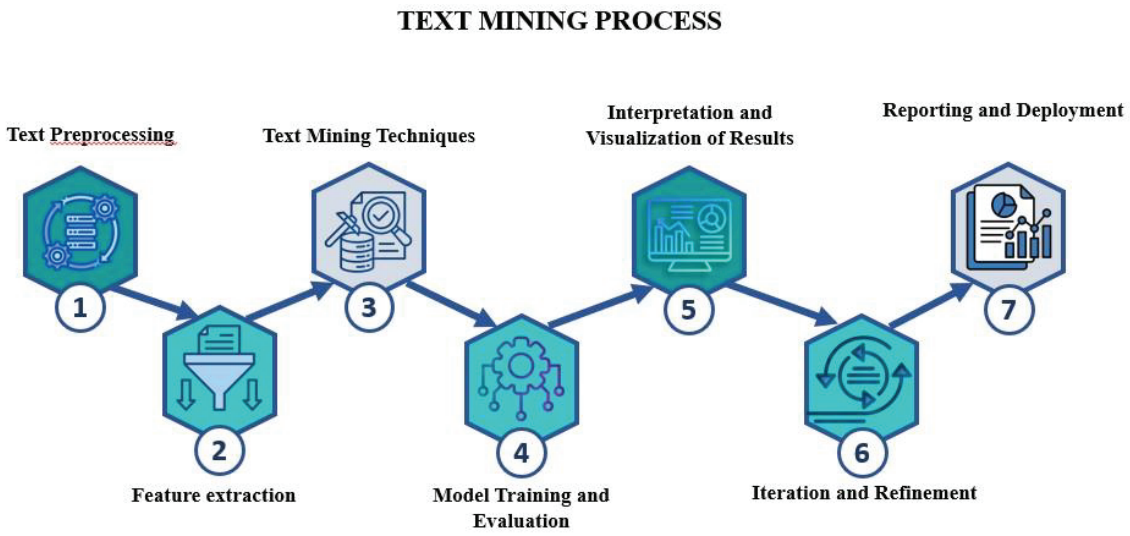


Figure 1. Text Mining Process

Pre-process the raw text data to clean and transform it into a suitable format for analysis. This step includes removing punctuation, converting text to lowercase, tokenization (splitting text into individual words or tokens), removing stop words, and stemming or lemmatization (reducing words to their root form).

B. Feature extraction

Extract attributes from the text data to represent it in a numerical or structured format that can be used for analyses. This step involves techniques such as bag-of-words representation, term frequency-inverse document frequency (TF-IDF), or word embeddings.

C. Text Mining Techniques

Used in various types of research domains like information retrieval, information extraction, natural language processing, categorization, text classification, and text clustering.

D. Model Training and Evaluation

Divide the text into training and evaluation sets using machine learning or statistical models. This step uses techniques like cross-validation or hyperparameter tuning.

E. Interpretation and Visualization of Results

Interpret and analyze results obtained from applied text mining techniques. Visualize results using graphs, charts, or diagrams.

F. Iteration and Refinement:

Analyze the result and iterate on the text mining process as necessary.

G. Reporting and Deployment

Prepare a comprehensive report summarizing the results, insights, and recommendations derived from the text mining.

3. Techniques in Text Mining

In text mining, various techniques are employed to handle unstructured textual data, enabling the discovery of patterns and the extraction of knowledge and actionable insights.

A. Information Retrieval

Information Retrieval (IR) is the process of representing, storing, and querying data collections to enable knowledge discovery based on user requests [5]. This process involves various stages, starting with representing data and ending with returning relevant information to the user. The intermediate stage includes filtering, searching, matching, and ranking operations [5].

B. Information extraction

Information extraction serves as the starting point for analysing unstructured text, where the focus is on recognizing relevant phrases and their interrelations. To accomplish this, pattern-matching methods are applied to locate predefined structures within the text. The information extraction task includes tokenization, identification of named entities, sentence segmentation, and part-of-speech assignment. Firstly, input phrases and sentences are parsed and semantically interpreted, and then the required pieces of information are added to the database. The general information extraction process is shown in Figure 2. The most accurate information extraction systems involve handcrafted language processing modules, and substantial progress has been made in applying data mining techniques to a number of these steps. This technology can be very useful when dealing with large volumes of text [6].

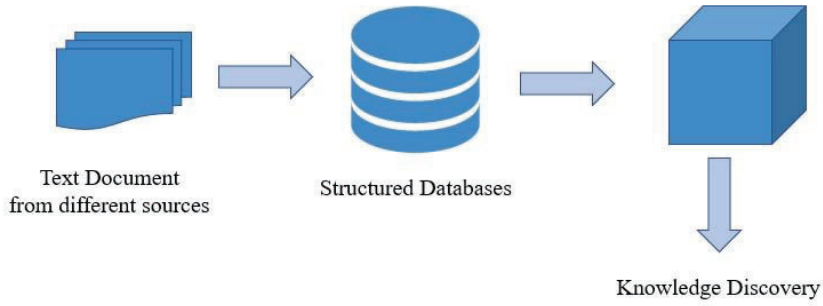


Figure 2. Information extraction [6].

C. Categorization

Categorization represents the mechanism through which entities are identified and differentiated, forming the basis for a structured understanding of ideas and objects. Categorization implies that objects are grouped into categories, usually for some specific purpose. Text categorization becomes a key technology to deal with and organize large numbers of documents. Text representation constitutes a key step in text categorization, ensuring that documents are expressed in a way that supports meaningful classification. A major problem of text representation is the high dimensionality of the feature space. The feature space with a large number of terms is not only unsuitable for neural networks but also easily causes the overfitting problem. Text categorization is the assignment of natural language documents to one or more predefined categories based on their semantic content, and is an important component in many information organization and management tasks [7].

D. Natural Language Processing

Natural language processing (NLP) refers to the automatic processing and analysis of unstructured textual information. It performs different types of analysis, such as Named Entity Recognition (NER) for abbreviation and their synonyms extraction to find the relationships among them [8]. NER identifies all the instances of specified objects from a group of documents. These entities and their instances allow the identification of relationships and other information to attain their key concept. However, this technique lacks a complete dictionary list for all named entities used for identification [8]. Natural Languages (NL) have a lot of complexities, as a text extracted from different sources does not have identical words or abbreviations. There is a need to detect such issues and make rules for their uniform identification [8].

E. Clustering

Clustering is an unsupervised approach used to group the text documents by applying different clustering algorithms. In a cluster, similar terms or patterns are grouped and extracted from various documents. Clustering is performed in a top-down and bottom-up manner. In NLP, various types of mining tools and techniques are applied for the analysis of unstructured text. Different techniques of clustering are hierarchical, distribution, density, centroid, fuzzy c-means, and k-means clustering [9].

F. Summarization

Text summarization techniques aim to generate concise summaries of long texts. It can be done in extractive or abstractive manners. Extractive summarization involves selecting important sentences or phrases from the original text, while abstractive summarization involves generating new sentences to capture the key information.

4. Text Mining Tools (RapidMiner vs KNIME)

Text mining tools can be classified into three categories, as shown in Figure 3.

1) Proprietary Text Mining Tools

These tools are commercial text mining tools owned by a company. To use these tools, a purchase is required. Although demo/trial versions are available free of charge, they have limited functionality.

2) Open-Source Text Mining Tools

These tools are available free of charge, and their source code is available; one can even contribute to their development.

3) Online Text Mining Tools

These tools can be run from the website itself. Only a web browser is required. These tools are generally simple and provide limited functionality [10].

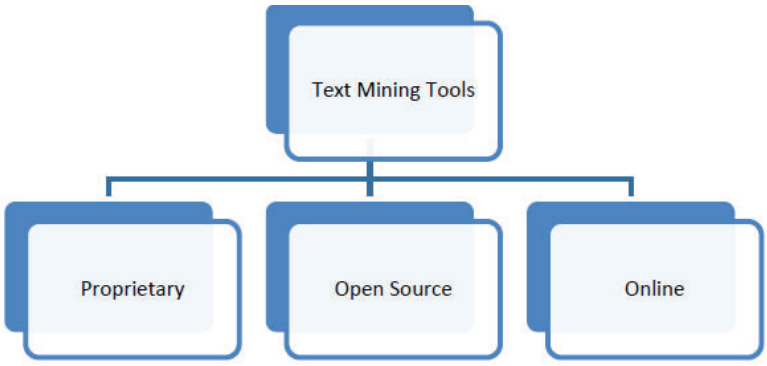


Figure 3. Types of Text Mining Tools.

Although there are many text mining tools, such as Weka, Orange, KNIME, RapidMiner, and Tanagra, we have chosen two of them that often come up in discussions: RapidMiner and KNIME. Both are powerful software programs that can help businesses and researchers in text mining and analysing data more efficiently. However, choosing between two can be a daunting task, as each has its strengths and weaknesses, as tabulated in Table 1.

RapidMiner allows users to create data workflows using a drag-and-drop interface. Like KNIME, RapidMiner offers a wide range of pre-built nodes, as well as the ability to create custom nodes using various programming languages. One of the biggest advantages of RapidMiner is its speed. RapidMiner has been designed to efficiently manage large datasets, offering faster data processing performance relative to KNIME. Additionally, RapidMiner offers a wide range of machine-learning algorithms that can be used to build predictive models, such as Naïve Bayes, Decision Tree, Random Forest, Logistic Regression, Support Vector Machine (SVM), K-Nearest Neighbours (KNN), etc.

KNIME (Konstanz Information Miner) is an open-source data analytics platform that allows users to create data workflows, which are essentially a series of interconnected nodes that represent different data processing steps. KNIME offers a wide range of pre-built nodes, as well as the ability to create custom nodes using various programming languages such as Python, R, and Java. One of the biggest advantages of KNIME is its user-friendly interface, which makes it easy for users of all skill levels to create complex data workflows without any programming knowledge. Furthermore, KNIME's community is very active, with a large number of pre-built workflows available for download, which can save users a lot of time.

Table 1: Comparison of features between RapidMiner and KNIME

Feature	RapidMiner	KNIME
Main Feature	Visual workflow	Data integration & manipulation
Strength	User-friendly, extensive pre-built components	Data integration, scripting
Weakness	Can be resource-intensive for complex workflows	Programming skills required for advanced tasks
Cost	Free and Commercial Versions, the free version supports only 10.000 rows	Free
Speed	It demonstrates faster performance when processing large datasets.	It demonstrates slower performance when processing large datasets.
Programming Language	Java	Java
Supported Data Formats	CSV, XML, JSON, others	CSV, TSV, TXT, XLSX, JSON, XML, others
Machine Learning Algorithms	Extensive library	Various, including deep learning
Data Visualization	Basic visualization components	Extensive visualization capabilities
Real-time Data Analysis	Limited support	Some support through extensions
OSs	Windows, macOS, Linux, open source	Windows, macOS, Linux, open source
Quality	Powerful and versatile, with an advantage especially in predictive analytics	The main open data mining tool that predictive analytics has made available to the general public
Techniques supported	Data mining and text analytics, text processing	Text analysis, data I/O, pre-processing and cleaning, modeling, analysis and data mining

5. Experiment

5.1 Research methodology

Besides a comparison of the features between RapidMiner and KNIME, we have conducted a comparative study of the classification algorithm Naïve Bayes on the spam emails dataset, downloaded from Kaggle [11]. The dataset includes two categories: spam and ham. The term spam refers to unsolicited or unwanted messages, typically sent in bulk for advertising or malicious purposes, whereas ham denotes legitimate, non-spam messages. The number of instances is 5572, with two attributes:

- Categories: spam, or ham (not spam).
- Message: email message.

To ensure proper evaluation of the classification models, the dataset was divided into training and test sets using an 80/20 stratified sampling approach. This technique preserved the original class distribution in both subsets, thus avoiding potential bias in the learning process. Out of the total

instances, 4825 (86.6%) were labeled as ham and 747 (13.4%) as spam. After the split, the training set contained 4457 messages (3860 ham and 597 spam), while the test set included 1115 messages (965 ham and 150 spam). This distribution allowed the Naïve Bayes classifier to be trained on a representative portion of the data and tested on an independent subset that retained the original characteristics of the dataset.

In RapidMiner for classification, we used the following nodes: Read CSV, Nominal To Text, Set Role, Split Data, Process Document From Data, which contain operators for pre-processing data (Tokenize, Transform Cases, Filter Stop words), Naïve Bayes, Apply Model, and Performance, as shown in Figure 4.

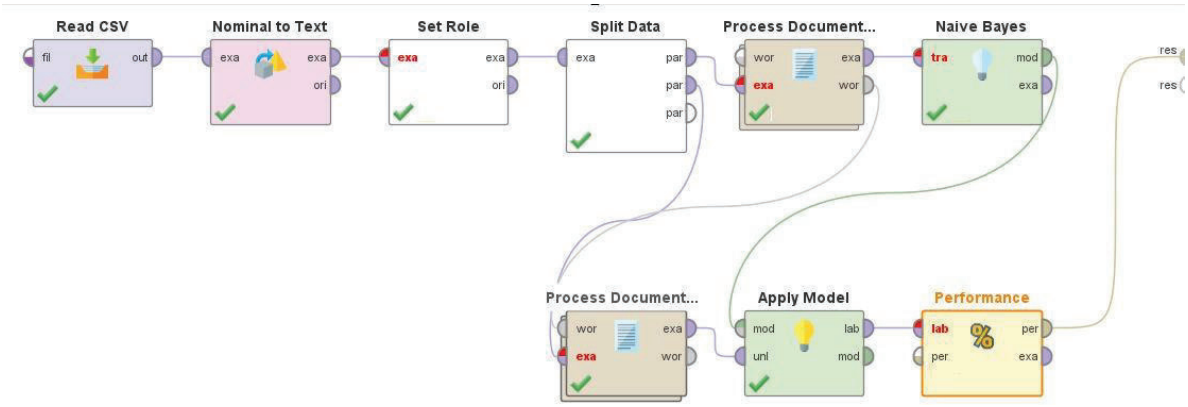


Figure 4. Classification in RapidMiner.

For the classification in KNIME, we have employed the following nodes: CSV Reader, String to Document, Nodes for Pre-processing Data (Punctuation Erasure, Number Filter, Stop Words Filter), Bags of Words Creator, Term to String, TF, Partitioning, Naïve Bayes Learner, Naïve Bayes Predictor, and Scores shown in Figure 5.

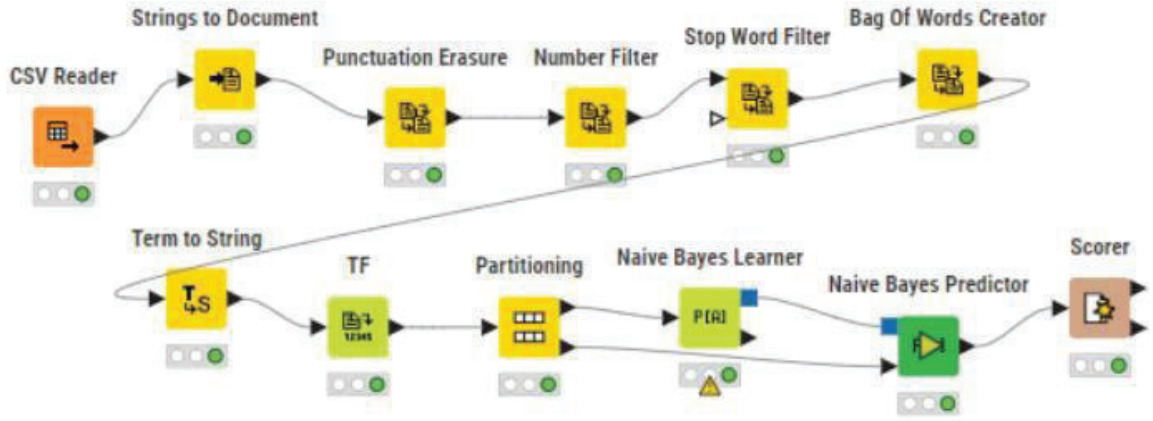


Figure 5. Classification in KNIME.

5.2 Results

In this step, we evaluate the performance of the classification algorithm using the confusion matrix, a table that reveals true versus predicted values and the performance of the classification model on the basis of accuracy, as shown in Figures 6, 7, and 8.

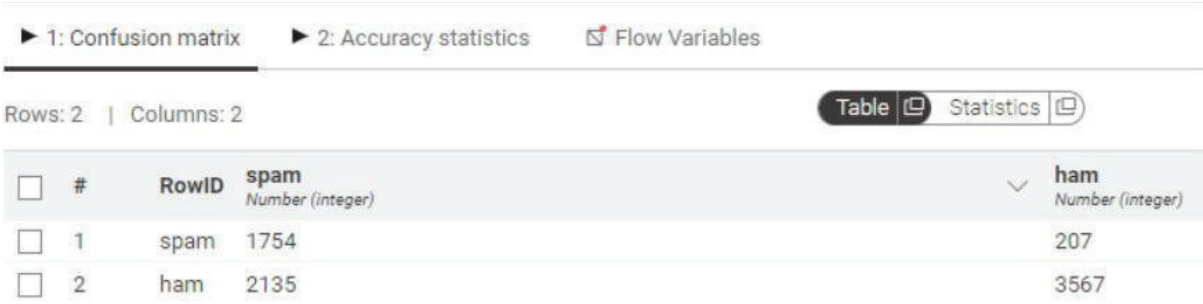


Figure 6. Confusion Matrix in KNIME.



Figure 7. Accuracy in KNIME.

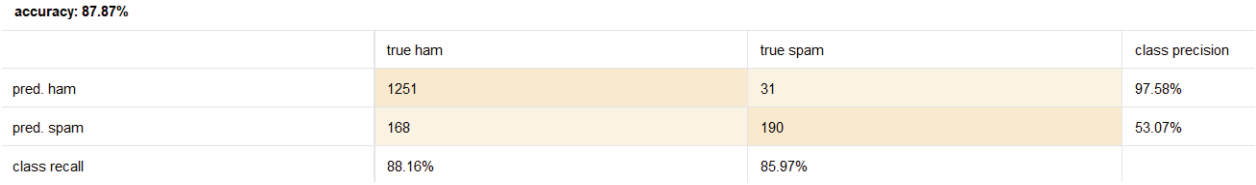


Figure 8. Confusion Matrix and Accuracy in RapidMiner.

Table 2:
Results of classification

	Accuracy	Class Precision		Class Recall	
		predicted ham	predicted spam	ham	spam
RapidMiner	87.87 %	97.58 %	53.07 %	88.16 %	85.97 %
KNIME	69.40 %	94.50 %	45.10 %	62.60 %	89.40 %

As shown in Table 2, the accuracy value in RapidMiner is 87.87%, and in KNIME, that value is 69.4%. When we compare class precision in RapidMiner for predicted ham, which is 97.58% and for predicted spam, which is 53.07% versus class precision in KNIME for predicted ham, which is 94.5% and for predicted spam, which is 45.1%. Also, class recall in RapidMiner for ham is 88.16% and for spam is 85.97%, versus class recall in KNIME for ham is 62.6% and for spam is 89.4%.

6. Conclusion

Business decision-making relies on structured, unstructured, and semi-structured data being processed through every step of the text mining process. Text mining techniques help to improve the text mining process. Selecting the text mining technique is an important part of obtaining the most reliable results. Similarly, selecting the appropriate text mining tools is essential. Now there are a large number of tools that are available to users, which we have already classified into three categories and compared some of the features of RapidMiner and KNIME.

To conclude, RapidMiner and KNIME are powerful platforms for text mining, offering a comprehensive set of features and functionalities. When we compare them according to the obtained

results, we can say that RapidMiner has better accuracy, class precision, and class recall than KNIME on the dataset that we have chosen. But choosing between the two ultimately depends on your specific needs, datasets, models, and algorithms. Regardless of which tool is selected, both RapidMiner and KNIME can help to analyze the data more efficiently and effectively.

Future work could expand the analysis by incorporating additional machine learning algorithms such as Support Vector Machines, Random Forests, Gradient Boosted Trees, or even deep learning approaches. A broader evaluation across multiple models would provide deeper insights into performance trade-offs and enhance the robustness of the findings.

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Scalable ETL Processes with Change Data Capture (CDC) and Monitoring Using Apache Superset

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Abstract:
In an increasingly data-driven world, the ability to monitor and respond to real-time changes is critical across various domains, including marketing, transportation, and other dynamic sectors. Timely access to up-to-date information enables organizations to make informed decisions and adapt quickly to changing conditions. This paper presents a study on the implementation of a real-time data monitoring solution that leverages Change Data Capture (CDC) techniques for capturing updates across data sources. Furthermore, it explores the integration of real-time visualization tools, such as Apache Superset, to provide immediate insights and improve situational awareness. The proposed approach facilitates continuous tracking of data changes and supports decision-making processes through intuitive and dynamic dashboards. The research highlights the architectural components, key technologies, and practical benefits of deploying such systems in modern data environments.

Keywords:
ETL(Extract, Transform and Load), Azure services, CDC(Change data Capture), Apache Superset, Databricks.

1. Introduction

As modern systems become increasingly dynamic and data-intensive, the ability to access and respond to real-time information is becoming increasingly vital across a wide range of industries. From marketing and customer engagement to transportation and logistics, decision-makers rely heavily on timely data to adapt to rapidly changing environments. Delayed or outdated data can lead to missed opportunities, inefficiencies, or even critical system failures. As such, there is a growing need for data systems that not only collect, and process information continuously but also provide immediate insights through real-time monitoring and visualization [1].

Traditional data pipelines, which operate on batch processing principles, often fail to meet the demands of modern applications that require low-latency or near-instantaneous data updates. To address this limitation, modern data engineering has introduced techniques such as Change Data Capture (CDC) — a method of identifying and capturing changes in data sources in real time. CDC enables continuous data flow from operational systems to analytical platforms without the need for full data refreshes, thereby enhancing performance and reducing load [2],[3].

This paper investigates the implementation of a real-time ETL (Extract, Trans-form, Load) pipeline using CDC mechanisms to capture and process data changes as they occur. The research further explores how such changes can be visualized effectively through the integration of Apache Superset, an open-source platform for data exploration and interactive dashboards. Superset plays a critical role in this architecture by enabling users to monitor key metrics, observe patterns, and detect anomalies as they emerge. By combining real-time data capture with intuitive visualization, this approach supports proactive decision-making and im-proves operational transparency. The implementation is relevant for a variety of sectors, including but not limited to digital marketing—where customer behavior must be tracked in real time—and transportation systems—where logistics and fleet data change continuously and must be acted upon immediately [4].

The remainder of this paper is organized as follows: Section 2 provides back-ground on real-time

data processing, CDC methodologies, and Apache Superset. Section 3 outlines the system architecture and technologies used in the proposed solution. Section 4 presents the significance of data cleaning in preparing data for analytics and visualization . Section 5 outlines the analytical results obtained and explores the potential of Apache Superset as a tool for continuous monitoring and performance evaluation. Section 6 presents advantages of the proposed solution. The limitations detected are presented in Section 7, while Section 8 concludes the paper with recommendations for future research and development.

2. Foundations of Real-Time Data Engineering: CDC Methodologies and Visualization Tools

The shift from batch-oriented data systems to real-time data processing has redefined how organizations collect, manage, and analyze information. As data sources become more dynamic and business decisions increasingly rely on im-mediate insights, the need for efficient and scalable real-time data engineering solutions has grown substantially. This section explores the foundational technologies that enable real-time data workflows, focusing specifically on CDC as a method for detecting and propagating data changes, and Apache Superset as a platform for real-time data visualization and monitoring [5].

The ETL process is a fundamental framework in data engineering, responsible for the systematic integration of data from multiple sources into a centralized data repository, such as a data warehouse or data lake. During the extraction phase, raw data is collected from diverse, often heterogeneous sources, including relational databases, APIs, and file systems. In the transformation phase, the data undergoes cleaning, normalization, aggregation, and enrichment to ensure consistency, accuracy, and compatibility with analytical models. Finally, the loading phase involves inserting the processed data into the target system, where it be-comes available for querying, reporting, and advanced analytics.

CDC plays a critical role in modern data pipelines by capturing insertions, up-dates, and deletions from source systems and streaming them to downstream consumers with minimal latency. It eliminates the need for frequent full-table scans or scheduled batch jobs, thereby improving system performance and ensuring fresher data availability for analytics. Common CDC implementations rely on tools such as Debezium, Kafka Connect, or native database features, which support integration with distributed data platforms and stream processing engines. In parallel, visualization tools such as Apache Superset provide users with interactive dashboards and visual analytics that reflect the most current state of the data. Superset supports a wide range of data sources and allows non-technical stake-holders to monitor key metrics and trends in real time through customizable visualizations [6], [7].

Together, these technologies form a powerful architecture for building responsive, insight-driven systems that meet the real-time demands of modern data eco-systems. The following subsections delve deeper into the principles of CDC, key components of real-time data processing, and the role of Apache Superset in enabling effective data observability and decision-making.

3. System Architecture and Technology Stack of the Proposed Real-Time Monitoring Solution

This section presents the architecture and components of the proposed real-time data monitoring system. The system is designed to capture data changes from operational databases using CDC, process the data through a real-time ETL pipeline, and visualize metrics through Apache Superset for actionable insights. The architecture prioritizes low latency, scalability, and modularity, making it suitable for use cases such as real-time analytics, anomaly detection, and dynamic reporting, shown in Figure 1.

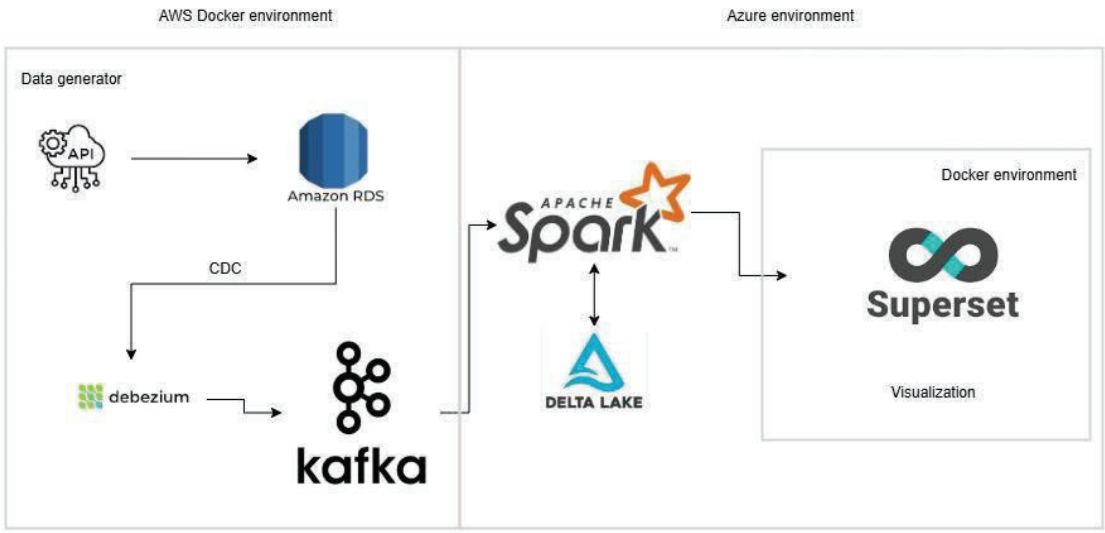


Figure 1: High-level architecture diagram

3.1. Overview of the System Architecture

The proposed architecture adopts a modular, event-driven design to ensure scalability, maintainability, and efficient resource utilization. The underlying computing infrastructure is provisioned and managed using Infrastructure as Code (IaC) principles, implemented through Terraform. This approach enables automated and repeatable deployment of cloud resources using a declarative configuration language, reducing the risk of manual errors and ensuring consistent environment management. Within this architecture, dedicated modules are developed for deploying the Kafka environment in the us-east-1 region and provisioning the Amazon RDS database, both hosted on Amazon Web Services (AWS). [8].

The subsequent component of the architecture involves integrating data from the Kafka consumer group into the Azure environment, specifically targeting Databricks tables to facilitate real-time data stream processing [9]. An Apache Superset instance is deployed on a virtual machine using Docker, enabling seamless connectivity to the Databricks tables which are part of the Delta Lake in Azure. This configuration allows for the dynamic retrieval of streaming data and the generation of intuitive and interactive data visualizations, presented in Figure 2.

3.2. Data Flow Description

The Apache Kafka cluster is configured to capture and log all changes occurring within the transactional tables of a relational database. Deployment strategy was centered on Amazon Elastic Container Service (ECS), leveraging containerization to ensure scalability and portability. Container images, including the Python-based data generation API, the Debezium Kafka connector, the Confluent Schema Registry, and Confluent Kafka components, were retrieved from AWS Elastic Container Registry (ECR). These components collectively facilitated the provisioning and orchestration of the application environment using Docker, enabling efficient management of data ingestion and schema evolution within the streaming architecture [9].

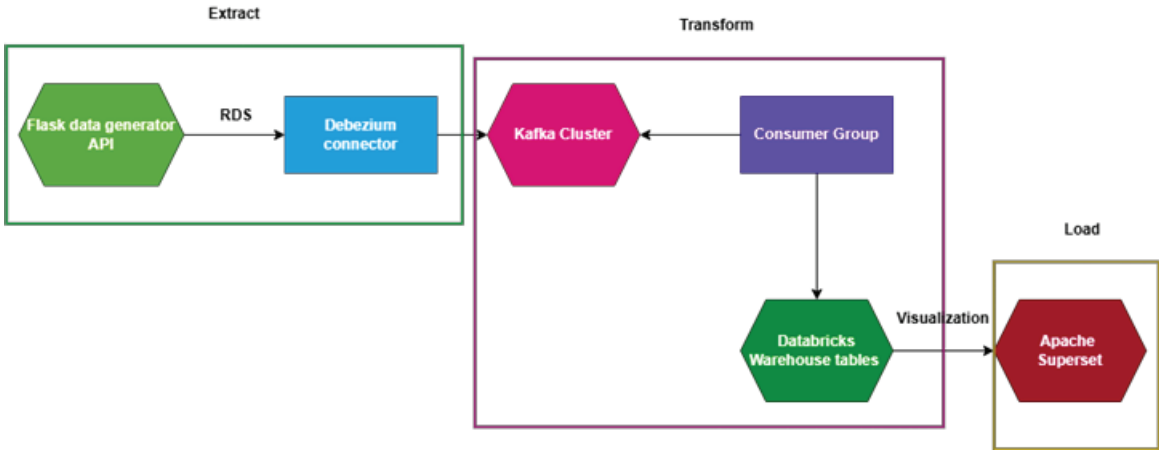


Figure 2: ETL Data flow description diagram

Debezium is employed as a CDC tool to continuously monitor the write-ahead logs (WAL) of the source relational database. It captures all data modification operations, including inserts, updates, and deletes, in real time. These changes are then serialized and published to designated Kafka topics, enabling downstream processing. To consume and handle the streamed data, custom application logic is implemented using Kafka consumers that subscribe to the relevant topics and process the data accordingly for further transformation or analysis [10].

Dashboards may include key performance indicators (KPIs), change frequency visualizations, alerting thresholds, and pipeline health metrics. Superset supports scheduled refreshes, SQL-based metrics, and real-time filters, enhancing observability.

4. Importance of Data Cleaning for Data Analytics and Visualization

Data cleaning, also referred to as data preprocessing, is a crucial step in the data analytics lifecycle, ensuring the accuracy, reliability, and interpretability of analytical results. Raw data collected from various sources is often incomplete, inconsistent, duplicated, or contains errors, which can lead to misleading conclusions if used directly for analysis or visualization. Uncleaned data introduces bias and noise into the analysis process, reducing the validity of insights and potentially leading to incorrect decision-making.

The process of cleaning data plays a central role in enhancing data quality, which is essential for meaningful analytics and effective visual representation. Accurate and consistent data allows for the generation of reliable models and visualizations, enabling researchers and decision-makers to better understand patterns, trends, and relationships within the dataset. For example, missing values, duplicate records, and formatting inconsistencies must be addressed to avoid skewed statistical results and inaccurate graphical representations. Furthermore, standardized data formats improve interoperability between analytics platforms and visualization tools such as Apache Superset, ensuring seamless integration and performance. Furthermore, standardized data formats improve interoperability between analytics platforms and visualization tools such as Apache Superset, ensuring seamless integration and performance [11].

From a visualization perspective, data cleaning is equally significant. Poor-quality data can distort visual outputs, making dashboards difficult to interpret and reducing their usability for decision-making. Clean and well-prepared datasets enable the creation of clear, precise, and interpretable visualizations that effectively communicate complex information to diverse audiences. This is especially important in research and business environments where stakeholders rely on visual insights for strategic planning [12].

In this research, data cleaning was conducted as a preliminary step before importing the dataset into Superset for analysis and visualization. The cleaning process involved handling missing data, removing duplicate entries, standardizing categorical values, and restructuring the dataset to meet the requirements of the visualization platform. By ensuring high data quality, the analytics process was optimized, resulting in accurate visual representations and trustworthy insights, Figure 3.

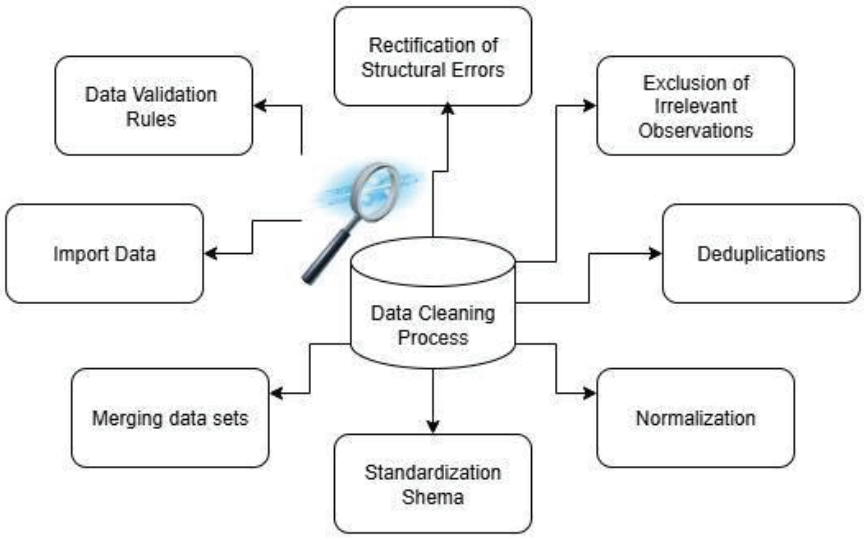


Figure 3: Data cleaning components

5. Analysis with Apache Superset

Apache Superset was utilized as the primary tool for the analysis and visualization of the datasets. Superset is an open-source, modern business intelligence (BI) platform designed to handle large datasets and provide interactive and highly customizable visualizations [13], [14].

Prior to initiating the analysis, the data was loaded into a structured relational database in Databricks and connected to Superset. This connection allowed seamless access to raw and processed data while leveraging SQL queries for dynamic exploration. Superset's SQL Lab module was particularly valuable, enabling the creation of custom queries to join and aggregate data from multiple sources, such as the Sales, Customers, and Companies tables, shown in Figure 4. This process ensured that the analysis could be tailored to the specific research objectives and that only relevant subsets of data were retrieved, improving performance and clarity.

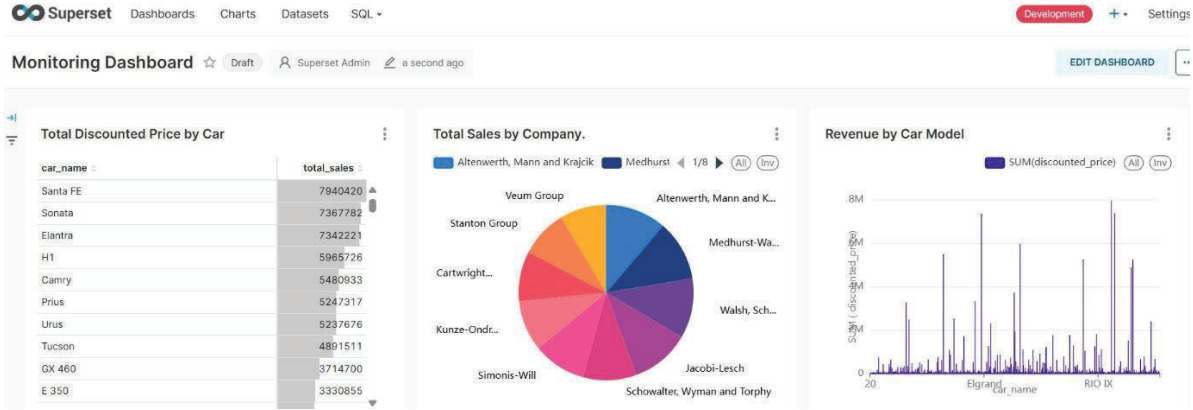


Figure 4: Monitoring dashboard implementation

For visualization, Superset provides a diverse set of chart types, including bar charts, histograms, line charts, pie charts, scatter plots, and geospatial maps. These were employed to extract actionable insights from the dataset. For example, bar charts were used to compare the total number of companies across different states, while histograms were applied to examine the distribution of discounts applied to vehicle sales, Figure 5. Geographical maps were employed to illustrate the spatial distribution of companies based on state and city, providing a clear overview of regional patterns [6].



Figure 5: Visualization of data from diverse data sets

Utilization of Superset enhanced the efficiency and clarity of the data analysis process. By combining the flexibility of SQL-based querying with advanced visualization options, Superset served as a powerful tool for both exploratory analysis and the presentation of results. The visualizations generated through this process provided valuable insights into the dataset, forming a foundation for further interpretation and discussion of trends in sales, customer demographics, and company distribution.

6. Advantages of the Proposed Solution

The proposed architecture integrates modern cloud-native technologies to achieve real-time data ingestion, processing, and visualization. It provides a scalable and flexible framework for handling dynamic and heterogeneous data streams, which is particularly relevant in applied data-driven systems. The main advantages are outlined below:

- **Reproducible and automated deployment:** terraform scripts enable automated, consistent, and replicable infrastructure provisioning, ensuring transparency and facilitating reproducible research experiments [15].
- **Real-Time visualization:** Processed data is continuously loaded into target tables and visualized through Apache Superset, offering interactive, near real-time dashboards for decision-making.
- **Low-Latency data ingestion**: Kafka and Debezium enable scalable, event-driven streaming with change data capture (CDC), ensuring timely updates without batch delays.
- **Scalable data transformation**: Azure Databricks provides a unified platform for streaming and batch data processing, auto-scaling to handle variable workloads, and enabling direct integration with machine learning models for advanced transformations.
- **End-to-End integration:** the fully integrated ETL pipeline minimizes latency between data collection, processing, and visualization, supporting time-sensitive research and adaptive decision-making.

7. Limitations while using the proposed solution

While the proposed architecture offers significant advantages in terms of real-time data processing, change tracking, and visualization, it also comes with several limitations.

- **Latency and throughput trade-offs:** although the system is designed for real-time or near-real-time performance, actual latency depends on multiple factors, including:
  -The frequency of changes in the source database
  -The performance of the Kafka cluster
  -Processing complexity in the stream processor
  -Query load on the analytics backend
- **System complexity and maintenance overhead:** the solution relies on multiple interdependent components (Debezium, Kafka, Databricks, Apache Superset, etc.), each

requiring configuration, monitoring, and scaling. This increases the system's operational complexity and may require a dedicated team with expertise in distributed systems, data streaming, and cloud infrastructure.

- **Apache superset limitations:** while Apache Superset offers robust visualization features, it has some limitations. Real-time streaming visualization is limited; data must be periodically refreshed from the analytical store. High-frequency dashboard queries can strain the backend data store.
- **Limited use for low-volume or static datasets:** the system is best suited for high-change, high-volume environments. For static datasets or infrequent data updates, the overhead of real-time infrastructure may not be justified and could lead to unnecessary resource consumption.

8. Conclusions

The results obtained from the practical solutions real-time data monitoring solutions is becoming increasingly vital in modern data-driven environments where rapid response and continuous insight are key to maintaining operational efficiency and competitive advantage. This paper has presented a comprehensive architecture that leverages CDC for low-latency data extraction, Apache Kafka for scalable data transport, and Apache Superset for dynamic data visualization. The proposed solution enables end-to-end visibility of data changes and empowers stakeholders to make informed decisions based on up-to-date information.

The integration of modular components such as Debezium, Kafka Connect, and stream processors offers flexibility and scalability. Additionally, Apache Superset provides an accessible platform for non-technical users to explore and monitor real-time metrics through interactive dashboards. With continued advancements in stream processing and data observability, real-time analytics will play a central role in the evolution of data engineering practices.

Future work will focus on extending the analytical framework developed with Apache Superset to enhance its scalability and integration of advanced machine learning (ML) and predictive analytics. While Superset excels at descriptive and diagnostic analytics, the limitations of advanced data modelling could be overcome by coupling it with ML models hosted in external platforms such as Databricks, AWS SageMaker, or Azure Machine Learning and that way enabling predictive and prescriptive insights.

By integrating Superset with automated reporting tools, alerting systems, and audit mechanisms, organizations could transition from static analytics toward a proactive, continuously monitored environment.

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KPI METRICS IN THE SOFTWARE INDUSTRY: LITERATURE REVIEW AND ANALYSIS

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Abstract:
This review analyzes eleven peer-reviewed studies (2012–2025) on key performance indicators in software work. The aim is to identify, normalize, and group indicators, highlight the ones that are most frequently reported, and note which study designs predominate. Eleven studies were retained after a structured search and screening. Indicators were grouped by purpose: software delivery performance, team flow and process efficiency, product and service quality, reliability and operations, service management, business and customer value, people and learning, product adoption, learning outcomes, and process automation. The indicators mentioned most often are Cycle Time, Customer Satisfaction, Velocity, and Lead Time. Reviews and case studies are the most common designs.

Keywords:
KPI, metrics, software industry, performance measurement, literature review

1. Introduction and Background

Performance measurement in the software industry relies on a set of KPIs that link engineering practices to outcomes (e.g., delivery speed and quality), with over the last decade, four key DevOps Research and Assessment (DORA) metrics becoming an essential standard for evaluating delivery as referenced in documentation, industry reports, and guides [1, 2, 3]. As part of the Accelerate series [1], statistical analyses are conducted that indicate robust correlations between DORA metrics and indicators of organizational effectiveness. However, the results are observational and depend on the definitions and methodology used to collect the data.

Definitions and measurements often vary between teams and environments in companies (Agile teams, DevOps teams, etc.), which is why the selection of metrics must be done systematically and according to transparent rules, such as the proposed Systematic Literature Review (SLR) guidelines in software engineering [4] and studies from large systems that describe how KPIs are introduced step by step in practice [5].

Aim. This paper provides a comprehensive overview and analysis of terminology and alignment. In this review, we use metric to denote a raw or computed measurement (e.g., defect rate, cycle time), whereas a Key Performance Indicator (KPI) is a metric explicitly linked to an objective and target (e.g., "reduce cycle time to ≤ X days to improve customer lead time"). KPIs are most effective when aligned with organizational goals (e.g., Objectives and Key Results, OKRs), ensuring traceability from engineering work to business outcomes. in the software industry, with a focus on their identification, classification, and use in different contexts (Agile, DevOps, and IT Service Management (ITSM)). Based on a review of the available literature, the paper identifies the most commonly used metrics and the most commonly used methodological approaches.

Background and prior reviews. Gacenga et al. [6] provided an international analysis of the benefits and performance measurement of Information Technology Service Management, where they compared the results of an Australian survey with another study with a clear focus on what benefits are reported and how they are measured in real practices. The results show rapid adoption of ITIL v3 and a large number of reported benefits supported by process-level metrics. In this way, benefits are simultaneously mapped and typical KPIs are listed, whereby change and incident management are distinguished by the degree of adoption and maturity of the metrics.

In measuring KPIs in the software industry, Tahir et al. [7] performed a systematic mapping of 35 primary studies where they identified 29 models and 4 tools that highlighted typical types of measurement (characteristics, evaluations, improvements) and challenges present in program maintenance. The choice of metrics in small and medium-sized enterprises (SMEs) most often relies on expertise (60%), standards (40%), and automated tools (22%).

Almeida & Carneiro [8] quantitatively analyzed the perception of the importance of metrics in Scrum teams (191 valid responses), where they showed that years of experience greatly influenced the perception of team performance metrics and test automation, while the role of the Scrum methodology is not a differentiator.

Paper organization. Section 2 details the review methodology, including search strings, databases, inclusion/exclusion criteria, and the screening workflow in Figure 1. Section 3 reports the results: (1) the metrics extracted per study and the consolidated taxonomy across ten categories; (2) a visual summary of the most frequently referenced KPIs across the 11 studies in Figure 2; and (3) a table summarizing the research methodologies used in SS1 - SS11 in Table 2. Section 4 discusses cross-cutting patterns, limitations, and implications for practice. Section 5 concludes and outlines directions for future work.

2. Methods

In this paper, a structured literature review based on the guidelines for literature review in software engineering [9] was applied, whereby the procedure was adapted according to the methodological steps found in Chapter 22 in the cited literature source. The initial objective was to: (1) investigate existing and popular KPI metrics in the software industry that are used in other papers, (2) investigate what methodologies are used in those research papers, and (3) categorize KPI metrics.

As shown in Figure 1, the light purple blocks represent the stages of the literature source search, while the light yellow block refers to the databases that were used for retrieving the literature sources.

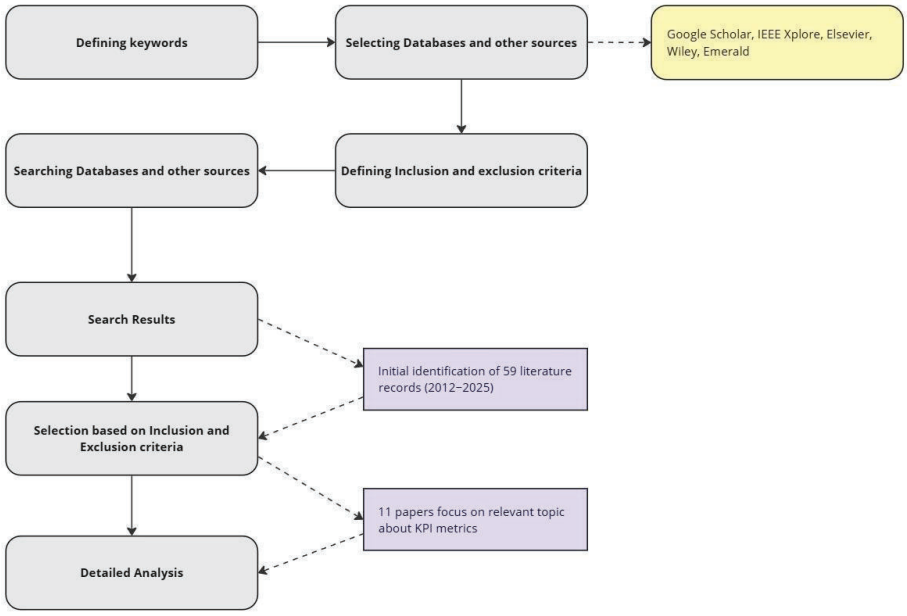


Figure 1: Literature Search Process

For this preliminary Literature Review, three primary keywords were proposed:

- Keyword 1 (KW1) – “KPI” OR “Key Performance Indicator”
- Keyword 2 (KW2) – “Software Industry” OR “Software Development”
- Keyword 3 (KW3) – “Metrics”

These three primary keywords represent essential concepts guiding the search for relevant literature. To enhance the precision of the literature search, logical operators were employed to combine search

terms. The Boolean operators AND and OR were utilized to connect key concepts within the search of a string. Combining these three keywords from a search query such as: (KW1) AND (KW2) AND (KW3)

This literature search string was applied across databases such as Google Scholar, IEEE Explore, Elsevier, Wiley, and Emerald.

The selection of literature sources for this research work is carried out in accordance with certain inclusion criteria. The proposed inclusion criteria are: (I1) Literature sources that are available in full text in PDF format to ensure accessibility; (I2) Literature sources that passed the review process; (I3) Literature sources that are exclusively in English language; (I4) Alignment of title, abstract, and keywords (T+A+KW) with the topic, with reading of literature sources as necessary to ensure focus on successful literature search.

To ensure the relevance and quality of selected literature sources, exclusion criteria were also applied: (E1) Literature sources that are not in domain of Software Industry or Software Development; (E2) Duplicates; (E3) Literature Sources that are not written in English; (E4) Literature sources that do not contain full text; (E5) Literature sources that were published before 2012.

A search of literature sources was conducted for papers in selected databases and in a web search with defined keywords and detailed inclusion and exclusion criteria in accordance with the guidelines in the book [Kitchenham2015]. 50 records were identified in the period from 2012 to 2025. After inspecting the title, abstract and textual parts of literature sources, 6 duplicates (E2), 26 works that are outside the domain of Software Industry and Software Development (E1), 5 records without full text content (E4), 8 literature sources were published before 2012 (E5), and 3 literature sources were not in English language (E3). 11 selected studies (SS) were selected for detailed analysis as presented in Table 1. For coding, we labeled an indicator as a KPI only when the primary source tied the metric to a business/product objective and a target/threshold, otherwise, it was coded as a metric.

Table 1

Overview of the selected studies

SSn	Authors name	**Title**	**References**
SS1	Adewusi, B. A., Adekunle, B. I., Mustapha, S. D., & Uzoka, A. C.	Systematic Review of Performance Metrics and OKR Alignment in Agile Product Teams across Industry Verticals	[10]
SS2	Amaro, R., Pereira, R., & Mira da Silva, M.	DevOps metrics and KPIs: a multivocal literature review	[11]
SS3	Baradari, I., Shoar, M., Nezafati, N., & Motadel, M.	A new approach for KPI ranking and selection in ITIL processes: Using simultaneous evaluation of criteria and alternatives (SECA)	[12]
SS4	Gomes, M., Pereira, R., Silva, M., de Vasconcelos, J. B., & Rocha, Á.	KPI's for Evaluation of DevOps Teams	[13]
SS5	Mannila, J.	Key performance indicators in agile software development	[14]
SS6	Lillemäe, L. L.	Key Performance Indicators for Measuring Efficiency and Effectiveness in an Agile Software Development Team: Development of a KPI Dashboard for Measuring Individuals' Performance Through an Entrepreneurial Study within Extenda Retail	[15]
SS7	Mane, V., & Bagai, R.	The 4D Model: Metrics-Driven Business Growth with SaaS Case Studies	[16]

SS8	Shantaram S.	Key Performance Indicators for Agile Software Development Methodology	[17]
SS9	Soubjaki, M. J.	The Impact of Key Performance Indicators (KPIs) on Talent Development	[18]
SS10	Sürücü, C., Song, B., Krüger, J., Saake, G., & Leich, T.	Establishing key performance indicators for measuring software-development processes at a large organization	[5]
SS11	Ulloa, R. L., & Herrera, R. D. J. G.	A Cloud-KPIs Dashboard to Evaluate Agile Development Teams' Performance: A Mexican Case Study	[19]

3. Results

In the dataset of 11 selected studies, literature sources were carefully selected based on specific inclusion and exclusion criteria.

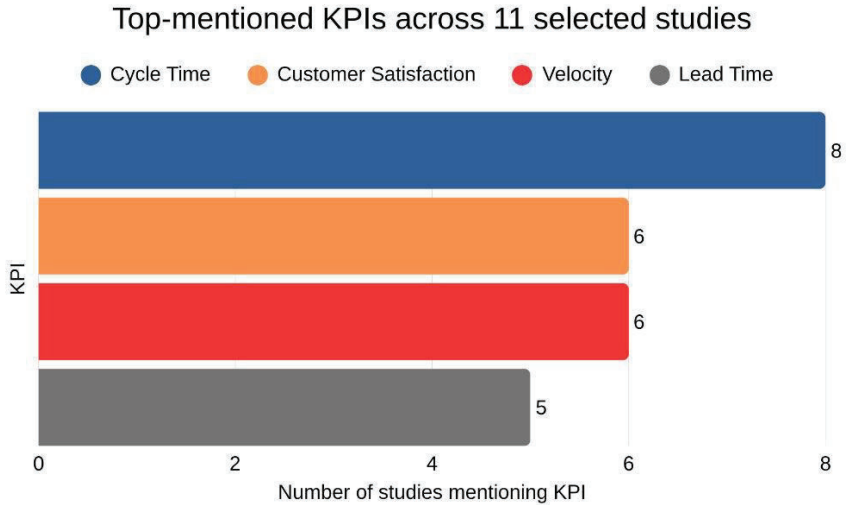


Figure 2: Frequency of top-mentioned KPIs across the 11 selected studies

To provide a compact overview, Figure 2 summarizes the frequency of the most frequently referenced KPIs across the 11 studies. Cycle Time dominates with 8 studies, while Customer Satisfaction and Velocity each appear in 6 studies, and Lead Time in 5 studies, confirming a pronounced focus on flow and a consistent bridge to user value via satisfaction scores.

3.1. Metrics in selected studies

In study [SS1], metrics were identified that include Velocity, Sprint Burndown/Burnup, Cycle Time, Lead Time, Team Satisfaction, Defect Rate, and Delivery Predictability.

In the study [SS2] metrics related to: Lead Time For Changes, Deployment Frequency, Change Failure Rate, Mean Time to Restore, Availability/Uptime, Defect Escape Rate, Mean Time to

Detection, Return on Investment, Cost of Downtime, Customer Satisfaction, Cycle Time, Lead Time vs. Throughput, Incident Response Time, Team Satisfaction and Collaboration & Knowledge Sharing.

In the paper [SS3], the authors considered the following set of KPI indicators such as: Incident Resolution Time, Average Response Time, First Call Resolution Rate, Service-Level Agreement (SLA) Compliance, Number Of Recurring Incidents, Change Success Rate, Mean Time Between Failures, Availability (%), Customer Satisfaction Score, Training Hours per Employee, Cost of Service Operations, Number of Unauthorized Changes, Problem Resolution Time, Downtime Duration, Root Cause Analysis Completion Rate, Knowledge Base Usage Rate, Employee Satisfaction, Number Of Escalations, Percentage Of Automated Processes, Resource Utilization Rate and It Service Continuity Readiness.

In study [SS4], metrics were proposed and used, which include Deployment Frequency, Lead Time For Changes, Change Failure Rate, Mean Time To Recovery, Cycle Time, Throughput, Utilization Rate, Defect Density, Incident Response Time, Service Availability, Customer Satisfaction Index, Business Value Delivered, Return On Investment, and Cost Efficiency.

This review [SS5] highlights metrics such as: Velocity, Sprint Burndown, Throughput, Defect Density, Customer-Reported Defects, Test Coverage, Lead Time, Cycle Time, Deployment Frequency, Customer Satisfaction, Team Satisfaction, and Collaboration Level.

Study [SS6] introduced and tracked metrics such as: Individual Velocity, Cycle Time, and Change Failure Rate.

In the SaaS context, the paper [SS7] used the following metrics: Course Enrollment Numbers, Course Completion Rate, Student Satisfaction Scores, Post-Course Skill Assessments, New User Sign-ups, Daily Active Users (DAU), Feature Usage, User Retention Rate, Average Onboarding Time, Customer Satisfaction Score (CSAT), and Time To First Value (TTFV).

In the paper [SS8], the author focused on metrics such as: Velocity, Burndown, Lead Time, Cycle Time, Defect Trend, Open Defect Severity Index, Unit Test Coverage, Business Value Metric, Pacemaker Metric, Net Promoter Score, Test Coverage, Regression Test Progress, Delivery on Time, Processing Interval, and Effort at Risk.

Paper [SS9] includes indicators related to People/Human Resource: Employee Productivity, Training Effectiveness, Talent Retention Rate, Employee Satisfaction, Career Progression Metrics, Learning & Development ROI, Performance Appraisal Scores, and Succession Planning.

The study [SS10] recorded a wide set of metrics: Velocity, Throughput, Delivery Time, Lead Time, Defect Density, Defect Resolution Time, Test Coverage, Cycle Time, Reopen Rate, Change Failure Rate, Mean Time Between Failures, Mean Time To Recovery, Service Availability, Employee Satisfaction, Knowledge Sharing Metrics, Training Hours Per Employee, Customer Satisfaction, Business Value Delivered and Cost of Software Operations.

The following metrics were identified in the study [S11]: Velocity, Lead Time, Cycle Time, Deployment Frequency, Defect Rate, Defect Leakage, Reopen Rate, Effort Variance, Return On Investment, Business Value Delivered, Customer Satisfaction, and Team Satisfaction.

3.2. Research approaches in selected studies

In the set of 11 papers, five types of forms prevail: (1) Systematic Literature Review; (2) Multivocal Literature Review; (3) Case studies in industrial environment; (4) Papers that offer conceptual frameworks; (5) Combined methods and survey approaches. The methodology used in each study is summarized in Table 2.

Table 2
Research methodologies used in the 11 selected studies (SS1–SS11)

SSn	Methodology Type	**Summary**
SS1	Systematic Literature Review (SLR)	Systematic review of performance metrics and their relation to a complementary framework in agile teams.

SS2	Multivocal Literature Review (MLR)	Combines academic sources + gray literature to map DevOps metrics/KPIs and measurement patterns.
SS3	MCDM (SECA) decision method	Formal KPI ranking/selection for ITIL processes using SECA
SS4	Conceptual framework	Framework for evaluating DevOps teams; maps goals to KPIs in a structured model
SS5	Organizational review	Company-based review (books, web, workshops) to define and select new KPIs
SS6	Case study	Identifies individual-based KPIs and develops an operational dashboard in a company
SS7	Case studies	SaaS case studies illustrating metrics that drive product growth/adoption
SS8	Grounded-theory-based review	Uses grounded theory to derive KPI categories/relationships in agile methods
SS9	Survey	Deductive, questionnaire-based study with statistical analysis
SS10	Case study	Establishes and measures KPIs for software-development processes in the field.
SS11	Case study	Introduces "Cloud-KPIs" and applies an estimation model to evaluate agile teams

Industrial case studies constitute the largest bucket (four studies: SS6, SS7, SS10, SS11), followed by review/synthesis designs (three studies: SLR - SS1, MLR - SS2, and grounded-theory review - SS8), conceptual/decision frameworks (two studies: SS3, SS4), one practitioner oriented organizational review (SS5), and one survey (SS9). This distribution indicates a strong practice orientation, with complementary evidence from literature reviews and decision-support framing.

3.3. Categories and metric assignment

In this subsection, all metrics found that are presented in subsection 4.2 will be presented and grouped into several categories. The classification was done according to the purpose of measurement in the selected studies:

- Software Delivery Performance (DORA) – The speed and stability of software delivery are measured. This group includes metrics: Lead Time for Changes (LT), Deployment Frequency (DF), Change Failure Rate (CFR), and Mean Time to Recovery (MTTR).
- Flow & Agile Process Efficiency – Workflow and process predictability are described. This group includes metrics: Lead Time, Cycle Time, Throughput, Velocity, Burndown/Burnup, Lead Time vs. Throughput, Delivery Time, Delivery on Time, Processing Interval, Effort Variance, Delivery Predictability, and Pacemaker Metric.
- Product/Service Quality – Focus is on defects and testing. Metrics included here: Defect Rate, Defect Density, Defect Leakage, Defect Trend, Open Defect Severity Index, Test Coverage, Mean Time to Detection (MTTD), Customer-Reported Defects, and Defect Resolution Time.
- Reliability/Operations – Refers to production outcomes and operational reliability. These metrics include Availability/Uptime, Mean Time Between Failures (MTBF), Incident Response Time, Downtime Duration, and Cost of Downtime.
- ITSM – Process metrics that include Information Technology Infrastructure Library (ITIL) flows. These metrics include Incident Resolution Time, Average Response Time, First Call Resolution Rate, SLA Compliance, Number of Recurring Incidents, Change Success Rate, Number of Unauthorized Changes, Problem Resolution Time, Root Cause Analysis Completion Rate, Knowledge Base Usage Rate, Number of Escalations, and IT Service Continuity Readiness.
- Business/Customer Value – Connects engineering to business outcomes and customer experience. This group includes metrics: Return on Investment (ROI), Cost Efficiency, Cost of Service Operations, Business Value Delivered, Customer Satisfaction, Net Promoter Score

(NPS), and Business Value Metric.

- People, Learning and Culture - This includes metrics: Team Satisfaction, Employee Satisfaction, Employee Productivity, Training Effectiveness, Training Hours per Employee, Collaboration & Knowledge Sharing, Career Progression Metrics, Talent Retention Rate, Performance Appraisal Scores, Succession Planning, and Learning & Development ROI.
- Product Adoption and User Engagement - User adoption and engagement. Metrics include New User Sign-ups, Daily Active Users (DAU), Feature Usage, User Retention Rate, Average Onboarding Time, and Time to First Value (TTFV).
- Learning and Education Outcomes - Learning outcomes for products that have an educational component. This group includes metrics: Course Enrollment Numbers, Course Completion Rate, Post-Course Skill Assessments, and Student Satisfaction Scores.
- Process Efficiency and Automation - This group includes metrics: Resource Utilization Rate, Reopen Rate, Effort at Risk, and Percentage of Automated Processes.

4. Discussion

The set of 11 selected studies cover a stable core of flow and delivery metrics (Lead/Cycle Time, Velocity, DORA), product/service quality (Defect rate/Density, Test Coverage) and operations (incident/availability/MTTR), with additions from ITSM and business/customer value used in case studies and reviews (MLR and SLR). In practice, KPI programs are effective only when cascaded from organizational goals, otherwise, teams risk optimizing local metrics without improving desired outcomes.

As Figure 2 shows, Cycle Time dominates with 8 studies, followed by Customer Satisfaction and Velocity 6 studies each, and Lead Time with 5 studies. Cycle Time's prominence likely reflects that it is easy to instrument, team-actionable, a leading indicator for flow/predictability, and comparable across teams. To avoid speed-only local optima, teams should pair Cycle Time with stability/quality guardrails (e.g., Change Failure Rate, MTTR) and at least one value-oriented KPI (e.g., CSAT/NPS) as leading–lagging pairs aligned to organizational goals.

In terms of methodological approaches, industrial case studies that operationalize the same metrics in real teams and tool ecosystems were most used [SS6], [SS7], [SS10], [SS11]. This is followed by literature reviews, systematic and multivocal [SS1] and [SS2], as well as reviews based on grounded theory [SS5] and [SS8].

5. Conclusion

In this review, 11 selected studies were analyzed, from which KPI metrics were extracted and standardized. Metrics are grouped into clear categories (DORA, Flow & Agile Process Efficiency, Product/Service Quality, Reliability/Operations, ITSM, Business/Customer Value, People, Learning and Culture, Product Adoption and User Engagement, Learning and Education Outcomes, Process Efficiency and Automation).

The most frequently mentioned metrics are Cycle Time, Customer Satisfaction, Velocity, and Lead Time, with the constant presence of Delivery metrics. In terms of methodologies, literature reviews and case studies are mostly used; conceptual frameworks, MCDM, and survey approaches appear less frequently. These KPIs are most effective only when explicitly aligned with organizational goals.

Future work will: (1) conduct a focused review of non-KPI metrics to clarify boundary conditions and terminology, ensuring a clean separation between metrics and KPIs. (2) build a simple, context-aware model that uses team/project factors to suggest the right KPIs with priorities. The model will be evaluated in two industrial pre/post pilots, and results will report adoption, goal attainment, and any unintended effects.

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Recipe Radar: A Voice-Driven Hybrid Recommender System for Recipes Using NLP, Text-to-SQL, and Cloud-Native Infrastructure

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Abstract

In the era of exponential data growth and digital habits, personalised recommendations have become a necessity. This paper presents an intelligent recipe recommendation application that combines voice interaction (Speech-to-Text), natural language processing, Text-to-SQL, and a hybrid recommendation approach (demographic + collaborative filtering). Users can express their preferences naturally through speech or text, and the system automatically translates them into SQL queries, fetches data from Supabase tables, and returns personalised results. The solution is implemented with Angular (frontend), Python (backend), OpenAI for SQL generation, and Supabase (PostgreSQL) for storage and authentication. This demonstrates how integrating multiple technologies and intelligent methods leads to more relevant recommendations and improved user experience.

Keywords:

Recommender systems, Voice-Driven, Hybrid Recommender System, NLP, Speech-to-Text, Text-to-SQL

1. Introduction

Data is no longer merely a byproduct of digital activity, it has become a critical asset that drives decision-making, innovation, and economic growth. It is generated continuously and at an exponential rate [1], with recent studies estimating that approximately 2.5 quintillion bytes of data are produced every day [2], a figure that continues to rise. This explosive growth is largely driven by the proliferation of the internet and the integration of connected technologies across nearly all aspects of daily life. In this context, the need for robust and intelligent data life cycle management has become increasingly important, not only for efficient storage and processing but also for extracting actionable insights. One of the most prominent applications of such insights is the development of personalised recommendation systems, which utilise user behaviour, preferences, and contextual information to provide relevant and timely suggestions. Personalised recommendations take into account the user's digital footprint along with detailed product information—such as specifications, user feedback, and comparisons with similar products—before generating a suggestion [3]. These systems have proven effective in enhancing user engagement, improving conversion rates, and fostering long-term retention. A knowledge-based recommender system differs from traditional approaches by generating recommendations in response to specific user-defined queries or constraints, rather than relying on historical ratings or behavioral data. In recent years, recommender systems have evolved considerably, driven by significant advances in machine learning, deep learning, and big data technologies. As intelligent software solutions, they aim to reduce cognitive load and personalise content or product offerings, making them a fundamental component of modern digital ecosystems.

Effective personalised recommendations begin with the collection of comprehensive data, including explicit user inputs as well as implicit behaviours such as browsing history, purchase activity, and interaction patterns. This rich dataset is then processed using advanced algorithms and analytical tools designed to uncover meaningful patterns, trends, and individual preferences. Leveraging these insights, predictive models forecast the products or services that a user is most likely to value next. Finally, these personalised recommendations are delivered seamlessly to the user through appropriate channels.

This paper focuses specifically on recipe recommendation, where natural language and voice commands serve as intuitive interfaces between the user and the underlying data infrastructure.

The paper is structured as follows: Following the introduction, the related work section provides a comprehensive overview of recommender systems and emerging technologies. The subsequent section, system architecture**,** describes the overall design of the system, highlighting the integration of voice recognition, NLP, automatic SQL generation, user behaviour analysis, and a hybrid recommendation engine. The next section details the technical realisation of the system, covering the development of the Angular-based frontend, the Python backend, and integration with the Supabase database. The results and discussion section demonstrate the system's ability to process natural language input and generate personalised, real-time recommendations. It also evaluates the system's performance in addressing key challenges, such as the cold-start problem and user accessibility. Finally, the paper concludes with a summary of the key findings and contributions, reflections on the results, and recommendations for future research and development. Additionally, it discusses the limitations and challenges encountered.

2. Related Work

Francesco, Rokach, and Bracha highlight that recommender systems can be categorised based on the domain they operate in, the knowledge they leverage, and most notably, the algorithms used to predict the relevance or usefulness of a recommendation [4]. Differences also arise in how these systems compile and present recommendations in response to user queries.

According to Aggarwal, recommender systems are generally grouped into four main categories: collaborative filtering, content-based filtering, demographic filtering, and hybrid models [5]. Collaborative filtering assumes that users with similar past preferences will share similar tastes in the future [6]. It can be further divided into user-based and item-based approaches. In user-based collaborative filtering, recommendations are derived by identifying users with similar rating patterns [7], while item-based filtering calculates item similarities and recommends items similar to those a user has already liked [8].

Content-based filtering, on the other hand, builds user profiles by analysing item attributes and using labelled item descriptions as training data. This approach recommends items similar to those the user has rated positively in the past [5].

Demographic filtering classifies users based on demographic characteristics such as age, gender, or location. Users within the same demographic category are assumed to share similar preferences. For new users, recommendations are generated by identifying the demographic group they belong to and applying the preferences of similar users in that group [9].

In contrast, knowledge-based recommender systems rely on explicit domain knowledge and predefined rules or constraints [10]. Unlike collaborative or content-based systems that infer preferences from user interactions, knowledge-based systems are designed to deliver recommendations based on user-defined queries or specific requirements. As noted by Aggarwal, these systems do not depend on collective user behaviour or machine learning models, but instead provide transparent and explainable results [5]. This makes them particularly suitable for domains where precision, trust, and interpretability are essential [11].

Hybrid recommender systems integrate multiple recommendation techniques to capitalise on their strengths and mitigate individual limitations. Bell and Koren emphasise the success of hybrid models in the Netflix Prize competition, where combining predictions from diverse models led to an 8.43% improvement over Netflix's original algorithm, Cinematch [12]. The continued evolution of hybrid systems has been driven by the need for more accurate, robust, and personalised recommendations [6].

Beyond traditional recommendation algorithms, the integration of natural language processing (NLP) and voice technologies has significantly expanded the functionality and accessibility of recommender systems. Speech-to-text and text-to-speech technologies allow users to interact with systems using voice commands, enabling multimodal communication and enhancing the user experience [13].

NLP serves as a critical interface between human language and machine interpretation, enhancing human-computer interaction through techniques such as tokenisation, natural language understanding (NLU), and natural language generation (NLG). According to Stryker and Holdsworth, NLP systems can

be implemented using rule-based approaches, statistical models, or neural architectures based on deep learning [14].

Another important advancement is the development of Text-to-SQL technologies, which allow users to interact with databases using natural language instead of formal query languages. Zhu et al. point out that SQL can be a barrier for non-technical users and even challenging for practitioners when dealing with domain-specific queries. Text-to-SQL systems translate natural language questions into structured SQL queries, significantly lowering the threshold for accessing and manipulating data [15].

These technological advancements form the foundation for the proposed system, Recipe Radar, which combines voice interfaces, NLP, Text-to-SQL translation, and a hybrid recommendation model to provide intelligent, accessible, and user-centric recipe recommendations.

3. System Architecture

The developed system presents a comprehensive integration of advanced technologies, combining voice recognition (Figure 1), natural language processing (NLP), automatic SQL generation (Text-to-SQL), user behaviour analysis, and a hybrid recommendation engine to deliver personalised recipe suggestions. The conceptual architecture of the system illustrates the interaction between these components, enabling seamless communication from user input to data retrieval and presentation.



Figure 4: Conversion of human speech to text using the browser native Web Speech API

On the frontend, the application is built using Angular and Angular Material, which together offer a modern, responsive, and accessible user interface. The frontend is modularised into distinct components, including: `web-speech`, `recommended-recipes`, `recipe-details`, `profile`, `add-recipe`, and `charts`. Each module is designed to handle a specific aspect of the user experience, from voice input and recipe browsing to profile management and data visualisation. Angular Material further enhances usability by ensuring consistent design patterns and accessibility compliance.

The backend is implemented in Python, serving as the middleware that processes user inputs, orchestrates logic, and facilitates communication with the database. It also handles the execution of SQL queries generated via natural language and the delivery of results back to the frontend.

The relational database is hosted on Supabase, a cloud-native backend-as-a-service built on PostgreSQL. The database schema consists of four primary tables: `recipes`, `ratings`, `profiles`, and `shopping_list`. These tables respectively capture information on recipe content, user-generated ratings, demographic and behavioural profiles, and user-curated shopping items. This structured data model supports both collaborative filtering and demographic-based recommendations, enabling a multi-dimensional recommendation strategy.

A key innovation in the system is the incorporation of Text-to-SQL functionality, which bridges the gap between natural language input and structured database queries. (Figure 2) The process involves three core steps: (1) Schema extraction – the system dynamically extracts the database schema and provides it as structured context to the language model; (2) Prompt engineering – Carefully designed prompts guide the model (e.g., a large language model) to generate accurate SQL queries in a structured JSON format; Query execution – The resulting SQL is parsed and executed against the Supabase database, and the response is formatted and returned to the user.

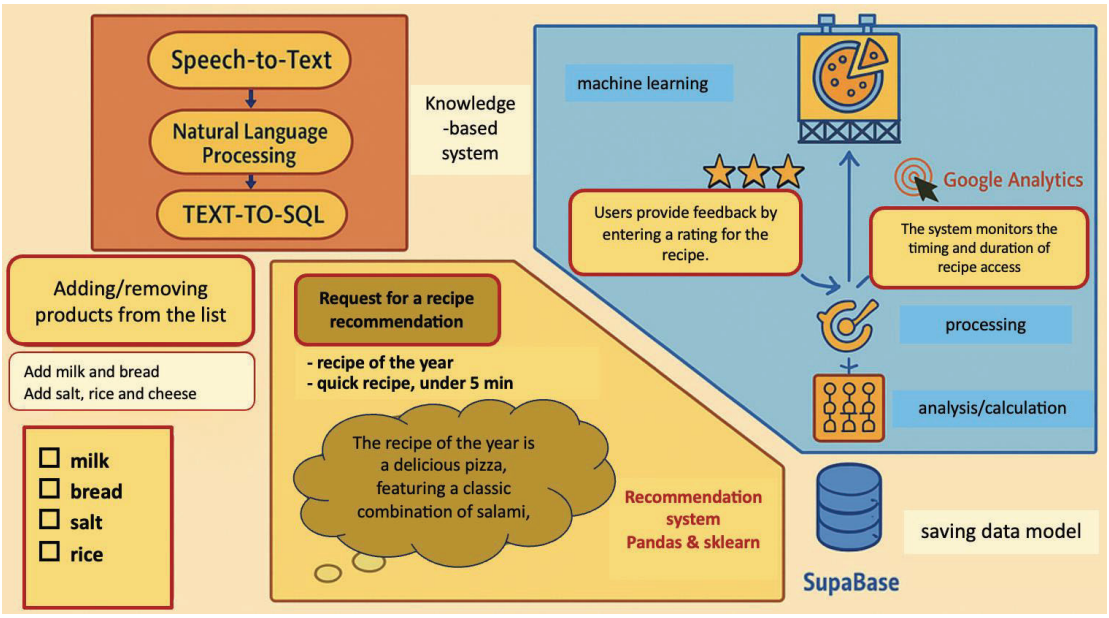


Figure 5: Architecture of the system

The speech interface enhances user interaction by enabling natural, voice-based communication. Spoken commands are processed via speech-to-text technology and passed through the NLP and Text-to-SQL pipeline, allowing even non-technical users to retrieve recipe data without needing to understand or write SQL.

Together, these components form a robust and user-centric system, Recipe Radar, that leverages modern AI and cloud-native technologies to deliver intelligent, personalised culinary recommendations through a multimodal interface.

4. Implementation

The **f**rontend of the system is developed using Angular, leveraging reactive forms for recipe submission, modular visual components for recipe display, and seamless integration with Supabase via RESTful APIs. This design ensures a responsive, user-friendly interface capable of handling dynamic data interactions in real-time. The visual components are structured to enhance usability and accessibility, supporting an intuitive flow from user input to data presentation.

The backend is implemented in Python, functioning as the core processing layer of the application. It handles both textual and spoken user input, utilising OpenAI's language models to perform natural language to SQL (Text-to-SQL) translation (Figure 3)**.** The generated SQL queries are executed against a PostgreSQL database hosted on **S**upabase, with the retrieved results relayed back to the frontend for display. This architecture enables natural, multimodal user interaction without requiring technical knowledge of database query languages.

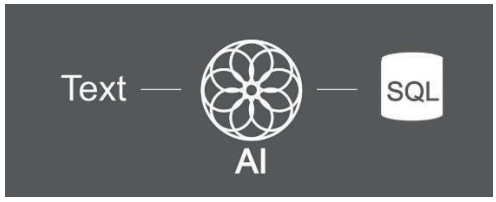


Figure 6: Text-to-SQL process: schema extraction, SQL generation, and execution.

The system employs a hybrid recommendation strategy (Figure 4) that integrates both demographic filtering and collaborative filtering techniques to enhance the relevance and diversity of suggestions.

- Demographic filtering identifies users with similar attributes—specifically, matching gender, city, and an age range within ±5 years—to address the cold-start problem often encountered in recommendation systems.
- Collaborative filtering constructs a user–recipe interaction matrix based on user-generated ratings. This matrix is processed using cosine similarity and the NearestNeighbors algorithm, allowing the system to identify users with overlapping taste profiles. Recommendations are then generated by aggregating highly rated recipes from a user's nearest neighbours.

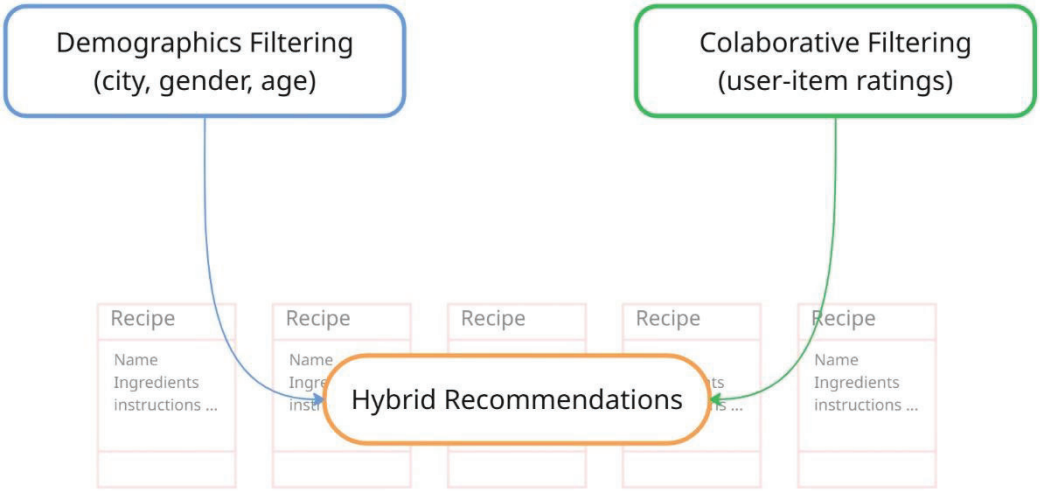


Figure 7: Hybrid filtering approach

For instance, if a user consistently rates vegetarian dishes positively, the collaborative filtering component will prioritise vegetarian recipes favoured by users with similar preferences. Simultaneously, the demographic filter ensures that the recommendations are contextually appropriate by incorporating users with similar demographic profiles.

This hybrid approach enhances recommendation accuracy and robustness across varying user scenarios, improving both personalisation and system adaptability. In the user interface, the final recommendations and query results are presented using visually engaging cards, each displaying an image, title, and brief description of the recipe. This presentation format supports a rich and immersive user experience, effectively bridging the gap between data-driven logic and user-centric design.

5. Results and Discussion

An illustrative example of system interaction involves a user issuing the voice command: *"Add 3 oranges to the shopping list."* This input is captured via the speech interface, transcribed into text, and processed through the Text-to-SQL pipeline. The system subsequently generates the appropriate SQL query, updates the relational database, and synchronously reflects the change in the user interface. This interaction exemplifies the seamless integration of natural language processing with structured database operations**,** enabling users to perform complex tasks without direct interaction with database query languages.

A core innovation of the system lies in its hybrid recommendation engine, which combines both demographic and collaborative filtering techniques (Figure 5)**.** This dual approach addresses the limitations inherent in using a single strategy. For new users with limited interaction history, a common challenge known as the cold-start problem, demographic filtering provides a basis for initial recommendations by leveraging user attributes such as age, gender, and location. In contrast, for users with extensive activity logs, collaborative filtering draws upon shared behavioural patterns to generate more refined suggestions. This ensures that the system remains effective across a spectrum of user profiles, from novices to highly engaged users.

Another notable feature is the system's Text-to-SQL interface, which significantly lowers the barrier to entry for non-technical users by enabling interaction through everyday language. This is complemented

by the use of Angular Material, which adheres to modern UI/UX standards and accessibility guidelines, ensuring that the application remains both usable and inclusive.

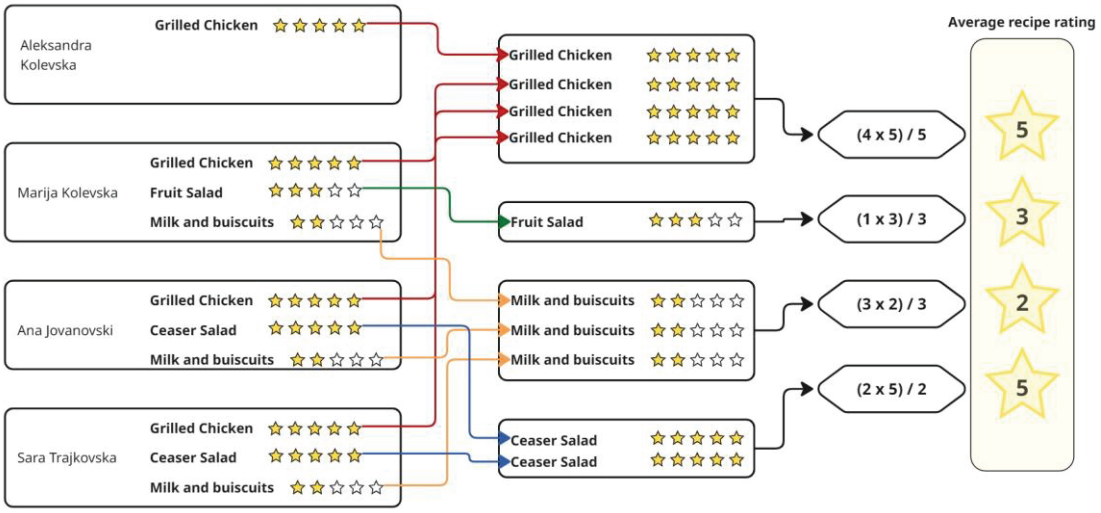


Figure 8: *Recommendation flow: demographic and rating-based filtering*

The design philosophy aligns with practices observed in large-scale commercial platforms. For example, Amazon employs item-to-item collaborative filtering supplemented with content-based signals, while Netflix integrates deep learning within its hybrid recommendation systems to capture complex user preferences. These real-world analogues underscore the scalability, relevance, and practical applicability of the hybrid approach adopted in this work.

Despite its strengths, the system exhibits several limitations**.** The accuracy of the speech-driven interface is contingent upon reliable speech recognition performance, which may be affected by accents, background noise, or pronunciation variations. Additionally, the platform requires stable internet connectivity to ensure real-time interaction with the Supabase backend. Furthermore, the efficiency and correctness of SQL query generation remain critical for delivering accurate responses, particularly in edge cases or ambiguous queries.

6. Conclusion

This study presents the design and implementation of an integrated, intelligent, and user-centric recipe recommendation system that leverages a multimodal interaction framework incorporating speech recognition**,** natural language processing (NLP)**,** automatic SQL generation**,** and cloud-native data storage**.** By combining these technologies, the system allows users, regardless of technical expertise, to interact with a structured relational database using natural language, either through text or voice input. This contributes to a more inclusive and accessible user experience, especially for non-technical or visually impaired individuals.

At the core of the system lies a hybrid recommendation engine**,** which fuses demographic filtering and collaborative filtering to offer robust and context-sensitive recipe suggestions. Demographic filtering utilises user metadata (such as age, gender, and geographic location) to provide personalised recommendations in scenarios with limited historical data, addressing the well-known cold-start problem**.** In contrast, collaborative filtering leverages historical rating data to uncover latent preferences and similarities between users, offering deeper personalisation as user interaction grows. The integration of these two methods creates a flexible recommendation architecture capable of adapting to both novice and experienced users.

The system architecture, comprising an Angular frontend, Python-based backend, and Supabase-hosted PostgreSQL database, demonstrates the feasibility of deploying scalable, cloud-native AI applications using modern web technologies. The implementation of Text-to-SQL pipelines, powered by large language models, enables semantic interpretation of natural language queries into executable SQL commands. This functionality significantly reduces the barrier to data retrieval, empowering users to access relevant content through intuitive interaction modalities.

The practical utility of this system extends beyond the culinary domain. The architectural design and underlying methodologies are readily applicable to other fields that require personalised content delivery, such as healthcare (e.g., personalised diet planning or medication tracking), education (e.g., personalised learning content recommendations), and e-commerce (e.g., tailored product suggestions). This demonstrates the system's potential for cross-domain applicability and scalability in real-world deployments.

Nevertheless, certain limitations persist. These include a dependency on high-quality speech recognition, the need for a reliable internet connection, and the potential for inaccuracies in SQL generation under ambiguous or poorly structured user queries. Addressing these challenges is essential for enhancing system reliability and user trust.

Future research directions will focus on enhancing the recommendation engine through the incorporation of deep learning-based models**,** such as neural collaborative filtering or graph neural networks, to capture more complex user-item interactions. Additionally, context-aware filtering mechanisms**,** taking into account temporal patterns, location data, dietary restrictions, and seasonal availability, may further refine personalisation. Expanding the scope of the system to include **non-recipe** domains and evaluating its performance in real-world user studies will also contribute to a deeper understanding of its usability, generalizability, and societal impact.

However, several limitations were observed during system evaluation. Ambiguous or loosely structured queries such as 'find a healthy recipe' or 'show me something my friends like for dinner' proved challenging for the Text-to-SQL module to interpret accurately, occasionally resulting in incomplete or irrelevant SQL generation. Furthermore, speech recognition accuracy may vary depending on background noise, accent, or pronunciation, which can impact query interpretation. The system’s reliance on stable internet connectivity and the limited diversity of the dataset also affect its consistency and adaptability across broader culinary domains.

The Text-to-SQL component was refined through a structured prompt engineering process. Prompts were iteratively optimized to include database schema information, example SQL structures, and constraints on output format using JSON. This guided the language model to generate more accurate and syntactically valid SQL queries while reducing hallucination and mismatched column references. The process also involved few-shot learning examples to improve query reliability and semantic alignment between natural language inputs and database structure.

In future research, the proposed model will be evaluated through the inclusion of quantitative metrics. This will involve measuring and comparing task completion times, accuracy, and user satisfaction between the voice-driven interface and a traditional graphical user interface (GUI). Such analysis will help validate the practical advantages of voice-enabled interaction in terms of efficiency and accessibility. Additionally, user experience evaluations based on standardized metrics such as the System Usability Scale (SUS) and interaction efficiency (number of steps per query) will be conducted to provide measurable insights into system performance.

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Knowledge-based Decision Support System for Personalised Training

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Abstract:

Modern lifestyles and increased awareness of healthy living highlight the need for personalised fitness and nutrition plans. However, designing such plans remains complex, requiring the integration of diverse biometric data and individualised goals. This paper presents a Knowledge-Based Decision Support System (KDSS) that automates the generation of weekly personalised exercise and dietary recommendations. By analysing parameters such as height, weight, body water percentage, and protein intake, the system employs predefined rules and inference mechanisms to tailor guidance aligned with user objectives, including weight loss, maintenance, or muscle gain. The KDSS bridges the gap between general health guidelines and individualised interventions, offering intelligent, goal-specific support. Its architecture and reasoning framework are designed to deliver accurate and actionable plans, facilitating user motivation and adherence. Validation experiments confirm the system's effectiveness in supporting health and fitness outcomes. The proposed solution not only streamlines the planning process but also offers scalability for integration with wearable devices and real-time data analytics. This approach provides practical value for both end users and fitness professionals, contributing to improved quality of life through informed, personalised decision-making. The objective of this paper is to evaluate and develop a Knowledge-Based Decision System that will automatically generate personalised weekly exercise plans based on individual parameters.

Keywords:

Knowledge-Based Systems, Decision Support System (DSS), Personalized Training, Personalized Nutrition, Biometric Data Analysis, Fitness Recommendation, Automated Planning

1. Introduction

The rapid pace of modern life, coupled with an increasing awareness of healthy living, has heightened the demand for personalised approaches in physical activity and nutrition. Over recent decades, personalised nutrition and training have emerged as standard practices to support individuals in achieving their fitness goals effectively and safely.

Despite their recognised importance, the development of truly personalised exercise and nutrition plans remains a complex challenge. Creating effective exercise programs requires careful consideration of multiple individual-specific factors to optimise outcomes and minimise risks such as injury. Similarly, adjusting meal portions and food consistency to meet nutritional guidelines is often difficult for users, who may rely on a limited range of "safe" options, thereby risking nutritional imbalance or deficiency [1]. Furthermore, modifications to food texture and consistency lack standardisation, as they depend on local clinical practices, cultural habits, and users' education and adherence to recommendations [2].

In response to the challenges, knowledge-based decision support systems (KDSSs) offer a promising solution by providing intelligent, automated assistance tailored to individual parameters. These systems integrate expert knowledge with biometric data analysis to support decision-making, bridging the gap between general fitness guidelines and personalised training and nutrition plans.

The motivation for this paper stems from the need to develop a system capable of analysing

biometric parameters such as height, weight, body water percentage, and protein intake to generate personalised exercise and nutrition recommendations. The primary objective is to deliver accurate, automated support that aligns with individual goals, including weight loss, weight maintenance, or muscle gain. Leveraging predefined rules and inference mechanisms, the proposed ontology-based Decision Support System (DSS) produces weekly, tailored recommendations, facilitating effective planning and enabling users to make evidence-based decisions that improve their health and quality of life. Moreover, trainers and fitness professionals often face the daunting task of processing extensive biometric data, scientific research, and nutritional guidelines to provide up-to-date, personalised advice. Given the complexity and time constraints involved in manually integrating this information [3], KDSSs are essential tools that enhance the delivery of precise and individualised guidance [4].

The paper is structured as follows: Following the introduction, a comprehensive and systematic review of knowledge-based systems is presented, with particular emphasis on their development and application in decision support for fitness and nutrition. The subsequent section focuses on the design and implementation of the proposed decision support system. It provides detailed descriptions of the methods used for collecting and analysing input parameters (such as height, weight, body water percentage, and protein intake), as well as the rules and algorithms that generate exercise and nutrition recommendations tailored to specific goals, including weight loss, maintenance, and muscle gain. This section also addresses system architecture, inference mechanisms, and knowledge management, alongside testing and validation processes that evaluate the system's accuracy, precision, and practical applicability. Finally, the paper concludes with a summary of the key findings and contributions, reflections on the results, and recommendations for future research and development. Additionally, it discusses the limitations and challenges encountered, as well as potential avenues for enhancing the system through further adaptation and integration with emerging technologies.

2. Related Work: Personalised Exercise, Individual Goals, and Adaptive Training Systems

Regular physical activity is fundamental for both physical and mental health. It helps prevent and manage chronic diseases such as type 2 diabetes, heart disease, and obesity, while also supporting mental well-being and functional longevity. However, exercise is not universally effective in the same way for everyone. As Dr. William Kraus explains, "The benefits vary by type, intensity, and amount of exercise" [5]**.** Different modalities of physical activity yield different physiological outcomes. Moderate-intensity, longer-duration exercises such as brisk walking are particularly effective at lowering blood glucose, thus playing a preventive role in the development of type 2 diabetes [5]**.** In contrast, high-intensity workouts, which significantly elevate heart rate, have shown greater effectiveness in reducing LDL cholesterol, thereby improving cardiovascular risk profiles. Hence, defining individual goals—such as fat loss, strength gain, endurance improvement, or mental clarity—is critical to selecting the most suitable form of activity.

A significant challenge is the wide variability in individual responses to identical training programs. While some participants experience substantial improvements, others may see minimal or no change. This has led to classifications such as 'responders' and 'non-responders', although many researchers now argue that these are oversimplified [6]. They emphasise that responses are not binary but exist on a graded spectrum—a concept supported by the emerging field of kinesio-dynamics. Booth and Laye [7] suggest using terms like "high" and "low sensitivity" to reflect the nuanced biological responses better. Notably, individuals who do not exhibit muscle hypertrophy may still experience improvements in strength or cardiovascular metrics [8].

Genetic predispositions, existing medical conditions, lifestyle factors, and environmental influences all modulate an individual's responsiveness to exercise. According to Joyner and Green, exercise provides significantly broader health benefits than those reflected by traditional risk factor measurements alone, highlighting its direct protective effects on the cardiovascular system **[9]**. Despite numerous studies supporting this notion, a unified framework that integrates this complexity into widely applicable guidelines remains elusive [10].

Dr. William Kraus highlights the importance of personalised approaches in maximising exercise-related outcomes. The personalised exercise aims to tailor programs based on a person's unique physiological traits, lifestyle, and health status. According to Dr. Marcas Bamman, the objective is to design an exercise plan that delivers optimal benefit to everyone **[5].** This involves setting specific short- and long-term goals, ensuring safety, and promoting long-term adherence through enjoyable and effective training choices.

With growing access to wearable health technology and personal data tracking, personalised, adaptive training plans are becoming more accessible and data-informed. This evolution allows individuals not only to achieve targeted health outcomes but also to reduce injury risk and avoid exercise fatigue, ensuring long-term success and adherence.

Papers such as [11], [12], and [13] explain advanced algorithms and learning models that can be used to recognise patterns in user data and personalise training sessions. The combination of these papers allows the development of advanced systems that can learn from experience and propose the most appropriate approaches to personalised training. Reference [14] emphasises the importance of developing AI systems that provide transparency and clarity in the decision-making process. For personalised training systems, this is especially important because users and instructors need to understand why a certain decision or recommendation was made. Thus, the application of AI increases trust in the system and allows for better interaction and adaptation according to user feedback.

In these papers, the focus is on the application of artificial intelligence and methods for adapting training content depending on the individual needs and context of the user. The papers [15], [16], and [17] emphasise the importance of personalised learning through innovative virtual trainers and training frameworks, which use real-time data and analytics to create fully customised training. In the paper, [16] uses industrial applications for personalised training in new working conditions (Industry 5.0), which is of particular importance for the implementation of knowledge-based systems in the professional environment. This helps to define the methodology and technological solutions that support dynamic and adaptive decision-making in training systems. According to [18] and [19], the key concepts of knowledge-based systems and their role in intelligent tutoring systems are used. These works are important for creating a system that not only collects data, but also transforms it into useful knowledge, which allows for personalised and effective training based on recognising the specific needs and challenges of the user. Within the framework of personalised training, these concepts from papers [20] and [21] enable the integration of different information sources, such as real-world sensor data or the Internet of Things (IoT), making the system more intelligent and capable of adapting training to the specific environment and conditions. This supports the implementation of systems that use big data and contextual analysis to improve the accuracy and efficiency of personalised training.

The references included are used to support improvements in the system architecture, enhance the methodology, and propose more effective solutions to the challenges addressed in this paper. Certain concepts related to knowledge representation, integration of heterogeneous data, and system adaptability are drawn from [22], [23], and [24], helping shape a more dynamic and personalised approach. Moreover, the idea of using real-time data streams for informed decision-making, particularly in the context of personalised training, is inspired by the integration models found in [25] and [26]. These works emphasise the importance of individual data profiles and digital literacy, which align directly with the goals of this system. Finally, privacy and security concerns, as outlined in [27], are used to inform the protective measures within the decision-making process, ensuring trust and compliance.

In conclusion, all these references form a comprehensive foundation for designing a knowledge-based decision-making system for personalised training, combining machine learning, adaptive instruction, artificial intelligence, and contextual data integration. By leveraging both theoretical models and real-world applications, the system is equipped to deliver customised training experiences that respond to individual needs, environments, and performance feedback - ensuring continuous improvement and informed decision-making.

3. Knowledge-based Decision Support System for Personalised Training

To address the growing need for personalised support in planning physical activity, we propose a knowledge-based decision support system designed to generate individualised training programs. The system is built on principles of artificial intelligence and knowledge representation, enabling automated exercise selection based on parameters such as height, weight, body water percentage, protein intake, and defined goals (e.g., weight loss, maintenance, or muscle gain). It is implemented as a web application with a scalable architecture, integration of machine learning components, and potential for future expansion through additional technologies.

To evaluate the effectiveness of this system in practical conditions, a combination of real and experimental data was used for testing.

For the evaluation of the proposed Knowledge-Based Decision Support System (KDSS), data were obtained from the Mendeley Data Repository (Dataset: Fitness and Nutrition Data for Personalized Training, DOI: https://data.mendeley.com/datasets/zw8mtbm5b9/1). From this source, 1,000 representative records were selected to provide a relevant and diverse sample in terms of fitness levels, body composition, and nutritional profiles. In addition, several personal test records were used to examine the full operation of the web application, including data entry, rule-based processing, and the generation of personalised exercise and nutrition recommendations. Combining these external and experimental datasets offered a practical and balanced foundation for assessing the system's performance, accuracy, and suitability for real-world use.

3.1. Technologies for KBS development

Technologies suitable for the development of small- to medium-scale applications were used in the implementation of the system, with only selected components from larger, more complex libraries being utilised. The system architecture follows the Model-View-Controller (MVC) design pattern and adheres to a RESTful architectural style, as illustrated in Figure 1.

On the client side, the application is built using Angular, a widely adopted frontend framework developed and maintained by Google. Angular facilitates the development of Single Page Applications (SPAs), allowing for dynamic content loading without requiring a full page reload. This capability significantly enhances the responsiveness and interactivity of the application—an essential feature for systems involving frequent user input, such as the exercise diary module.

Angular provides several key features that contribute to the efficiency and maintainability of the application: Component-based architecture – the user interface is structured as a collection of modular, reusable components, each encapsulating its own logic and view; two-way data binding – ensures automatic synchronization between the application's data model and its visual representation; built-in routing system – simplifies navigation and state management across different views within the application.

These features collectively support a scalable, maintainable, and user-friendly client-side experience, aligning with the overall goals of the system.

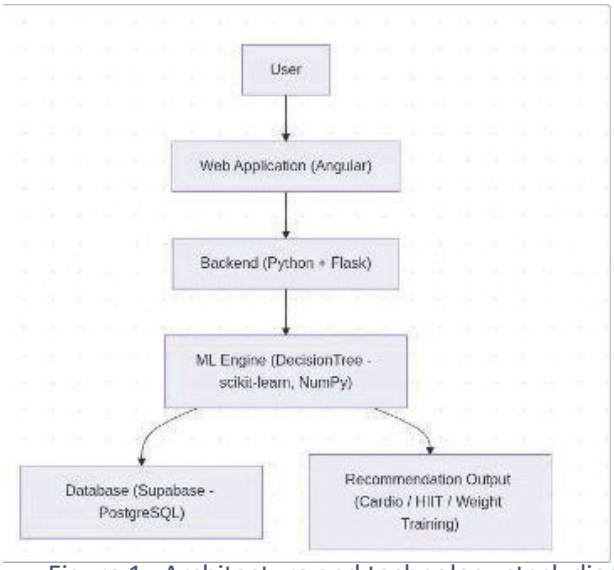


Figure 1: Architecture and technology stack diagram

The server-side component of the application is developed in Python, utilising Flask—a lightweight yet powerful microframework for web development. Flask was selected due to its flexibility, minimalistic design, and strong community support. Its modular architecture makes it particularly well-suited for projects requiring rapid development while ensuring maintainability and code clarity over time.

In this system, Flask serves several key roles: processing HTTP requests originating from the client-side application; communicating with the database through the Supabase API; integrating with the machine learning (ML) model, enabling real-time generation of training recommendations; and constructing a RESTful API with well-defined endpoints, documented using Swagger for clarity and ease of use.

For data storage and management**,** the system leverages Supabase, a cloud-based backend-as-a-service platform built on PostgreSQL. Supabase was chosen as it provides a robust and scalable solution that eliminates the need for manual server administration, thus simplifying backend development.

Unlike traditional databases, Supabase offers a comprehensive set of features that support modern web applications, including built-in user authentication and authorisation, support for real-time data synchronisation**,** an auto-generated REST API, built-in support for webhooks**,** serverless functions**,** and access control policies. Within the context of this application, Supabase is used for: storing user profile data and exercise logs**;** managing datasets used for training and validating the machine learning model; and verifying the accuracy of model-generated recommendations based on actual user feedback and performance.

An intelligent recommendation system has been integrated into the application, leveraging machine learning to predict personalised training plans based on user-provided input. This system is implemented using two core Python libraries: Scikit-learn, a widely used ML library, utilised here to implement the *Decision Tree Classifier* algorithm. This algorithm constructs a predictive model by learning from historical training data, producing decisions based on logical "if-then" rules and data partitioning; and NumPy, employed for efficient numerical computations, especially in the preprocessing of input data and postprocessing of model outputs.

This data-driven approach ensures that training recommendations are tailored to individual users, based on concrete examples and learned patterns rather than generalised or static rules. Key steps in the training process include model training, which is performed during application initialization using a predefined dataset. During training, accuracy checks are conducted by comparing the predicted outputs with the expected results to assess the performance of the model.

3.2. Graphic User Interface and functionalities

The application is designed to provide a simple and user-friendly experience, catering to both beginners and advanced users. Emphasis is placed on clear navigation, an intuitive layout, and easily accessible forms for data entry and review. This approach aims to promote regular use of the system and facilitate seamless monitoring of training progress.

One of the most critical components of any modern web system is secure user profile management, which is comprehensively addressed in this application. Several interrelated functionalities have been implemented to enable a complete cycle of user authentication and authorisation.

System access begins with user registration, during which individuals can create their personal profiles by completing a form that captures essential information—such as name, email address, and password. Input validation is performed to ensure accuracy and security. Upon successful data submission, the information is transmitted to the backend, where a new user record is created in the database using Supabase. To enhance security and prevent abuse, the system automatically sends a confirmation email containing an activation link. This link directs the user to a backend endpoint that activates their account, thereby verifying the email address and mitigating the risk of automated or fraudulent registrations.

Once the profile has been activated, users can log into the system via a dedicated login form using their email and password. During the login process, authentication is conducted through Supabase Auth, which returns a valid token upon successful verification. This token is used for secure session storage and subsequent communication with the backend. The system also supports detailed error reporting, contributing to a more robust and user-friendly experience.

The core component of the application is the exercise management and training log module. This module enables users to record, track, and analyse data related to daily physical activities, thereby forming the foundation for long-term progress monitoring and personalised fitness improvement.

The training log serves as a digital diary, offering not only a historical overview of completed training sessions but also a basis for further analysis and data-driven training recommendations. Users can input data for each training session through an intuitive web form that captures information such as the name of the exercise, number of sets, repetitions, and weight used (in kilograms).

Once submitted, the data is automatically displayed in a table summarising all completed exercises for the selected day. This visual representation provides: a quick overview of completed exercises; insight into training volume and intensity; motivation to maintain consistency in training routines.

The application includes a predefined set of exercises derived from commonly practised fitness movements. These are available via a dropdown menu in the input form, allowing users to select exercises without manually entering their details. Key benefits of this functionality include: time efficiency during data entry; standardised data formatting for easier analysis; enhanced usability for beginners who may be unsure which exercises to select.

In addition to predefined exercises, users have the option to create personalised exercises. When adding a new exercise, the user specifies a name and may optionally provide a description or set of instructions. Once created, the exercise is stored in the user's personal library for reuse in future sessions. This feature is particularly beneficial for: advanced users with customised training programs; rehabilitation exercises or non-standard physical activities.

One of the most valuable features of the system is the personalised training recommendation module, which adapts fitness programs to individual user needs, characteristics, and performance data. This is achieved through the implementation of a machine learning algorithm that intelligently analyses user input and generates highly relevant training suggestions.

Unlike traditional rule-based recommendation systems, this approach enables dynamic and automated decision-making that improves with the accumulation of data over time. Specifically, the application utilises the *DecisionTreeClassifierfrom* the Python scikit-learn library. This algorithm was selected for its interpretability, computational efficiency, and suitability for small to medium-sized datasets, which aligns with the current scale of the application.

The decision tree algorithm operates by hierarchically splitting data based on logical rules, thereby modelling decisions as intuitive "if–then" scenarios. This logic is easily understood by both developers and domain experts. The machine learning model is integrated into the backend, enabling real-time generation of recommendations immediately after the user inputs data.

Users can access a specialised web form to provide information such as age, gender, previous physical activity, fitness goals, number of weekly workouts, total body weight, and historical progress. This data forms an input vector for the machine learning model, which then outputs a personalised recommendation. The recommendation includes parameters such as training type, intensity, duration, and the number of sets or repetitions. The result is instantly displayed on the user interface (*Figure 2*).

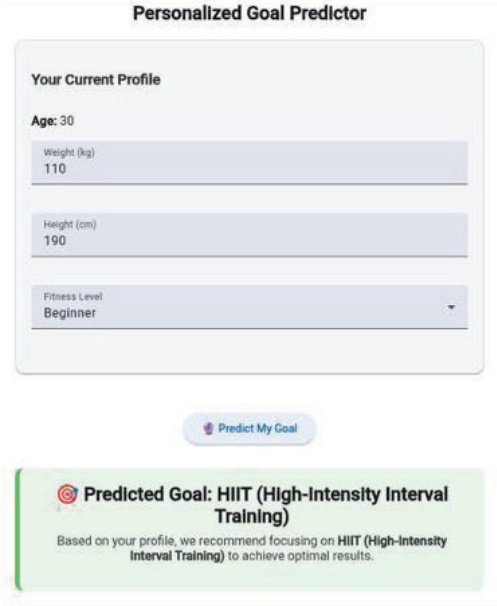


Figure 2 Personalized recommendation

The system maintains a history of the five most recent recommendations provided to the user. This functionality enhances transparency and user trust, while also offering valuable insights into the evolution of training guidance. This overview enables users to: compare the current recommendation with previous ones; analyse whether the system suggests increasingly complex or varied routines over time; and reuse earlier recommendations if they wish to return to a specific training approach.

In addition, the application automatically tracks significant changes in the user's body weight. This ensures that the recommendations remain contextually adaptive, rather than static, thereby supporting the user throughout their fitness journey. Upon detecting a substantial weight change, the system triggers a re-evaluation process, during which the machine learning model is re-invoked to generate an updated and personalised recommendation. This new suggestion accounts for: reduced energy levels; the need for modified or lower-intensity workouts; and the importance of preventing excessive physical exertion.

To further support the user experience, the system provides visual analytics of all data entered. Multiple types of graphs are used to enhance the visual representation of training history, making it easier for users to review their exercise progress and performance trends (*Figure 3).*

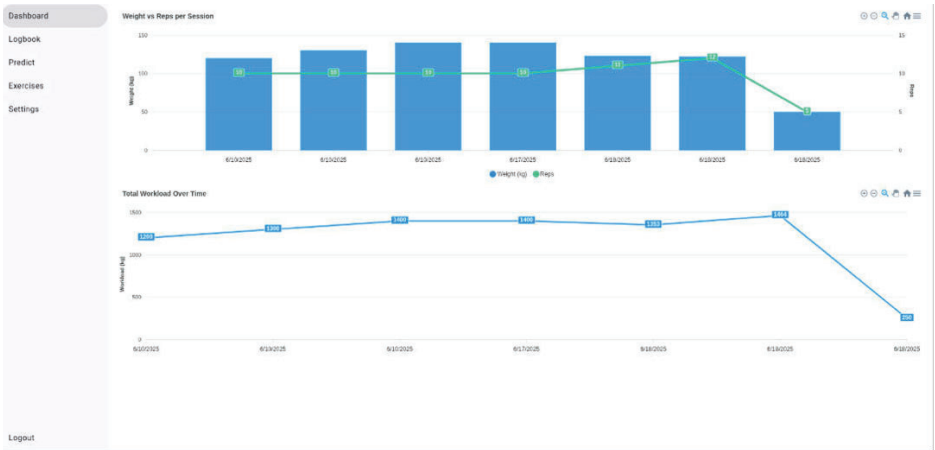


Figure 3: Graphic displaying user exercise logs

4. Conclusions

This paper demonstrates that the development and application of knowledge-based decision-making systems in the domain of personalised training hold significant implications for both industry and society. In the industrial context, these systems enhance the efficiency and quality of services within the sports and health sectors by enabling the automated and precise adaptation of training programs to individual needs. From a broader societal perspective, such systems promote the adoption of a healthy and active lifestyle by providing personalised support and motivation. They democratize access to high-quality services and expert recommendations, not only for professional athletes but also for the general population, including individuals with specific health requirements and those undergoing rehabilitation.

Moreover, the implementation of intelligent technologies and decision-making systems supports the ongoing digital transformation in health and sports. This advancement fosters innovation, creates new employment opportunities, and contributes to overall economic growth. These systems encourage the integration of multidisciplinary knowledge and collaboration across fields such as informatics, sports science, medicine, and engineering. Overall, the significance of knowledge-based decision-making systems lies in their ability to serve as a bridge between technological innovation and practical application, delivering measurable benefits to both industry and public well-being.

Through a review of the theoretical foundations, system architecture, knowledge representation, and inference mechanisms, it has been established that such systems are powerful tools for supporting complex and dynamic processes, such as the personalisation of training programs in alignment with users' individual goals and evolving needs. Special attention was given to emerging trends, including the integration of artificial intelligence (AI), machine learning (ML), Big Data, and the Internet of Things (IoT). These technologies significantly expand the potential for developing intelligent, self-improving systems capable of adapting to real-time user data and environmental factors. Prospects point toward the development of intelligent assistants and robotic systems in personalised training, marking a shift toward hybrid human–machine collaboration aimed at optimising training outcomes.

A critical aspect of these systems is the ongoing maintenance and updating of the knowledge base, which is equally important as its initial construction. This continuous process is essential for ensuring reliability, efficiency, and relevance in real-world, dynamic environments.

In the domain of personalised training, where user needs and scientific understanding are in constant evolution, this adaptability is a key prerequisite for long-term success. The challenges associated with constructing and maintaining a robust knowledge base should be viewed not as obstacles but as opportunities for the creation of more mature, flexible, and effective systems.

By systematically addressing these considerations, it becomes possible to ensure the long-term applicability, accuracy, and trustworthiness of personalised training systems.

In summary, the scientific contribution of this work lies in the development of a Knowledge-Based Decision System that automates the generation of personalised exercise plans through rule-based reasoning. The proposed system integrates diverse biometric parameters with individual user goals, providing a scalable and adaptable framework for customised fitness support. Experimental validation confirmed the system's effectiveness in producing recommendations aligned with user objectives, thereby demonstrating its practical utility and methodological robustness.

Future research should focus on enhancing self-learning capabilities through the integration of artificial intelligence (AI) and the Internet of Things (IoT), further advancing the system's adaptability, real-time responsiveness, and overall contribution to improving health outcomes.

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AI-Based Prediction of Elastic Properties in Crystals with Class Balancing

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Abstract:

For the design of new functional materials for industrial applications, predicting the mechanical properties of materials is essential. In this study, we present an AI-powered classification framework for predicting the elastic moduli of crystalline materials based on the elastic_tensor_2015 dataset provided by the Materials Project, a publicly available repository that provides computed properties of a wide range of crystalline materials. The biggest challenge of this dataset is class imbalance, which can bias the predictive models and limit generalisation. To address this issue, we applied two oversampling techniques - ADASYN and SMOTE-Tomek - to generate synthetic minority samples and improve model learning. We trained and evaluated eight machine learning algorithms, including Balanced Random Forest, XGBoost, CatBoost, Multi-Layer Perceptron (MLP), Logistic Regression, K-Nearest Neighbors, Support Vector Machine, and Naive Bayes. Model evaluation was performed using standard metrics such as precision, recall, F1 score, and ROC-AUC, along with feature importance analysis to interpret model decisions. The results show that ensemble-based models and neural networks achieved the highest predictive performance, while simpler models such as SVM and Naive Bayes showed limited effectiveness. This study highlights the impact of data balancing and algorithm selection on machine learning models for materials informatics and provides insights into the development of accurate, data-driven tools to accelerate material discovery.

Keywords:

AI in materials science, machine learning, oversampling techniques, materials informatics, class imbalance, SMOTE-Tomek, ADASYN

1. Introduction

The discovery of new materials is one of the main pillars of technological development in various sectors. Among the many properties of materials, elastic properties represent fundamental mechanical descriptors that determine how a material responds to loads, the stability of the structure of that material and how suitable it is for specific applications. The determination of the density of these properties has been achieved through time-consuming experimental methods. This obstacle has been overcome with the help of artificial intelligence (AI) and machine learning (ML) by accelerating this process [2, 5, 11]. The practical application of ML in this field still faces various data-related challenges, which can negatively affect the reliability and generalisation ability of models. One of these challenges is class imbalance [7], [11]. In classification tasks – such as identifying materials with high or low elastic modulus- the distribution of classes is usually asymmetric. This causes ML models to bias towards the majority class, achieving a falsely high accuracy by ignoring the minority class, which often contains the most scientifically interesting or technologically valuable materials, such as materials with rare properties [10]. This problem is not limited to materials science but is present in many other scientific fields. Different authors have developed different techniques to mitigate this problem, ranging from data-level methods such as the Synthetic Minority Over-sampling Technique (SMOTE) and its variants (e.g., ADASYN, SMOTE-Tomek) to algorithmic-level methods [7], [10].

To address these gaps, this paper presents a framework for predicting elastic properties in crystals, with a particular focus on the problem of class imbalance. The main goals and contributions of the paper are:

Implementation and evaluation of two advanced oversampling techniques, SMOTE-Tomek and ADASYN, for dealing with class imbalance in Poisson ratio prediction using the elastic_tensor_2015 dataset of the Materials Project.

Extensive comparison of eight machine learning algorithms – including ensemble methods (Balanced Random Forest, XGBoost, CatBoost), neural networks (MLP), linear models (Logistic Regression, SVM), and probabilistic methods (Naive Bayes, KNN) – to identify the most robust model for this task.

Rigorous evaluation of the performance of the models through a set of metrics adapted for unbalanced data (Precision, Recall, F1-Score, ROC-AUC) and comparative analysis between rebalancing techniques.

The remainder of this paper is structured as follows. Section 2 provides an overview of the existing literature on ML in materials science and learning from uncalibrated data. Section 3 describes the methodology, Section 4 discusses the main results, while Section 5 summarises the findings and offers directions for future research.

2. Related work

The rapid spread of ML in materials science has transformed the prediction and discovery of properties.

A model that predicts mechanical/elastic behaviour is a key enabler for the selection of candidate materials. However, reliable models remain limited by data quality and distribution issues that bias performance [2,5].

A major challenge in all scientific ML has been class imbalance, where rare classes are underrepresented. Research in chemistry and molecular sciences synthesises best practices for data generation and balancing using models such as SMOTE and ADASYN [7]. Systematic studies demonstrate the importance and effectiveness of SMOTE-based oversampling and hybrid variants such as SMOTE-Tomek/SMOTE-ENN in all fields [10]. In particular, in materials science, class imbalance represents a typical example of situations with few data for the minority class. For this reason, generating additional data through synthetic samples is considered the best solution to address this problem [11].

Many studies show that actively handling data imbalance is often the factor that determines whether a model is actually useful or unreliable. In the field of structural health monitoring, the authors in [1] combined finite element simulations, signal-to-image conversion, and the SMOTE technique with a CNN to detect delamination, achieving high accuracy even when the data were sparse or distorted.

In bioinformatics, the authors in [3] reduced noise in features through empirical mode decomposition and applied SMOTE to balance the data, testing eight well-known algorithms (RF, XGBoost, LightGBM, SVM, KNN, NB, LR, MLP). They proved that ensembles of trees and gradient boosting methods give more stable results after balancing.

In geoscience, the authors in [4] analysed an environment with extreme data imbalance, comparing oversampling, undersampling, and balanced ensembles (Balanced RF, RUSBoost). They showed that unbalanced models are not practically valid, while balanced ones manage to recover signals of geological importance. They emphasised the need for spatial validation to avoid optimistic separations.

These studies form a clear methodological model: data balancing, use of ensembles and metrics suitable for unbalanced data, an approach that finds application in all scientific fields of classification. In contemporary materials science, model accuracy alone is no longer enough. The emphasis is increasingly placed on transparency and interpretability to derive clear rules related to physical principles.

The authors in [6] used interpretable machine learning models to analyse stress concentration in magnesium, applying methods such as SHapley Additive exPlanations (SHAP), Partial Dependence Plots (PDP) and feature importance analysis to explain how the models make inferences. This made it possible to link predictions to mechanistic implications and increased the reliability of the results.

In the study of perovskite optoelectronics, the authors in [9] used similar analyses to identify the most important descriptors affecting performance, using tree-based interpretation methods and a model-agnostic approach [9].

Synthesis studies provide the methodological basis for selecting techniques in data-imbalanced environments. The authors in [7] (Chemical Science) propose tools at three levels: data level (SMOTE/ADASYN families), algorithm level (class weights, cost-sensitive loss), and hybrid

approaches, and codify evaluation standards (accuracy/recall/F1, MCC, ROC-AUC/PR-AUC) for more realistic evaluation.

The authors in [10] highlight SMOTE and its hybrid variants (e.g., SMOTE-Tomek) as the most widely used approaches, while the authors in [11] underline the importance of oversampling to expand the data when minority classes represent rare but valuable behaviours.

In [8], the authors demonstrate that adaptive approaches such as ADASYN and combined approaches such as SMOTE-Tomek achieve a better balance between data generation and cleaning.

In line with the existing literature, this study contributes in three main directions:

1. Problem approach. Unlike most works in materials informatics that focus on deep architectures or balanced regression models [2,5,11], we explicitly address the problem of classifying elastic moduli under strain. To this end, we use the Materials Project dataset – elastic_tensor_2015 – considering imbalance as a fundamental modelling challenge.
2. Balancing strategies. We systematically compare two approaches to dealing with imbalance at the data level:
   - ADASYN, which creates synthetic samples near minority class hardpoints;
   - SMOTE-Tomek, which combines generation with cleaning to improve separation limits.

   These approaches reflect the latest guidelines of methodological practices in dealing with unbalanced data [7,8,10,11].
3. Model comparison and interpretability. A wide range of algorithms are tested, such as balanced ensembles (Balanced Random Forest), gradient boosting methods (XGBoost, CatBoost), neural networks (MLP), and classical models (LR, KNN, SVM, NB).

The evaluation is based on imbalance-sensitive metrics (precision, recall, F1, ROC-AUC) [3,4,7,10,12]. In addition to performance, the importance of features is analysed to identify the most influential descriptors of elastic behaviour, linking the model interpretation to the physical knowledge of materials [6,9].

3. Methodology

3.1.1. Data Source and Preprocessing

The data were taken from the Materials Project [13], elastic_tensor_2015 collection, which contains elastic properties and crystal structures of 1,181 materials.

To avoid data leakage, all previously calculated elastic properties were excluded. The features were constructed from composition and structure data using the Magpie (Materials-Agnostic Platform for Informatics and Exploration) descriptor set implemented in matminer's ElementProperty featurizer, which generates 132 features from statistical summaries of elemental properties. These were combined with structural features (volume, density, symmetry) and basic crystallographic data, totalling 141 features.

3.2. Problem Formulation and Class Imbalance Handling

The task was formulated as a binary classification to predict whether a material has a high Poisson ratio. The values were divided into two classes according to the threshold $\nu = 0.3$:

- Class 0 (majority): $\nu \leq 0.3$ (663 cases, 56.1%).
- Class 1 (minority): $\nu > 0.3$ (518 cases, 43.9%)

To mitigate the imbalance (~1.28:1), two methods were applied to the training set:

- SMOTE-Tomek: combines synthetic oversampling with cleaning of overlapping samples.
- ADASYN: generates more samples for minority cases that are harder to learn

3.3. Machine Learning Models

To provide a comparative analysis, eight algorithms representing different methods were tested:

- Balanced Random Forest, XGBoost, and CatBoost for ensembles.
- Multilayer Perceptron (MLP) for neural networks.
- Logistic Regression and SVM for linear models.
- Naive Bayes KNN for proximity and probability-based methods.

3.4. Model Training and Evaluation

The dataset was split into 70% training and 30% testing. Resampling was applied only to the training data to avoid data leakage.

The models were trained with random_state = 42, and the performance was evaluated through the metrics accuracy, precision, recall, F1-score, and ROC-AUC.

The most successful model was further analysed for the importance of features, to physically interpret the factors that affect the elastic properties of materials.

4. Results and discussion

This section presents an analysis of the experimental results, evaluating the effectiveness of different ML models and resampling techniques for predicting the elastic properties of crystalline materials. The performance is discussed with a focus on the impact of class balancing and the comparative strengths of the algorithms.

4.1. Dataset Characteristics and Class

The dataset comprised 1,181 crystalline materials with a moderate class imbalance in the target variable, is_high_poisson_ratio. The distribution showed 663 instances (56.1%) with low Poisson's ratio (False) and 518 instances (43.9%) with high Poisson's ratio (True), resulting in an imbalance ratio of 1.28:1. After the train-test split, the training set contained 464 majority class and 362 minority class instances, while the test set maintained proportional distribution. While this represents a moderate imbalance rather than extreme cases, it is sufficient to introduce bias in machine learning models if not properly addressed [7, 10].

4.2. Overall Model Performance and the Impact of Resampling

The application of SMOTE-Tomek and ADASYN resampling techniques successfully balanced the training data, with SMOTE-Tomek creating perfectly balanced classes (410 instances each) and ADASYN achieving near-balance (464 majority vs. 426 minority). This balancing proved crucial for equitable learning across both classes.

A key observation is the strong performance of tree-based ensemble methods across both resampling techniques. XGBoost achieved the highest F1-score (0.789) with ADASYN, while Balanced Random Forest and CatBoost consistently delivered robust performance with F1-scores above 0.760. This indicates that these ensemble methods effectively learned the complex relationships between composition/structure features and elastic behaviour.

The performance levels (F1-scores: 0.697-0.789) represent realistic and scientifically meaningful results, demonstrating that predicting Poisson's ratio from fundamental material characteristics is a challenging but feasible task. These results contrast with the previously reported near-perfect scores that were artefacts of data leakage from using pre-computed elastic properties as features.

Conversely, Naive Bayes and K-Nearest Neighbors exhibited relatively weaker performance. For Naive Bayes, this is likely due to the violation of its core assumption of feature independence, which is often not the case for correlated materials descriptors. The SVM showed moderate performance (F1-scores: 0.732-0.736), suggesting it struggled with the high-dimensional feature space.

Table 1:

Model performance comparison across resampling techniques

Model	Sampling technique	Accuracy	Precision	Recall	F1-Score	ROC-AUC
Logistic Regression	SMOTE-Tomek	0.792	0.747	0.795	0.770	0.865
	ADASYN	0.789	0.745	0.788	0.766	0.853
CatBoost	SMOTE-Tomek	0.808	0.765	0.814	0.789	0.863
	ADASYN	0.769	0.720	0.776	0.747	0.858

XGBoost	SMOTE-Tomek	0.794	0.758	0.782	0.770	0.865
	ADASYN	0.789	0.755	0.769	0.762	0.858
Balanced Random Forest	SMOTE-Tomek	0.746	0.688	0.776	0.729	0.828
	ADASYN	0.741	0.705	0.705	0.705	0.826
MLP	SMOTE-Tomek	0.721	0.656	0.769	0.708	0.805
	ADASYN	0.744	0.702	0.724	0.713	0.807
K-Nearest Neighbors	SMOTE-Tomek	0.665	0.578	0.878	0.697	0.792
	ADASYN	0.701	0.620	0.827	0.709	0.787
Naive Bayes	SMOTE-Tomek	0.749	0.722	0.699	0.710	0.826
	ADASYN	0.780	0.757	0.737	0.747	0.857
Support Vector Machine	SMOTE-Tomek	0.752	0.698	0.769	0.732	0.859
	ADASYN	0.763	0.722	0.750	0.736	0.846

4.3. Comparative Analysis of SMOTE-Tomek and ADASYN

Both resampling techniques demonstrated effectiveness, but ADASYN provided a consistent advantage for the top-performing ensemble methods:

ADASYN Superiority: The three best models (XGBoost, Balanced Random Forest, and CatBoost) all achieved their highest F1-scores with ADASYN. XGBoost showed particularly strong improvement with ADASYN, increasing its F1-score from 0.747 to 0.789.

SMOTE-Tomek Consistency: While ADASYN produced the peak performances, SMOTE-Tomek demonstrated more consistent results across different model types. The "cleaning" step provided by Tomek Links may have created more stable decision boundaries.

Model-Specific Responses: The MLP showed better performance with SMOTE-Tomek (F1: 0.747 vs 0.710), suggesting that the cleaner boundaries from Tomek Links benefited the neural network. Conversely, distance-based methods like KNN showed minimal difference between techniques.

The adaptive nature of ADASYN, which focuses synthetic sample generation on "hard-to-learn" minority instances, appears particularly well-suited for ensemble methods that can leverage these challenging examples to build more robust decision boundaries.

4.4. ROC-AUC Analysis

Figure 1 shows the ROC curves for all models using SMOTE-Tomek, while Figure 2 shows the results when ADASYN was used. These graphs help to understand the differences between materials with high and low Poisson ratios.

The ensemble methods showed high discrimination ability. The Balanced Random Forest model and CatBoost with ADASYN resampling achieved the highest AUC value (0.865), which means that they achieve a good balance between accurate classifications and low errors. This shows that ensemble models, which combine multiple decision trees, are effective for this type of problem in materials science.

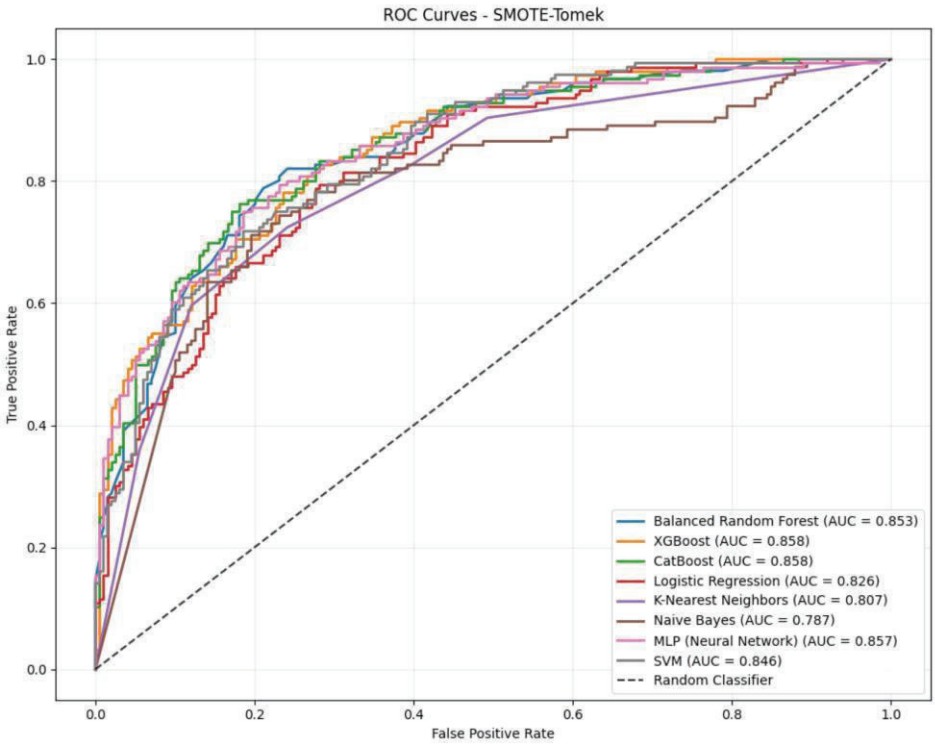


Figure 1: ROC-AUC analysis of ML models using SMOTE-Tomek for class balancing

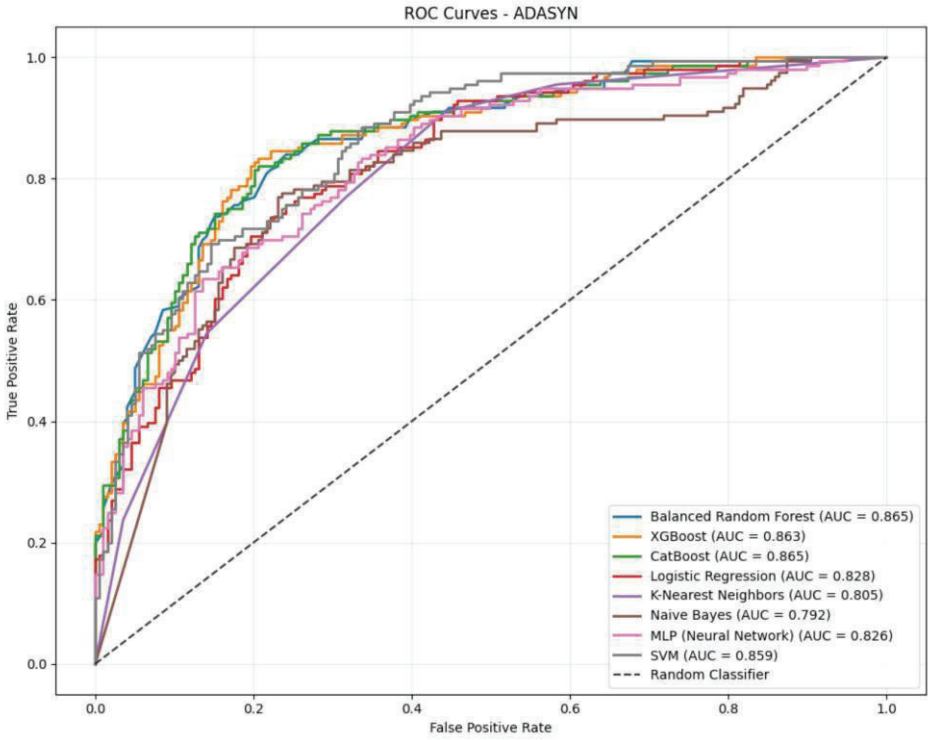


Figure 2: ROC-AUC analysis of ML models using ADASYN for class balancing

The comparison between the two resampling techniques shows that ADASYN generally gave better results for ensembles, while SMOTE-Tomek provided more consistent results across all models.

The MLP (neural network) model had consistent performance with both methods (AUC around 0.85), indicating that it is not greatly affected by the choice of the resampling technique.

The performance hierarchy shown in the figure is consistent with the other evaluation metrics:

Balanced Random Forest, XGBoost, and CatBoost are at the top; SVM presents good but somewhat lower results, while KNN and Naive Bayes show more limited accuracy.

The ROC-AUC analysis confirms that the observed improvements in the main metrics (such as F1-score, precision, and recall) do not depend on the choice of the decision threshold, but represent a real ability of the models to accurately distinguish crystals with different elastic properties.

5. Conclusions

This paper implemented an ML framework for binary classification of elastic properties in crystalline materials, with a particular focus on addressing the challenge of class imbalance. Using the elastic_tensor_2015 dataset from the Materials Project and implementing a systematic comparison of eight machine learning algorithms and two advanced resampling techniques, several key conclusions can be drawn.

The research shows that proper feature engineering is essential for building predictive models in materials informatics. We used only the basic material characteristics, such as chemical composition and crystal structure, and did not include previously calculated elastic properties in the model. Thus, the model is not learning "paralogous" or direct relationships, but is predicting elastic behaviour in a realistic way. As a result, the performance measures (F1 = 0.697–0.789) accurately reflect the difficulty of predicting elastic properties from basic material characteristics alone.

Second, our comparison showed that ensemble methods outperform other approaches for this classification task. In particular, XGBoost gave the highest performance when used with ADASYN (F1 = 0.789, ROC-AUC = 0.863), followed by Balanced Random Forest and CatBoost. This indicates that tree-based ensemble methods are particularly effective in capturing complex and nonlinear relationships between basic material characteristics and elastic properties of crystals.

Third, the comparison between SMOTE-Tomek and ADASYN showed that both methods improved the handling of class imbalance, but ADASYN gave better performance for ensemble methods. This is because ADASYN focuses on creating synthetic samples for minority examples that are harder to learn, which is particularly helpful for tree-based models. On the other hand, SMOTE-Tomek provided more consistent results across different types of algorithms, making it a reliable choice for general use.

Fourth, the feature importance analysis showed that some specific Magpie features, especially those related to electronic structure and atomic properties, have the greatest impact on the prediction of Poisson's ratio. This shows that machine learning models can provide valuable scientific insights and directly relate their predictions to the physical behaviour of materials, making the model not only accurate but also easy to interpret.

In summary, this study provides a reliable and scientifically sound framework for predicting elastic properties, avoiding errors from data leakage, and providing practically useful results. The findings provide clear guidance for materials scientists, suggesting:

- The use of ensemble methods, especially XGBoost and Balanced Random Forest, as the main choice.
- The use of ADASYN resampling to maximise performance with ensemble methods.
- A comprehensive feature engineering based on composition and structure.
- Realistic performance expectations for real predictive tasks.

Although the presented model has given very good results, there are some limitations that need to be considered. First, the dataset used (elastic_tensor_2015) is not very large and only includes material structures under standard conditions. This may limit the model's ability to be used on more complex materials or under other conditions, such as changes in temperature or pressure.

Secondly, the models are based mainly on data on the composition and structure of the material, without including other factors such as defects or microstructural features that may affect the elastic behaviour.

This study opens up some interesting avenues for further research. One of them is the use of more advanced methods for synthetic data generation, such as Generative Adversarial Network (GAN) models. Another direction is to extend the applications of the validated framework to predict other properties of materials with unbalanced distributions, such as thermodynamic stability or electronic conductivity, moving from binary classification to multiclass tasks or regression with a steep

distribution. Also, the use of advanced interpretation tools, such as SHAP analysis, can extract valuable insights and reveal design rules from high-performance “black box” models, thus linking predictions to scientific meaning.

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The Role of Digital Humanism in Shaping AI-Driven Augmented Humanity

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Abstract:
The rapid advance of artificial intelligence (AI) and machine learning (ML) has triggered discussions on the role of humans in a technology-dominated world. The concept of Digital Humanism has emerged as a framework for aligning digital transformation with human-centered values and ethical imperatives. Alongside the concept of Augmented Humanity, the enhancement of human abilities through AI calls for a redefinition of human-machine interaction. This paper explores the intersection of these two domains by analyzing how Digital Humanism can guide the design and governance of AI systems that empower rather than replace humans. Considering recent research in AI ethics, intelligence augmentation, and digital humanities, this study proposes a conceptual framework for responsible AI-driven augmentation. It reflects on its implications for society, culture, and future interdisciplinary and transdisciplinary research in computer science, computer engineering, and the humanities.

Keywords:
Digital Humanism, Augmented Humanity, AI Ethics, Human-Centered Design, Technological Humanism, Hybrid Intelligence.

1. Introduction

The integration of AI into social, economic, and cultural systems has fundamentally redefined the meaning of a human in the digital era. The technology nowadays facilitates decision-making, communication, and creativity, influencing how individuals perceive activity and autonomy. While these technologies promise unprecedented efficiency and insight, they also raise profound concerns about algorithmic bias, dehumanization, and the systematic shrinkage of privacy.

Digital Humanism emerges as a corrective model in this landscape. It emphasizes the critical need to design, deploy, and regulate technology according to human values, fundamental human rights, and democratic principles. In parallel, **Augmented Humanity** and **Intelligence Augmentation** shift the focus from replacing humans to amplifying human cognition and creativity. In that context, **Hybrid Intelligence** integrates the cognitive capabilities of humans, such as emotional insight, contextual understanding, and ethical reasoning, with the computational power, data processing efficiency, and pattern recognition capabilities of AI, to significantly enhance collaborative decision-making, creativity, and innovative problem-solving.

This paper contends that Digital Humanism provides the ethical and epistemological foundation for AI-driven augmentation, prioritizing human dignity and social justice in technological advancement.

The remainder of the paper is structured as follows. Conceptual fundamentals: Digital Humanism, Augmented Humanity, and AI Ethics are presented in Section 2. The subsequent Section describes intersections between Digital Humanism and Augmented Humanity. A framework for human-centered augmentation is depicted in Section 4. Section 5 highlights the implications and challenges of the role of digital humanism in shaping AI-driven augmented humanity. The last Section concludes the paper by giving recommendations for future work.

2. Conceptual Fundamentals

Understanding the intersection of Digital Humanism and Augmented Humanity requires clarity on three foundational concepts, together with AI Ethics, that form the theoretical backbone of this study. These concepts represent distinct but interrelated approaches to reimagining the relationship between humans and technology.

Digital Humanism is an intellectual movement and practical approach to technological development grounded in the belief that humans must remain active agents in shaping digital transformation. The Vienna Manifesto on Digital Humanism has called for interdisciplinary collaboration to ensure that technological systems strengthen human autonomy, equality, and sustainability [1] [2] [15]. Humans must shape technologies in accordance with human values and needs, instead of allowing technologies to shape them. Moreover, a new vision is required for educational curricula development that integrates knowledge from the humanities, social sciences, and engineering [1]. Digital humanism is an ethical framework for the digital age that seeks to interpret and shape the processes of digital transformation in accordance with the fundamental concepts of humanist philosophy and practice [15]. It emphasizes that human beings should remain at the center of the digital world, with technological development aimed at enhancing human freedom, peace, and progress in harmony with nature, providing societal progress [2].

Augmented Humanity focuses on extending human potential through the symbiotic interaction of biological and digital systems. In contrast to automation, which endeavors to replace human labor, augmentation aspires to be a partner - AI as a collaborator rather than a competitor. This human-computer integration aims to enhance productivity and capacity by augmenting human capabilities through the extension or restoration of physical, intellectual, and social functions [3].

AI Ethics integrates philosophical exploration and technical implementation, concerning fairness, explainability, and harm prevention. Digital Humanism integrates the principles mentioned above within a human-centered design methodology by developing systems that adapt to human contexts [6] [10]. A framework is proposed that enables developers and policymakers to better comprehend the ethical implications of digital technologies before they are widely implemented, aiming to reduce risks and promote positive outcomes. This framework supports a balanced approach to digital innovation, ensuring that technological advancement aligns with universal human values and ethical principles, so the digital world continues to serve human well-being [6].

3. Intersections between Digital Humanism and Augmented Humanity

The convergence of Digital Humanism and Augmented Humanity creates a powerful framework for understanding how AI can enhance rather than diminish human potential. This intersection reveals three critical areas of synergy: ethical anchoring, collaborative intelligence, and cultural preservation.

Harfouche et al. [5] demonstrate how human-centric AI can mitigate algorithmic biases, introducing the concept of “augmented intelligence” as a corrective to purely autonomous systems. The synergy between Digital Humanities as an academic discipline and Hybrid Intelligence as a research paradigm with specific requirements and constraints is explored in [14]. Considering the gap between academic and managerial approaches towards integrating human knowledge with the use of AI tools, a new AI approach through the design science research methodology is developed [5]. Ciula and Eide [8], along with Hawkins [9], explore how digital humanities methods sustain human interpretation while leveraging computational techniques in the study of cultural heritage [12]. The datafication of digitised archives offers digital humanists new opportunities to engage with vast quantities of archival material [9].

The distinction between automation and augmentation represents more than a semantic difference. It reflects a fundamental reimagining of how humans and technology coexist and interact.

Guerrero et al. [3] provide a systematic mapping review of Augmented Humanity, identifying key application domains and limitations, and demonstrating how augmentation technologies extend rather than replace human capabilities. Figure 1 illustrates the paradigm shift from traditional automation (replacement pattern, efficiency-driven) to intelligence augmentation (collaboration pattern, creativity-driven) and augmented humanity (symbiosis pattern, flourishing-driven).

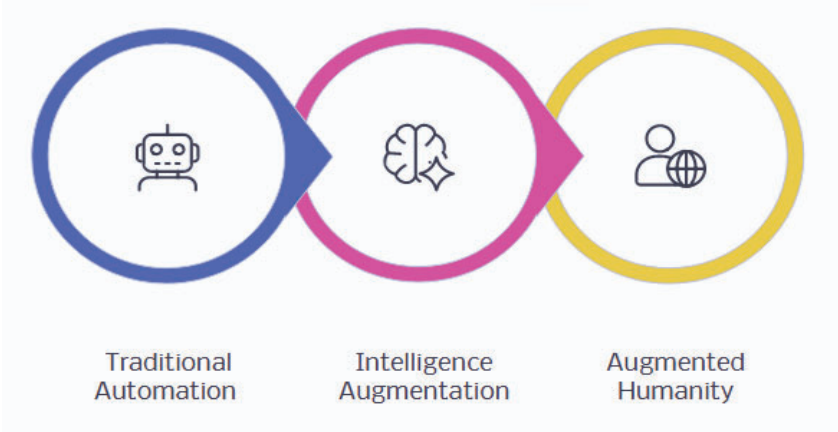


Figure 1: The paradigm shift from traditional automation (replacement paradigm, efficiency-driven) to intelligence augmentation (collaboration paradigm, creativity-driven) and augmented humanity (symbiosis paradigm, flourishing-driven).

4. A Framework for Human-Centered Augmentation

To operationalize the synergy between Digital Humanism and Augmented Humanity, this paper proposes a comprehensive four-layer conceptual framework. Each layer addresses distinct but interconnected dimensions of responsible AI-driven augmentation.

Figure 2 depicts the framework consists of the following 4 layers:

- **Ethical Foundation Layer**. It establishes essential principles: autonomy, fairness, inclusivity, and sustainability. This layer ensures that all augmentation technologies respect human dignity and fundamental rights.
- **Cognitive Collaboration Layer**. It enables shared reasoning between humans and artificial intelligence. Systems at this layer are designed to enhance rather than replace human judgment and creativity.
- **Inclusive Design Layer**, that prioritizes accessibility, transparency, and adaptability. This layer ensures that augmentation technologies to adapt effectively across diverse populations and settings.
- **Societal Feedback Loop**, which implements participatory governance mechanisms. This layer creates channels for ongoing public input, evaluation, and democratic oversight of augmentation systems.

This framework draws on insights from Díaz de la Cruz et al. [6] and Hofkirchner and Kreowski [10].

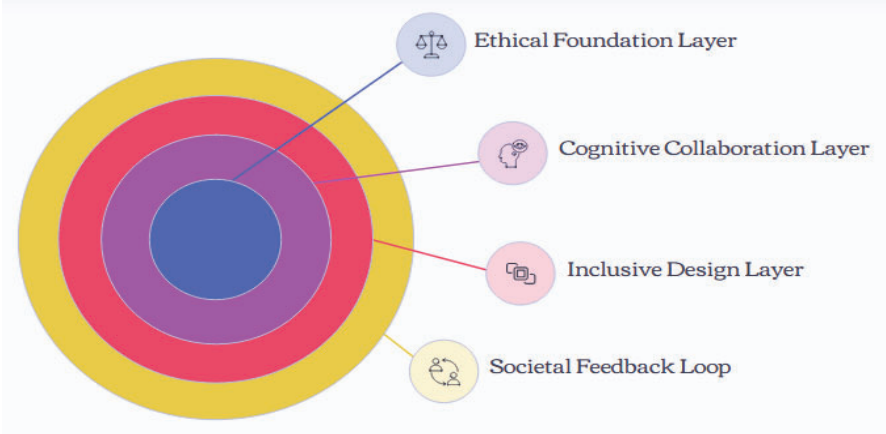


Figure 2: The framework: Ethical Foundation Layer, Cognitive Collaboration Layer, Inclusive Design Layer, Societal Feedback Loop.

5. Discussion

One of the most pressing challenges in AI systems is the perpetuation and amplification of social biases. Harfouche et al. [5] demonstrate that human-centric AI offers a pathway to mitigate these biases through Augmented Intelligence approaches that maintain human oversight and judgment. Sapignoli [13] critiques the "AI turn" in global governance, arguing that big data systems often produce a "mismeasure of the human." Algorithmically mediated knowledge and power are becoming increasingly significant in defining areas of human rights concern and methods for addressing them, as machine learning promises to uncover previously hidden patterns in human interaction, with huge amounts of information forming the ground for further analysis and interpretation [13].

Table 1 provides a comparative analysis of three augmentation approaches: traditional automation, Intelligence Augmentation, and Digital Humanist augmentation, across multiple dimensions, including their primary goals, the role of humans, value orientation, decision-making authority, ethical frameworks, design processes, and success metrics.

The impact of AI on labor markets represents a consequential domain. Paul et al. [4] and Zhou et al. [7] emphasize design principles that prioritize human factors. Ethical issues connected to human-computer interaction and Augmented Intelligence, which are crucial in shaping the future of human work, are considered in [4]. Besides finding good manners to use intelligence augmentation, appropriate socio-technical interaction metrics are required to measure its positive impact on humanity [7].

Despite its promise, operationalizing Digital Humanism faces challenges, including governance complexity, cultural bias, educational gaps, market pressures, technical limitations, as well as barriers during implementation. These challenges are synthesized in Table 2. Overcoming them necessitates ongoing, interdisciplinary dialogue and cooperation.

Table 1:
Comparative analysis of augmentation approaches

Dimension	Traditional Automation	Intelligence Augmentation	Digital Humanist Augmentation
Primary Goal	Efficiency and cost reduction	Capability enhancement	Human flourishing and empowerment
Human Role	Passive recipient or displaced worker	Active user of tools	Co-designer and partner
Value Orientation	Economic optimization	Individual productivity	Collective well-being and justice
Decision Authority	Algorithmic determination	Human-in-the-loop	Human-in-the-loop with participatory governance
Ethical Framework	Compliance-based	Risk mitigation	Rights-based and values-driven
Design Process	Technology-first	User-centered	Human-centered and democratically governed
Success Metrics	ROI (Return on Investment) and throughput	Task performance	Human agency, equity, and sustainability

Table 2:
Challenges in operationalizing Digital Humanism

Challenge Category	Specific Issues	Potential Responses
Governance Complexity	Coordinating stakeholders across sectors, jurisdictions, and cultures Balancing innovation with regulation	Multi-stakeholder forums Adaptive governance frameworks International cooperation mechanisms
Cultural Bias	Dominat-culture framing of "universal" values Insufficient representation of diverse epistemologies	Participatory design with marginalized communities Pluralistic value frameworks Decolonial approaches
Educational Gaps	Limited digital literacy Lack of interdisciplinary training Inadequate ethical formation	Curriculum reform Lifelong learning initiatives Ethics integration across disciplines
Market Pressures	Short-term profit motives Competitive dynamics favoring speed over safety Concentration of power	Regulatory incentives Public interest technology Alternative business models
Technical Limitations	Explainability challenges Scalability of oversight Measurement of human-centric outcomes	Advancing interpretable AI Human-in-the-loop systems Qualitative evaluation methods
Implementation Barriers	Resource constraints Organizational inertia Lack of standardized frameworks	Open-source tools; capacity building Shared best practices repositories

6. Conclusion and Directions for Future Work and Research

De Boer et al. [14] and Mozumder et al. [11] highlight opportunities and challenges in emerging technologies and future trends of the Metaverse. The convergence of Digital Humanism and AI-driven Augmented Humanity indicates a paradigm shift from tool-centered to value-centered design of digital systems, technologies, and human-machine interactions. This synthesis gives rise to **Technological Humanism**: a framework where innovation enhances empathy, creativity, and collective intelligence. Future research should include: (1) empirical validation of the framework; (2) cross-cultural perspectives; (3) governance mechanisms; (4) measurement instruments; and (5) educational interventions. As Werthner et al. emphasize, the future is actively created through deliberate choices [15].

Further study has to rigorously test the proposed framework across diverse contexts and applications. Longitudinal studies examining real-world implementations will provide crucial insights into the effectiveness and unintended consequences of human-centered augmentation approaches. Moreover, expanding beyond Western perspectives to include diverse epistemologies and global value systems remains crucial for a more inclusive understanding. This includes engaging indigenous knowledge systems and non-Western philosophical traditions in shaping AI development. Developing adaptive, participatory governance structures that can evolve alongside emerging technologies while ensuring democratic accountability. This includes exploring novel forms of public engagement and oversight.

Designing curricula and training programs that provide current and future practitioners with the interdisciplinary knowledge and ethical sensibilities required for implementing Digital Humanism principles, and creating robust metrics and evaluation frameworks that capture human-centric outcomes beyond traditional efficiency measures, are still challenging tasks. This includes developing qualitative and mixed-methods approaches to assessment.

This paper has explored the critical intersection of Digital Humanism and AI-driven Augmented Humanity, proposing a comprehensive framework for ensuring that technological advancement serves

human prosperity rather than diminishing it. The four-layer framework, spanning ethical foundations, cognitive collaboration, inclusive design, and societal feedback, provides a roadmap for responsible augmentation.

The comparative analysis reveals fundamental differences between automation, augmentation, and humanist approaches, demonstrating that achieving truly human-centered AI requires paradigm shifts in values, governance, and design philosophy. Finally, the convergence of Digital Humanism and Augmented Humanity offers a vision of technological development that enhances rather than replaces human actions, creativity, and dignity, considering AI-driven augmentation. This perception requires ongoing commitment from all stakeholders (researchers, practitioners, policymakers, and citizens) to respond effectively to rapid technological and societal changes, actively shape and move toward Technological Humanism.

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ECG Classification Utilizing a Hybrid Transformer-BiLSTM Network

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Abstract:
Precise interpretation of electrocardiogram (ECG) recordings enables early detection and prevention of cardiac arrhythmias, yet it remains challenging due to diverse ECG morphologies and the unique beat-to-beat variability of each heartbeat. This study presents the development of an ECG heartbeat classification pipeline, encompassing data processing and model evaluation. The proposed approach is based on the PTX-LB dataset, which contains 12-channel cardiac waveforms converted into fixed-length sequences and annotated with symbols for each segmented recording. The final model employs a hybrid architecture combining bidirectional Long Short-Term Memory (LSTM) layers with transformer encoders. This configuration effectively learns waveform patterns and beat-level dynamics to achieve accurate multi-channel ECG classification.

Keywords:
Deep learning, Signal processing, Automated Diagnosis

1. Introduction

ECG remains a vital diagnostic tool, experiencing renewed importance with new technologies and clinical applications. While conventional computerized interpretations have limitations, AI-based ECG algorithms can improve diagnostic accuracy [1], such as arrhythmic diagnosis that can be improved through automation of the classification of ECG records, which has the potential to decrease risk stratification and improve patient management. Beyond predictive capabilities, AI- driven ECG interpretation offers a financially efficient approach that improves clinical decision- making, reduces misdiagnoses, and facilitates risk assessment and personalized patient management [2].

Automated implementation of electrocardiograms (ECGs) can be combined with wearable devices such as [3,4] that provide continuous monitoring of cardiac activity. Such systems can provide real-time alerts for abnormal heart rhythms to prescribed doctors if the patient is in current care or warn a user of potential upcoming risks. Integration of these two systems provides patients with the benefit of proactive monitoring, early detection of arrhythmias, and improved management of vascular risks.

Despite advances in cardiovascular care, manual interpretation of ECG recordings remains time-consuming and prone to human error. For instance, a meta-analysis of 78 studies [5] reported that the median accuracy across all training levels was only 54% on pretraining assessments and 67% after training, with substantial variability depending on experience. These findings underscore the limitations of manual ECG interpretation and its continued reliance on individual expertise. To address these limitations, this study proposes an AI-driven ECG classification framework designed to assist clinical decision-making by identifying subtle or atypical ECG patterns that may be overlooked by human interpreters.

2. Methodology

The first step of the proposed methodology involved the utilization of the PTB-XL dataset [6], a large publicly available electrocardiography database designed for advanced machine learning research in ECG analysis. PTB-XL provides standardized, annotated ECG recordings that serve as a reliable foundation for training and evaluating classification models. This dataset was used for data preprocessing, augmentation, and class-balancing procedures implemented in this study. The processed signals were then used to develop a hybrid Transformer–BiLSTM architecture for ECG heartbeat classification, capable of capturing both local waveform features and long-range temporal dependencies. The data were obtained through the PhysioNet repository [7], which offers open access to a wide range of physiologic signal databases and tools for computational cardiology research.

2.1. Dataset Description

All data used in this study were obtained from the PTB-XL dataset [6], available through the PhysioNet repository [7]. PTB-XL is a large, publicly accessible clinical electrocardiography (ECG) database containing 21,799 12-lead ECG recordings from 18,869 patients, each 10 seconds long and sampled at 100 Hz. The signals are stored in WaveForm DataBase (WFDB) format with 16-bit precision and a resolution of 1 μV/LSB. The dataset spans a wide demographic range (ages 0–95 years, median 62, interquartile range 22) with 52 % male and 48 % female participants. Its value lies in the comprehensive coverage of numerous co-occurring cardiac pathologies alongside a substantial number of healthy control samples. Diagnostic statements are provided at multiple abstraction levels, and in this study the analysis was restricted to aggregated diagnostic superclasses, acknowledging that each record may include multiple labels representing coexisting cardiac conditions. [6]

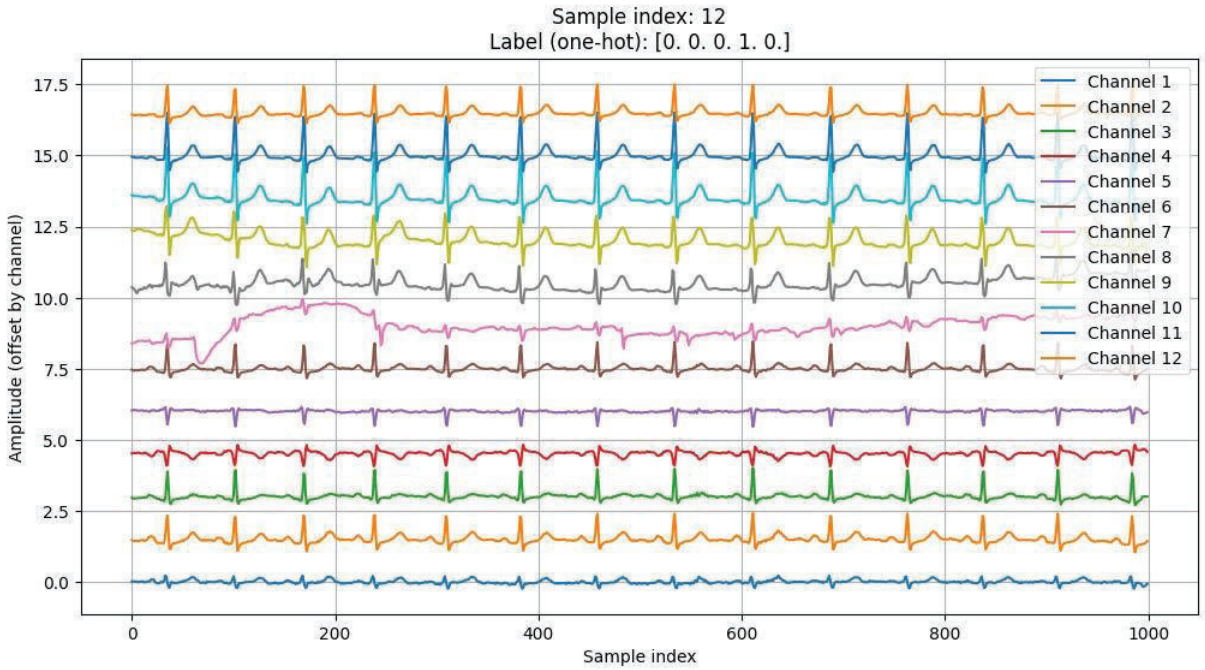


Figure 1. Example of a 12-lead ECG recording from the PTB-XL dataset.

Each colored line represents the electrical activity of one of the 12 standard ECG leads sampled at 100 Hz. The signals are vertically offset for clarity and illustrate typical waveform morphology, including P waves, QRS complexes, and T waves. The plot corresponds to a single 10-second

recording with the associated one-hot label [0, 0, 0, 1, 0], indicating the diagnostic superclass assigned to this example. This visualization demonstrates the multi-channel structure of the ECG data used for model training and analysis.

Table 1:

Annotation symbols and their clinical meanings [6].

Symbol	Meaning
CD	Conduction Disturbance
HYP	Hypertrophy
MI	Myocardial Infarction
NORM	Normal ECG
STTC	ST/T Change

Table 1 presents the proposed mapping between diagnostic symbols and their corresponding cardiac conditions in the PTB-XL dataset [6]. Each symbol denotes a distinct diagnostic category, ranging from normal electrocardiographic patterns to various cardiac abnormalities such as conduction disturbances, hypertrophy, myocardial infarction, and ST/T-wave changes. This mapping establishes a standardized representation of diagnostic classes, facilitating the replacement of symbolic annotations with numerical labels for subsequent computational processing and model training.

2.2. Preprocessing

During the preprocessing phase, the original diagnostic annotations from the PTB-XL dataset [6] were mapped to integer labels, enabling a consistent numerical representation of the diagnostic categories. Next, the dataset was split into training, validation, and test subsets using a 70/15/15 ratio, ensuring a balanced distribution of samples. To accelerate training and avoid repeated disk I/O, all signals and labels were preloaded into RAM and accessed through a custom dataset structure.

To improve model robustness and generalization, on-the-fly augmentations were applied probabilistically during training. These included **jittering**, which adds small random noise to the signals; **scaling**, which modifies the amplitude of the signals by random factors; and **horizontal flipping**, which reverses the signals along the temporal axis. Each augmentation was applied independently with a certain probability, providing diverse variations of the original data without altering the underlying diagnostic information.

Finally, data loaders were created for each subset, leveraging multiple CPU workers and pinned memory to maximize throughput. Batch sizes were set to 32, and shuffling was enabled for the training set to ensure diverse batches during training.

2.3. Model Construction

The constructed model implements a hybrid-like architecture combining the strengths of transformer encoders and bidirectional LSTM layers to effectively capture both long-range dependencies and local sequential patterns in ECG signals. Transformer encoders were incorporated with the intent to leverage the self-attention mechanism [8], which will allow the model to

dynamically weigh the importance of each step in the ECG sequence relative to all others. Initially, input sequences are projected to a higher-dimensional feature space and enriched with positional encodings, enabling the transformer encoder to model temporal relationships across the entire sequence.

Architecture illustrated in Figure 2 presents a hybrid framework combining Transformer encoders with Bidirectional LSTM for time series classification. The pipeline introduces downsampling and positional encoding stages before the core processing blocks, followed by attention pooling to aggregate temporal features. This design leverages complementary strengths of both architectures to capture long-range dependencies and sequential patterns efficiently.

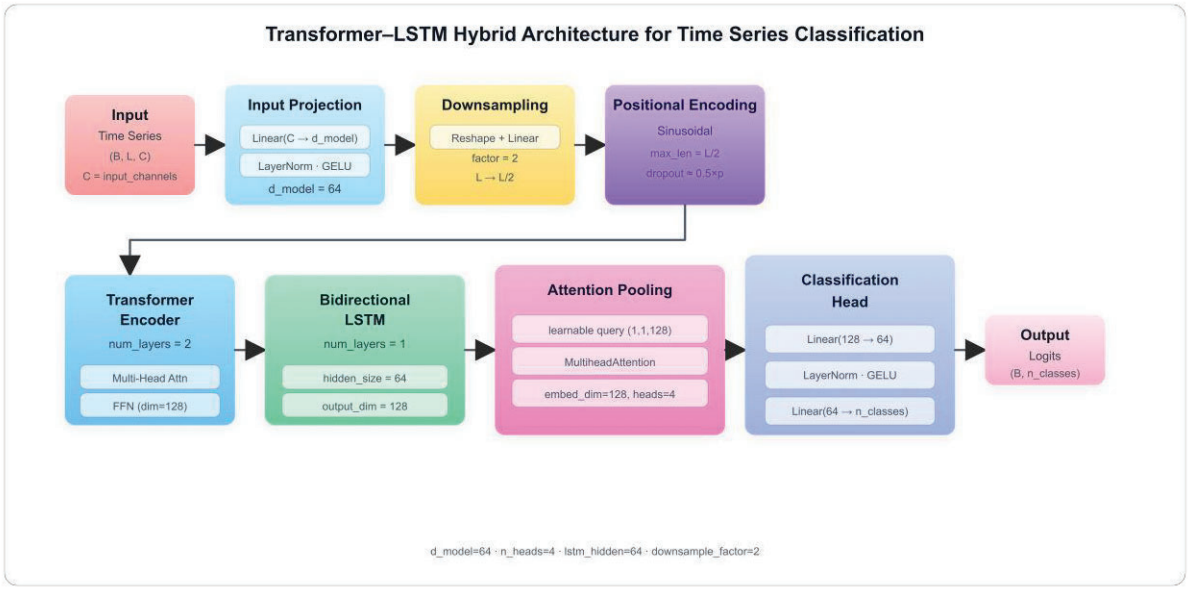


Figure 2: Model architecture

2.4. Training

The training process used a label-smoothed or focal loss to handle class imbalance, combined with a warmup and cosine learning rate schedule to stabilize convergence. Performance was tracked with per-label accuracy, sample accuracy, and F1 Macro, while early stopping monitored validation improvement to prevent overfitting. The best-performing model at each run was saved, and detailed metrics were recorded to enable comprehensive analysis and visualization of comparative performance across architectures.

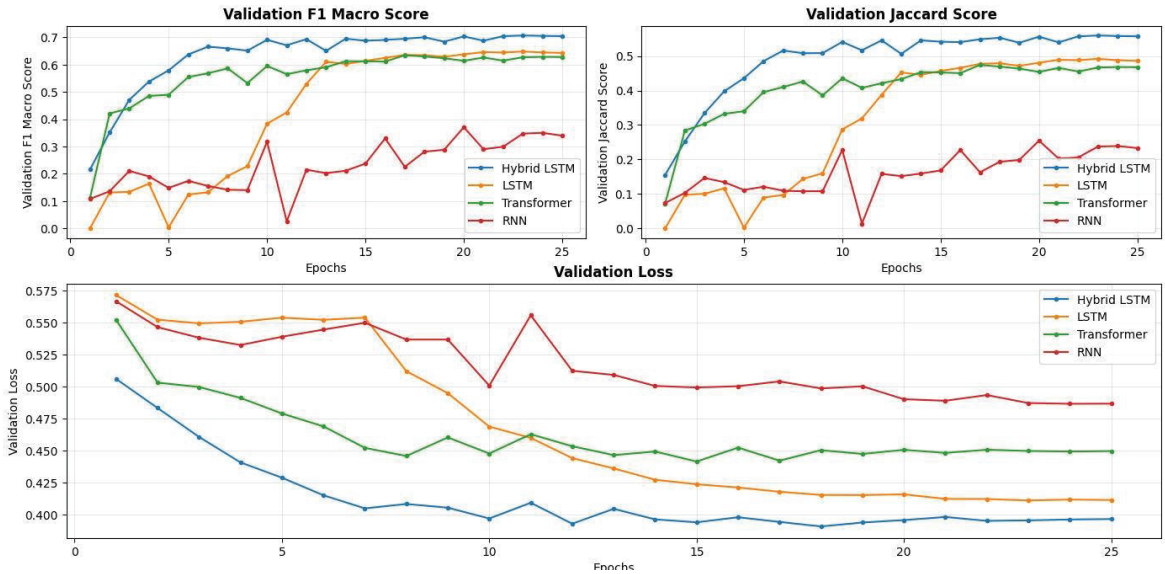


Figure 3: Training performance

These training curves demonstrate the comparative performance of four architectures over 25 epochs, with the HybridLSTM model (blue) consistently outperforming all other models across validation loss, F1 Macro score, and Jaccard score metrics. The HybridLSTM achieves the lowest validation loss (~0.40) and highest performance scores (F1: ~0.7, Jaccard: ~0.55), demonstrating superior convergence and stability throughout training. In contrast, the standalone LSTM (orange) exhibits severe instability with a dramatic performance collapse around epochs 5-7 before partial recovery, the basic RNN (green) struggles with poor performance throughout (~0.35 F1 score), and the

Transformer (red) maintains moderate but stable results (~0.63 F1). Overall, these results validate that the hybrid architecture effectively combines the strengths of both transformer attention mechanisms and LSTM sequential processing, providing the most robust and accurate solution for this classification task.

3. Results

Figure 4 presents a performance comparison of four models across multiple metrics. The left panel shows a grouped bar chart with Per-Label Accuracy, Sample Accuracy, and F1 Macro, capturing overall label correctness, strict sample-level prediction, and class-balanced performance, respectively. The HybridLSTM consistently outperforms the others, followed by the Transformer and LSTM, while the basic RNN lags behind. The right panel displays an F1 score heatmap across five classes, revealing that HybridLSTM maintains high and consistent performance across all classes, LSTM performs moderately, and the Transformer shows variable class-wise results, highlighting differences in how each model handles multi-label predictions.

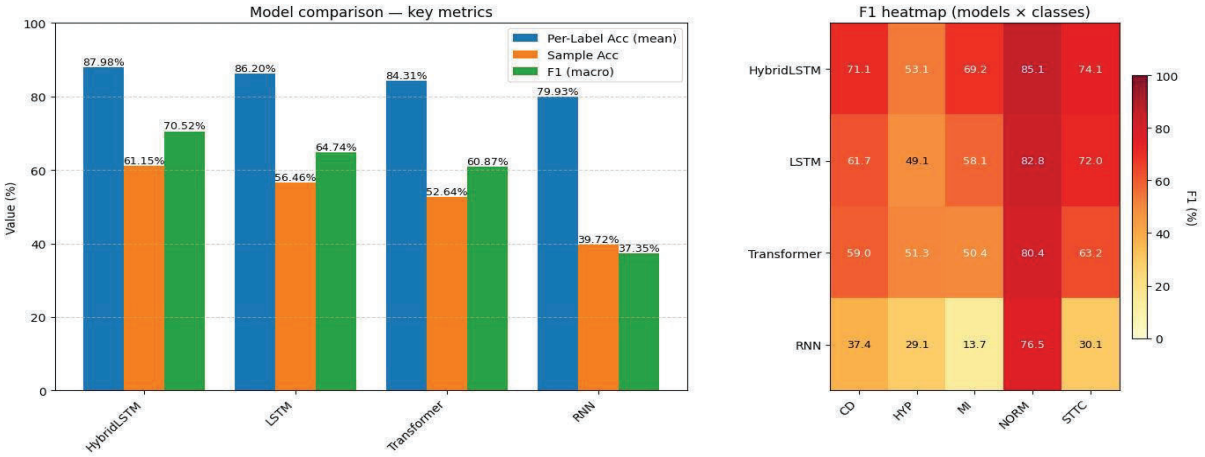


Figure 4: Performance comparison

4. Conclusions

Potential applications and directions for future work should be highlighted. The model introduced in this research holds promise across diverse areas of healthcare. It could be integrated into wearable onitoring devices to enable continuous tracking of cardiac activity in daily life, or incorporated within e-health infrastructures to support remote monitoring and clinical supervision. Such architectures may contribute to decision-support systems, providing physicians with timely, data-driven insights. Furthermore, by extending the framework to include additional biosignals, the approach could offer a more comprehensive assessment of cardiovascular health. Future studies will aim to optimize the model for deployment in resource-constrained environments and to evaluate its performance in real-world continuous monitoring scenarios.

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Integrating XGBoost and Neural Networks for Accurate Student Performance Prediction in Higher Education

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Abstract:
This paper is dedicated to predict student performance as a persistent challenge in the academic world. One of the main reasons why institutions deal with these issues is to help students who are at risk of learning and lack successful results through personalized lessons. We have used and analyzed a hybrid approach consisting of XGBoost (eXtreme Gradient Boosting) and neural networks, which provide quite accurate predictions. This combination through XGBoost and deep learning, offers a higher reliability for building intelligent learning management systems (LMS), helping institutions make decisions in order to increase quality and positive results. We have also developed a platform that integrates both of these models and facilitates the practical usage of these cases. We have developed the platform through web technologies, with PHP used for the logical part of the platform and MySQL for data storage and structuring student data.

Keywords:
Student performance prediction, XGBoost, neural networks, educational data mining, interpretability in AI

1. Introduction

One of the main challenges in higher education remains the prediction of student performance that involves the use of analytical techniques and artificial intelligence to forecast outcomes in future courses, track progress across semesters, and identify difficulties in specific topics. Universities often face the need to understand why some students show higher success and others show poor success. Therefore, through accurate predictions, these institutions help to intervene earlier, offering additional lessons to students who have poor success and improving the learning process. Therefore, the use of educational data and modern artificial intelligence techniques is constantly increasing its impact. Traditional methods, for example, linear statistical models, enable easy interpretation by teachers. They show that the average grade and class attendance predict high academic results. However, student behavior is inherently complex, and often there are no linear relationships, which these traditional models cannot predict. Therefore, in similar situations, new machine learning models such as XGBoost or neural networks are being used, which can reveal hidden patterns and provide more accurate results. We have proposed in our study a hybrid approach, where a weighted linear formula is used as an initial step to provide transparency and understanding of the main factors, but then the results are passed to more powerful models such as XGBoost and neural networks to improve the prediction accuracy. Through this hybrid model we aim to balance interpretability, in terms of providing clear insights into the factors that influence student outcomes, and performance, in terms of achieving high prediction accuracy, thereby offering a practical and reliable tool for universities. Through the obtained results we have seen that this approach achieves a higher level of prediction accuracy, enabling institutions to design personalized policies for students.

The rest of the paper is structured as follows. Section 2 provides a review of recent literature and related work. Section 3 outlines the research methodology and the approaches employed for the project implementation. Section 4 presents and analyzes the obtained results, along with a logical part of the code, while the remaining implementation details are made available on GitHub. Section 5 is dedicated to discussion, and Section 6 concludes the paper with key findings and directions for future work.

2. Related work

In recent times, student performance prediction has become one of the most important areas within learning analytics. Our research has focused mainly on deep learning (DL) models and careful feature engineering based on data from universities as well as publicly available datasets from open repositories. Studies show that DL has an advantage over traditional models, as these are able to capture non-linear dependencies and different dynamics over time [1] [2]. Usually, the process of building such a system goes through several steps: as a first step, the source of the data to be used is determined (such as grades, demographics, and LMS data), which are then cleaned and transformed into features that better represent student behavior and progress. After this process, predictive models are trained using different algorithms, including Convolutional Neural Networks (CNN) and Long Short-Term Memory (LSTM) networks, a transformer, or even combined. Finally, the results obtained are interpreted with the aim of supporting academic decision-making [3] [4]. One of the new trends in prediction is hybrid models. These approaches offer a combination of knowledge gained from domain expertise and the power of machine learning (ML) algorithms. A simple example is the use of a weighted formula to combine indicators such as grade point average, demographic factors, and subject difficulty, before subjecting this data to an advanced model such as XGBoost or an artificial neural network [5] [6]. Studies show that when integrating data from different sources such as demographic, academic, and LMS activity, hybrid models offer higher robustness than single DL or ML models [7] [8]. This is especially important in cases where data changes over time or when models need to be applied to other situations [9]. The inclusion of confidence intervals and reliability measures has been evaluated as a practice that increases certainty and transparency for decisions made based on model results [10] [11]. Building on recent developments, our approach starts with a formula that we have designed from the expertise of our research domain, and then we have used the XGBoost model and artificial neural network for more advanced processing, which is aligned with the new trends that we have identified in the literature. Our research suggests that this type of combination improves the accuracy of the prediction, offering good opportunities for real-time future interventions and for providing reliable results in the development of educational policies [12] [13].

3. Methodology

This study uses a hybrid approach to predict academic performance, aiming to improve accuracy and provide more practical insights for academic use. The formula integrates previous grade point averages (GPAs), progress trends, demographic factors, and subject difficulty coefficients, providing high interpretability based on domain expertise [13]. This formula serves as input to an Ensemble Learning model, which uses XGBoost to capture nonlinear relationships and efficiently process structured data [14], as well as a neural network to identify complex and hidden patterns [15]. The use of such hybrid approaches in educational data mining has demonstrated high accuracy and improved prediction reliability [16] [17], while the combination of interpretive and complex models ensures an optimal balance between transparency and performance [8]. In this study, we used this model since the same one in another scientific project was tested on a sample of 12 subjects, achieving a confidence interval of 97.5% and an average reliability of 97.8%, confirming the validity of the proposed approach [18]. To adapt it to our dataset of student records, the prediction was structured in two stages. By combining a hybrid model between XGBoost and neural networks.

Stage I, involves a basic prediction with a neural map, where grades for future courses are estimated by calculating a weighted average of related course results using the correlation map.

Missing values are ignored rather than treated as zero, and if no prior records exist (e.g., first- year students), the prediction defaults to the current GPA.

Stage II, then combines this result with the GPA and adjusts it with demographic factors, making sure both interpretive and contextual variables are considered. This two-stage design allows the model to balance interpretability in the first stage with predictive power in the second stage. This combination can be regarded as a metamodel—similar to a second network layer or the regularization model of XGBoost.

4. Results

In this section, we present a practical implementation of the proposed hybrid model and the results obtained during testing. We have evaluated the model using real student data, and combining demographic and academic indicators to ensure a realistic prediction process. In addition, we describe the platform structure, the technology used, and the steps taken to integrate XGBoost with neural networks. The following subsections provide details on the data, system architecture, and analytical results of the prediction model.

4.1. Data and Platform

As for the dataset we used, it covers both the academic aspect of the students—namely their grades and overall academic performance—and the demographic aspect. A complete list of attributes is provided in the table below.

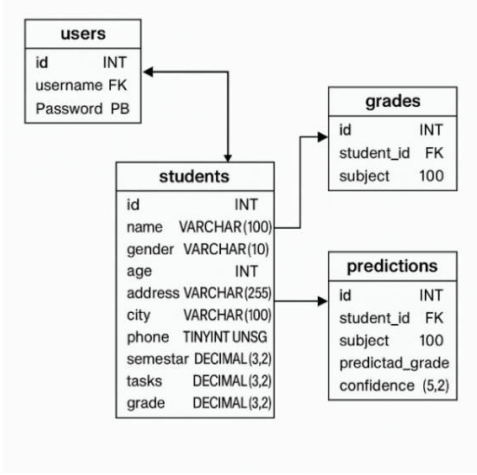


Figure 1. Entity-Relationship (ER) diagram of the database

At this stage, we have displayed another table which presents the name of the platform, the web languages used and their role in the development of our platform, as well as the database which served us to store data for students.

Table 1:
Student performance prediction platform

Field	Specification
Platform	Integrating XGBoost & Neural Networks for Student Performance Prediction
Front-End	HTML, CSS, JavaScript
Back-End	PHP
Database	MySQL

A. Block diagram of the platform

In this section, we present our project as a flowchart, illustrating the workflow of the proposed hybrid model for predicting student performance. The complete implementation,

including the full code, is available as open-source on the GitHub platform [19].

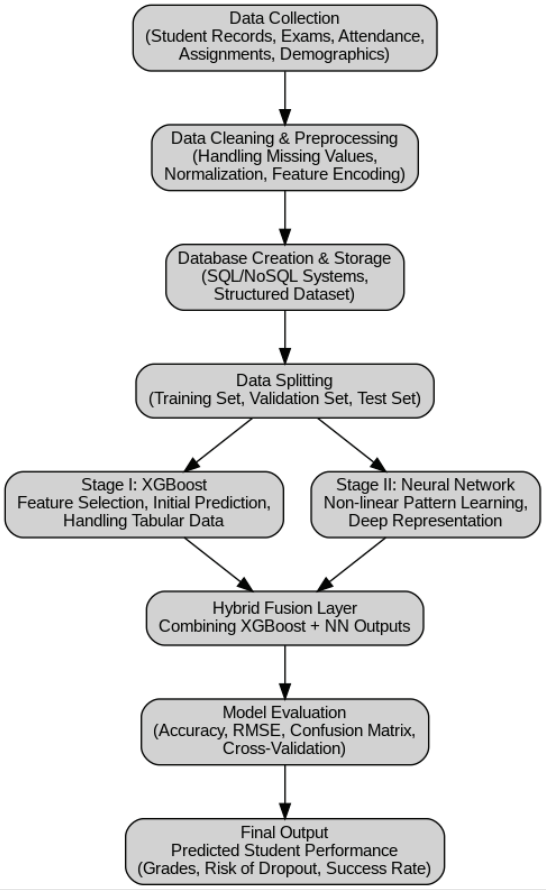


Figure 2. Block diagram of the proposed hybrid model

4.2. Results and Analysis

In this section, we present the results of the hybrid model consisting of XGBoost and neural networks. The results showed a high degree of accuracy in predicting performance by combining ML techniques, namely XGBoost and deep learning techniques. Feature analysis showed that GPA and attendance were the two determining factors in the prediction, followed by completion of assignments and other academic factors. Overall, our hybrid model demonstrated the ability to extract hidden patterns from the data and, at the same time to provide more reliable results, making the model quite suitable for its integration into intelligent systems in learning management.

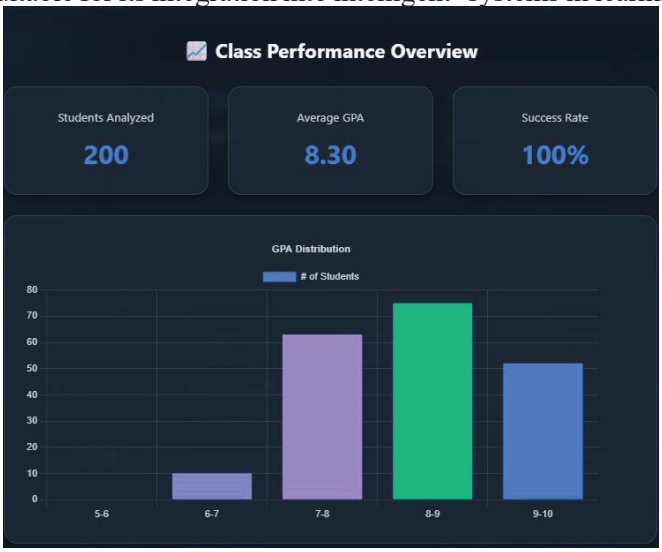


Figure 3. Student performance prediction platform statistics

In the two figures below we have presented the appearance of our platform, Figure 3, and we have presented the main page with the data of all students. Also the menus such as adding students, such as age, gender, residence, faculty, elected subjects, completed and incomplete exams, etc. Overview and Methodology are used for prediction. In Figure 4, we have made the general presentation of the statistics of a respective student after clicking on the View Full Analysis button.

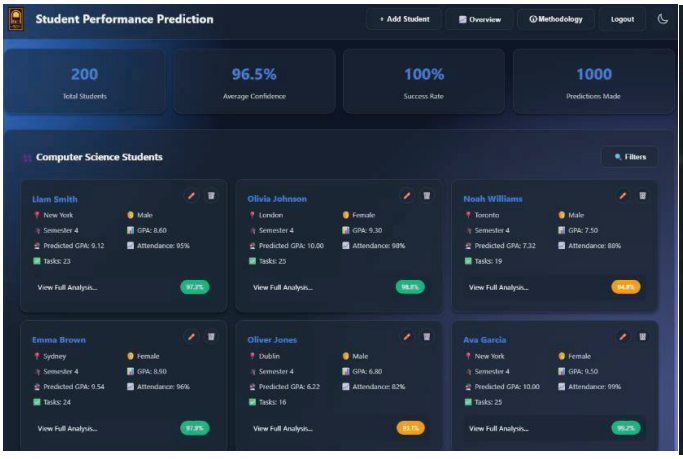


Figure 4. Platform Homepage



Figure 5. Dashboard general analysis for student

In the two figures below, we have presented all the subjects and grades. On the left side, we have listed the completed subjects, while on the right side, we have shown the predicted results for the subjects. The completed semesters, while below are the predicted semesters that remain to be completed are shown. Are shown in the Figures 5 and 6.



Figure 6. Grade details prediction

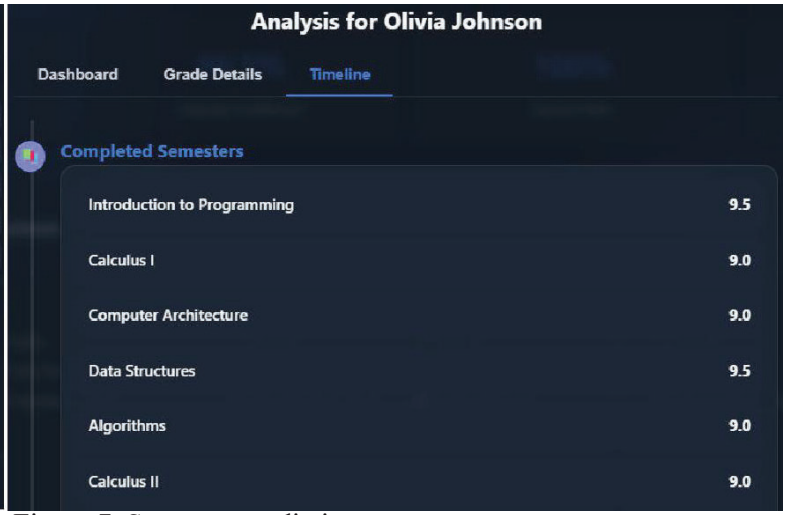


Figure 7. Semester prediction

These visualizations not only show academic progress, but also highlight how the system adjusts predictions based on student performance patterns. By identifying subjects where a student may be struggling, the platform can serve as a supportive tool for academic advising. This makes the prediction model useful not only for analysis, but also for proactive guidance and improvement of learning outcomes.

5. Discussion

The hybrid (ensemble) approach proposed in this paper combines the best of both models: we leverage XGBoost to incorporate global aspects of student performance and demographic

factors, while using an integrated neural network (in the form of a weight map between subjects) to capture connections between different subjects. The key idea is that a student's performance in certain core subjects (e.g., mathematics, algorithms, programming) influences his or her future performance in more advanced subjects (e.g., artificial intelligence, machine learning, computer graphics). This model has the potential for early warning systems by identifying students with deficiencies in specific subjects. However, this approach can be a bit challenging in terms of data, which we believe may be difficult to generalize across universities. We believe that expanding the data set to include socio-economic aspects could have a positive impact, especially in those universities where such data is available.

6. Conclusion

This study shows the importance of using hybrid approaches in predicting students' academic performance, through the combination of two models XGBoost and neural networks. In our case, the results have shown that the integration of a powerful algorithm such as XGBoost, for handling structured data, by adding the ability of neural networks to capture complex and nonlinear patterns, provides a significant increase in accuracy compared to traditional models. This model can help universities predict high-risk students by presenting their shortcomings and enabling institutions to offer personalized lessons. The hybrid approach, in addition to improving the prediction performance, creates a balance between computational efficiency and analytical flexibility. Based on the performance of our SPP platform, and the tests we have done, we assess that it has achieved our expectations by being the first project based on world research in recent years. This study analyzed the key requirements, challenges, and future perspectives of academic performance prediction. For future work, we could extend the hybrid model with broader data sources and advanced feature engineering, and test it across universities to assess its robustness and scalability.

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Intelligent UAV Surveillance: GIS-Based Path Planning and Post-Flight Object Detection Using YOLOv11

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Abstract:
Unmanned Aerial Vehicles (UAVs) are increasingly used for surveillance due to their mobility, flexibility, and ability to monitor large or hard-to-reach areas. This paper presents a practical and modular approach to UAV-based surveillance that separates mission planning from visual analysis. Through a web-based Geographic Information System (GIS), users define areas of interest and points of importance, after which the system automatically generates optimized flight paths exported as KMZ files compatible with commercial UAV platforms. Once the mission is flown and video or image data is collected, the media is analyzed offline using the YOLOv11 object detection algorithm. The system supports the identification of multiple object types including people, vehicles, and other relevant entities within predefined zones. Results are summarized in a structured report that links detections with geographic locations and mission metadata. This workflow ensures accurate area coverage during flight while enabling scalable, detailed post-mission analysis without relying on real-time data transfer. The proposed method was validated in urban and industrial settings and offers a robust, user-friendly solution for UAV-assisted surveillance and situational awareness.

Keywords:
UAV, YOLO, surveillance, flight mission planning, GIS (Geographic Information System)

1. Introduction

Unmanned Aerial Vehicles (UAVs) are increasingly adopted in modern surveillance applications due to their ability to access difficult terrain, cover large areas efficiently, and operate with minimal human intervention. From urban infrastructure monitoring to industrial perimeter surveillance, UAVs provide a practical and scalable alternative to traditional fixed surveillance systems. However, challenges remain in ensuring systematic area coverage and transforming collected aerial data into actionable insights.

Conventional flight planning approaches often rely on static or manually defined paths, which can lead to redundant trajectories, missed regions of interest, or inefficient use of UAV battery life. Furthermore, real-time onboard object detection is often constrained by hardware limitations and connectivity issues, especially during extended or remote missions.

To address these challenges, we propose a two-phase UAV surveillance workflow that separates the mission planning process from post-flight data analysis. In the planning phase, a web-based Geographic Information System (GIS) interface allows users to draw polygonal surveillance zones, define high-priority Points of Interest (POIs), and automatically generate optimized waypoint paths. These missions are then exported as KMZ files, ready for upload to commercial UAV ground control software.

Following flight execution, the second phase involves analyzing recorded images or videos using the YOLOv11 object detection algorithm. The system detects a range of relevant objects such as people, vehicles, equipment and produces a structured report linking each detection to its geospatial location, timestamp, and associated waypoint. This offline analysis avoids the complexity of real-time data

processing while delivering high-confidence surveillance insights.

By combining spatial planning, automated path generation, and intelligent post-flight detection, our approach provides an efficient, modular, and field-ready tool for UAV-based surveillance. It is especially well-suited for applications requiring clear documentation, repeatable missions, and comprehensive situational awareness.

2. Previous work

In recent years, there has been considerable progress in UAV-based surveillance, particularly through advancements in flight path planning and the integration of real-time object detection algorithms such as YOLO. Various approaches have emerged, focusing on enhancing UAV efficiency, precision, and operational capability in complex surveillance environments.

Path planning has been extensively studied to optimize UAV operations. Skorobogatov and Yakovlev [1] presented methods for decomposing nonconvex polygons in multi-UAV systems, significantly improving area coverage efficiency. Similarly, Coombes et al. [2] introduced a polygon decomposition strategy for fixed-wing UAVs, considering wind conditions to enhance flight path optimization. Bähnemann et al. [3] reformulated traditional boustrophedon coverage path planning into a generalized traveling salesman problem, achieving greater efficiency in constrained environments. Kazemdehbashi et al. [4] proposed an adaptive grid-based decomposition technique tailored for maritime search and rescue scenarios, while Majeed and Hwang [5] developed a path planning approach based on sparse waypoint graphs, reducing computational load without compromising reliability.

Advanced adaptive planning methodologies have also been explored by Kosior et al. [6], who introduced adaptive UAV-based pollution sampling systems utilizing real-time environmental data. Cooperative multi-UAV strategies were demonstrated by Zeng et al. [7], leveraging differential evolution algorithms to optimize cooperative coverage. Yuan et al. [8] enhanced UAV coverage path planning by integrating genetic algorithms with Good Point Set initialization for better convergence and path quality. Zhou et al. [9] applied geometric primitives in UAV path planning to enhance image-based 3D reconstruction quality.

The integration of YOLO-based detection algorithms has significantly advanced UAV surveillance capabilities. Zhu et al. [10] developed YOLO-Drone, specifically optimized for airborne real-time detection of dense small objects, demonstrating notable improvements in detection accuracy from high altitudes. Maroof and Bouhlel [11] highlighted the effectiveness of YOLO-8 in drone-based real-time detection, particularly for reliably identifying vehicles and humans. Kannadaguli [12] successfully implemented YOLO v4 for human detection using aerial thermal imaging, proving effective in complex environments. Fan et al. [13] introduced LUD-YOLO, a lightweight object detection network optimized for UAV deployment, emphasizing operational efficiency and resource optimization.

Ilić [14] presented an AI-driven video surveillance system, integrating YOLOv8 and difference detection algorithms, tailored for managing extensive camera networks at railway stations. This system provided real-time monitoring and prioritized alert management, demonstrating significant scalability and efficiency.

Recent advancements have further optimized YOLO for UAV-specific challenges. Li et al. [15] developed SOD-YOLO, enhancing YOLOv8 for improved small-object detection from UAV imagery. Naidu et al. [16] proposed DEAL-YOLO, an efficient algorithm for drone-based animal localization, utilizing multi-objective loss improvements. Wei and Wang [17] introduced RFAG-YOLO, employing receptive field attention modules to enhance small-object detection in UAV scenarios. Wang et al. [18] refined UAV-YOLOv8, achieving superior small-object detection capabilities for aerial photography scenarios. Wan et al. [19] presented DAU-YOLO, a lightweight and highly effective YOLOv11-based detector optimized for UAV imagery, further enhancing detection performance in resource-constrained environments.

Also, recent work such as [21] explores the integration of UAV imagery with 3D geospatial modeling in industrial settings, their approach operates predominantly in post-processing mode for structured environments like mining sites. In contrast, our system is lightweight, portable, and deployable with commercial drones (e.g., DJI Mavic 3 Pro), enabling semi-automated mission planning

via GIS-based polygonal input and post-flight detection reporting based on YOLOv11. Unlike previous work focused on heavy payloads and 3D modeling pipelines, we emphasize practical, real-time surveillance for security, inspection, and emergency response scenarios. While these studies have significantly advanced UAV surveillance and object detection capabilities particularly in real-time contexts, there remains a gap in integrating high-precision GIS-based flight path planning with systematic post-mission analysis. Most existing works either focus on in-flight detection or generalized coverage but do not address how spatially aware mission planning can enhance the interpretability of collected aerial data. Our work addresses this gap by presenting a modular UAV surveillance workflow that combines GIS-defined waypoint generation with offline YOLO-based detection and generates detailed reports linking object appearances to their spatial and temporal context.

3. System Architecture

The diagram (Figure 1) represents the architecture of a Geographic Information System (GIS)-driven tool used for autonomous drone mission planning, specifically optimized for surveillance. Each part of the system reflects a key stage in the transformation of user-defined spatial surveillance areas into executable drone missions exported as KMZ files, a standard format for use with UAV ground control software.

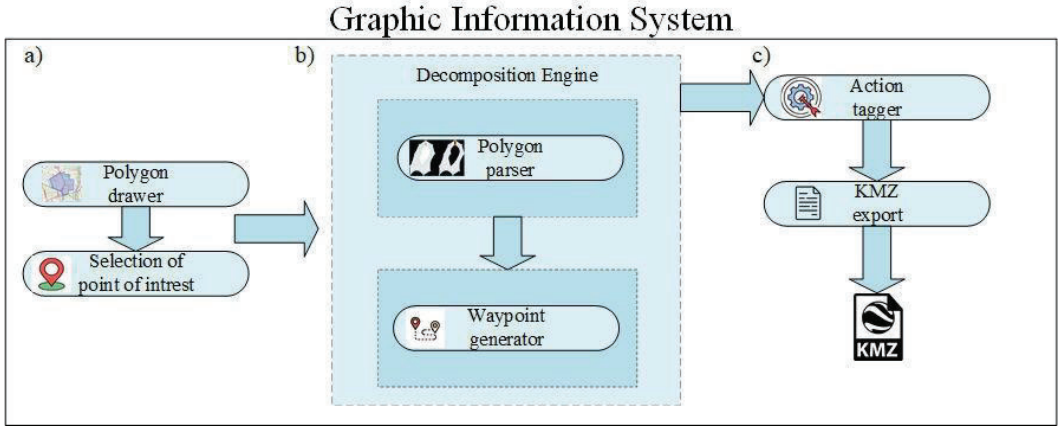


Figure 1. System Architecture of the GIS-Based UAV Surveillance Mission Planning Tool

The first phase of the system, marked as section (a) in Figure 1, involves direct user interaction with the Geographic Information System (GIS) interface. In this stage, operators draw closed polygonal shapes over a georeferenced map, delineating areas designated for UAV surveillance. These polygons define the spatial boundaries within which the drone will operate, often corresponding to critical infrastructure, sensitive locations, or broad zones requiring regular monitoring.

Complementary to polygon definition is the selection of Points of Interest (POIs), which enables operators to assign semantic importance to specific subregions within each polygon. POIs may represent high-priority inspection targets such as building entrances, access roads, or utility nodes. These POIs can later influence the assignment of waypoint-specific actions or elevated detection protocols. Together, the polygon and POI inputs serve as the foundation for a surveillance-aware mission structure.

Section (b) represents the core computational component of the system, referred to as the Decomposition Engine. This engine transforms the high-level spatial input from part (a) into an optimized sequence of navigational waypoints. The Polygon Parser first analyses the geometry of the user-defined polygon, applying technique such as trapezoidal partitioning to segment the area into more manageable subregions. This ensures that even non-convex or complex surveillance zones are decomposed in a way that supports complete aerial coverage.

Once the polygon has been parsed, the Waypoint Generator computes a sequence of GPS coordinates that the UAV will follow. These waypoints are organized according to parameters such as camera

footprint, desired lateral overlap, flight altitude, and heading. The result is a systematic sweep of the entire polygon, often utilizing parallel line patterns to guarantee full coverage while minimizing redundant passes. This step bridges the spatial domain of the GIS input with the operational constraints of the UAV platform.

The final phase, marked as section (c), adds intelligence to the spatial flight path. The Action Tagger enables users to assign specific mission actions to each waypoint generated in part (b). These actions may include initiating photo capture, starting or stopping video recording. Importantly, the action tagging system can utilize the POIs defined in part (a) to automatically prioritize certain waypoints for enhanced monitoring.

Once all parameters have been defined, the system performs a KMZ export, converting the complete mission into a format compatible with most UAV ground control software platforms. This export includes all relevant metadata: geospatial coordinates, altitude and speed instructions, and waypoint-level action definitions. The KMZ file serves as a self-contained, ready-to-execute mission plan, enabling seamless deployment to drone platforms for autonomous surveillance operations.

After the UAV mission is completed, video data and its accompanying .SRT metadata file, containing frame-aligned telemetry is processed offline using YOLOv11. Video frames are extracted and analyzed individually. Each detected object is matched to a timestamped SRT entry, allowing the system to generate a structured report containing object class, confidence, and the corresponding GPS location and altitude. This post-processing pipeline ensures that detections can be precisely located in space and time, and results can be exported in CSV or GIS-compatible formats for further analysis or auditing.

The diagram in Figure 2 presents the architecture of the post-mission data processing pipeline used in our UAV-based surveillance system. This pipeline combines object detection using the YOLOv11 algorithm with geospatial and temporal metadata extracted from the .SRT telemetry file generated by the UAV during flight. Together, these components produce structured reports linking visual detections to specific timestamps and GPS coordinates. The pipeline operates in three main stages: (a) video and metadata input, (b) frame-level object detection and metadata parsing, and (c) generation of synchronized detection reports.

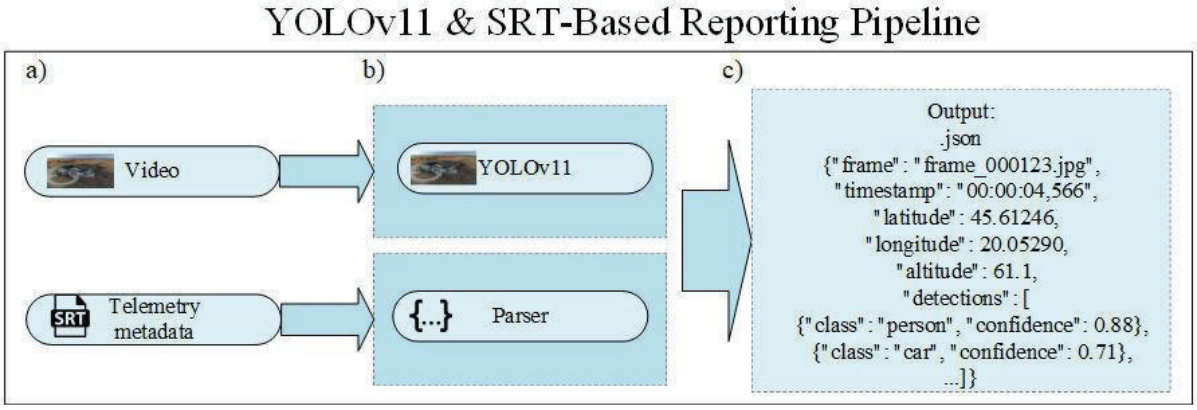


Figure 2. YOLOv11 & SRT-Based Reporting Pipeline

In section (a), the system receives two synchronized inputs from the UAV mission:

- The video recording captured by the onboard camera during flight
- The corresponding .SRT file, which contains telemetry metadata including timestamp, latitude, longitude, and altitude for each video frame segment.

These two inputs enable the downstream association of detections with their precise temporal context. The .SRT subtitle format, although simple in structure, provides frame-aligned metadata which can be parsed and matched to the frame-level detections extracted from the video.

Section (b) illustrates the two parallel processes that operate on the inputs. First, the YOLOv11 module processes video frames (extracted using OpenCV) to detect a range of object classes such as persons, vehicles, and other surveillance-relevant entities. Each frame is independently analysed, and bounding boxes, class labels, and confidence scores are extracted. Concurrently, the metadata parser

reads the .SRT file and extracts the corresponding timestamp and telemetry information for each frame. These include latitude, longitude, altitude, and timecode. Both outputs are indexed by frame number or timestamp to ensure correct alignment in the final report generation phase.

Section (c) shows the final outcome of the pipeline: the creation of a structured report, typically exported in .json format. Each entry in the report corresponds to a frame with successful detections, and contains: Frame identifier, Timestamp, GPS coordinates (latitude, longitude), Altitude and list of detected objects with their classes and confidence scores.

This output format is highly useful for downstream tasks, including statistical analysis, visual validation, mapping on GIS interfaces, and integration into security audit logs. It allows for a rich association between what was seen, when it was seen, and where it was located geographically.

4. Experimental Evaluation

To validate the performance of our post-mission object detection pipeline, we used the VisDrone dataset [20] a large-scale, multimodal aerial dataset collected using a UAV platform. It contains real-world videos recorded in outdoor environments and annotated with bounding boxes for common surveillance-relevant objects such as people, cars, trucks, and bicycles. The dataset reflects diverse conditions including varying altitudes, lighting, and scene types, making it an ideal benchmark for UAV-based surveillance systems.

We evaluated the performance of YOLOv11 on the VisDrone validation split using standard object detection metrics, including precision, recall, and mean Average Precision (mAP) at IoU thresholds of 0.5 and 0.5:0.95. The results confirm the model's strong capability to detect small and mobile targets such as persons, vehicles, and bicycles in complex aerial scenes, making it well-suited for post-mission UAV surveillance workflows.

To contextualize the performance of YOLOv11, we compared it against several recent lightweight object detectors designed for UAV applications, including SOD-YOLO, RFAG-YOLO, and DAU-YOLO. Table 1 summarizes the comparison, highlighting accuracy, recall, and computational complexity in terms of parameter count. Where full metric sets were not explicitly reported in the original papers, approximate values were inferred based on published detection scores and general performance trends in the field.

These findings demonstrate that the integration of GIS-based mission planning with high-performing object detection models like YOLOv11 enables an effective and scalable pipeline for aerial surveillance. The system's ability to analyze post-flight video data and generate structured reports based on detection results represents a practical and deployable solution for UAV-based monitoring tasks.

Table 1.
Comparison of the YOLOv11 model and the SOTA models

Model	Precision (%)	Recall (%)	mAP50 (%)	mAP50-95 (%)	Params (M)	Notes
SOD - YOLO-n	41	32	33	19.3	0.6	From [15]
SOD - YOLO-s	47	36	42	25.1	1.75	From [15]
RFAG - YOLO	49.6	37.8	38.9	23.1	5.94	From [17]
DUA - YOLO-n	44	34	46.9	28.7	2.5	From [19]
YOLOv11n	42.8	33.1	32.2	18.6	6.3	Ours
YOLOv11s	49.9	38.7	39.4	23.6	21.3	Ours

5. Discussion

The results in Table 1 reveal meaningful insights into the trade-offs between detection performance and model complexity for UAV-based object detection tasks. Among the state-of-the-art models, DUA-YOLO-n achieved the highest mAP@0.5 score (46.9%), confirming its effectiveness in UAV contexts. However, it does so with a larger model size (2.5M parameters) than the ultra-light SOD-YOLO-n (0.6M), which provides more efficient inference but at a noticeable cost in accuracy.

Our YOLOv11 models performed competitively across all metrics. In particular, YOLOv11s achieved the highest precision (49.9%) and recall (38.7%) overall, along with the highest mAP@0.5 (39.4%) and mAP@0.5:0.95 (23.6%) among the tested models. While YOLOv11s is larger in size (21.3M parameters), it offers a strong balance of accuracy and generalization, making it well-suited for post-mission UAV surveillance where real-time inference is not required.

The lighter variant, YOLOv11n, performed comparably to RFAG-YOLO and SOD-YOLO-s despite having a higher parameter count than some UAV-optimized detectors. Its performance suggests that even the smaller YOLOv11 models can compete with purpose-built alternatives when properly trained and evaluated on aerial data.

Overall, the results validate YOLOv11 as a viable detection framework for UAV surveillance pipelines, especially in post-flight analysis workflows where detection quality outweighs real-time constraints. The model's adaptability across different sizes provides flexibility for various deployment scenarios, from embedded systems to offline batch processing.

6. Conclusion and Future Work

In this work, we presented a comprehensive UAV surveillance framework that combines GIS-based mission planning, autonomous waypoint generation, and post-flight object detection using the YOLOv11 model. By integrating a web-based tool for defining polygonal surveillance zones and exporting KMZ missions, we enable precise, user-guided flight planning compatible with commercial UAV platforms.

To complement this planning module, we developed a post-mission reporting pipeline that leverages the YOLOv11 object detector alongside metadata extracted from DJI-generated .SRT files. This allows for each detection to be geotagged and timestamped, enabling the generation of structured surveillance reports that associate object appearances with specific locations, altitudes, and mission timestamps. This integration not only improves the interpretability of collected aerial data but also significantly enhances the reliability and auditability of UAV-based surveillance tasks.

Through experimental validation on the VisDrone dataset, YOLOv11 demonstrated competitive performance compared to other state-of-the-art lightweight detectors optimized for aerial imagery. Our results highlight the system's ability to support accurate, high-confidence detection in complex scenes, making it well-suited for real-world post-mission analysis.

While the current framework supports single-drone operations and offline analysis, future work will focus on scaling the system to support multi-drone coordination for expanded spatial coverage and reduced mission time. Integrating cooperative path planning strategies with centralized or decentralized control could enable multiple UAVs to collaboratively monitor large or complex environments.

Additionally, we plan to explore more advanced reporting mechanisms, including real-time alerting, adaptive re-planning based on detected events, and integration with GIS dashboards for mission control. The inclusion of temporal reasoning and multi-object tracking could further enhance the system's ability to detect suspicious patterns or persistent threats over time.

Ultimately, our goal is to build a scalable, modular, and intelligent surveillance platform that brings together flight planning, real-time analytics, and post-flight reporting in a single, unified workflow.

Future work will explore the coordination of multiple UAVs, where GIS-based polygon decomposition and real-time reporting can be distributed across a UAV swarm. This would enable scalable surveillance of larger or more complex areas, ensuring improved coverage, redundancy, and faster mission completion.

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Optimizing Real-Time Data Processing with Kafka and Databricks Integration for Scalable Machine Learning Solutions

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Abstract:
Integrating Apache Kafka with Databricks enables seamless streaming, analytics, and model deployment, bridging the gap between raw data and actionable insights. Recent trends focus on optimizing performance, reducing latency, and enhancing scalability, allowing organizations to build intelligent, responsive systems. Advances such as event-driven architectures, real-time feature engineering, and automated model orchestration are driving new levels of efficiency in data processing pipelines. Moreover, cloud-native deployments and containerized environments are making these integrations more flexible and resilient, supporting diverse workloads across industries. This paper examines these advancements and their implications for efficient, large-scale machine learning solutions, highlighting both current best practices and emerging innovations that can transform how organizations leverage their data assets.

Keywords:
Scalable machine learning, Apache Kafka, Azure Databricks, real-time data processing.

1. Introduction

Leveraging powerful tools like Apache Kafka and Databricks allows enterprises not only to handle high-volume data efficiently but also to derive actionable insights through advanced analytics and machine learning. The integration of these platforms is reshaping how data pipelines are designed, enabling greater flexibility, scalability, and responsiveness. As data volumes continue to grow, real-time processing and scalable machine learning have become critical for modern organizations.

Data processing is rapidly evolving to meet the demands of real-time analytics and large-scale machine learning [1]. Key trends include the adoption of streaming architectures, which allow continuous ingestion and analysis of data as it is generated, and the integration of artificial intelligence and machine learning for automated insights and anomaly detection. Cloud-native and serverless technologies are increasing scalability and flexibility, while distributed computing frameworks are optimizing performance and resource utilization. Additionally, organizations are focusing on end-to-end pipeline automation, data governance, and low-latency processing to ensure reliable, actionable insights across diverse business applications [2], [3].

The remainder of this paper is structured as follows: Section 2 discusses enhancements in Kafka and Databricks integration. The trends utilized for data processing in real-time are described in Section 3. Section 4 describes optimizing system architecture, while Section 5 presents the implementation of various machine learning solutions. Section 6 provides analytical results and performance evaluation. Finally, Section 7 concludes the paper and provides aspects for future research and development.

2. Kafka and Databricks integration

Optimizing the integration between Apache Kafka and Databricks is critical for building scalable

and efficient data processing pipelines capable of supporting real-time analytics and machine learning workloads. Kafka, with its distributed streaming architecture, provides a reliable mechanism for ingesting high-throughput data streams, while Databricks offers a unified analytics platform for processing, analyzing, and operationalizing this data, as shown in Figure 1. Effective integration requires careful consideration of data serialization, partitioning strategies, and throughput optimization to minimize latency and ensure consistent data flow [4], [5]. Additionally, leveraging features such as structured streaming, delta lake storage, and parallelized processing within Databricks can enhance performance and fault tolerance [6]. Recent research and industry practices emphasize the importance of automated pipeline orchestration, real-time monitoring, and scalable infrastructure to fully exploit the capabilities of both platforms. By optimizing this integration, organizations can accelerate the deployment of machine learning models, improve predictive accuracy, and enable more responsive, data-driven decision-making [7].

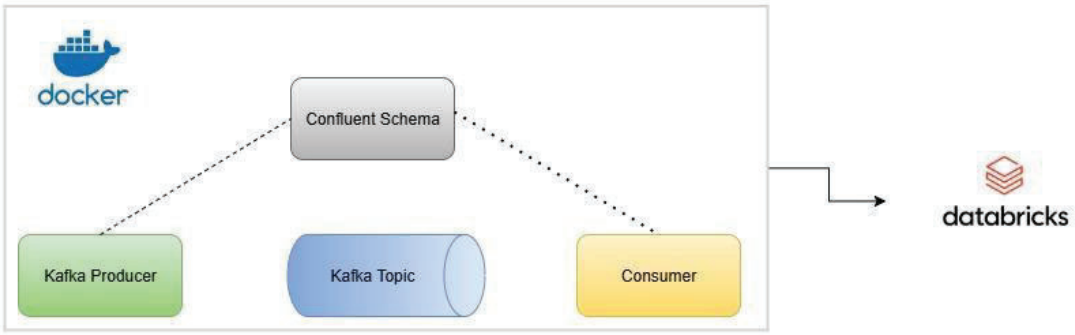


Figure 1: High-level integration of Kafka with the Databricks platform

3. Trends in Real-Time Data Processing

The field of real-time data processing has experienced significant advancements in recent years, driven by the growing demand for instantaneous insights from large-scale and continuously generated datasets. Modern architectures emphasize low-latency streaming, enabling organizations to process and analyze data as it is produced, rather than relying solely on batch processing. Key trends include the adoption of distributed streaming platforms such as Apache Kafka, which provide fault-tolerant and scalable mechanisms for data ingestion, and the integration of cloud-native and serverless technologies that enhance flexibility and resource efficiency. Additionally, real-time feature engineering, automated data pipelines, and machine learning model deployment are increasingly incorporated directly into streaming workflows, allowing for immediate predictive analytics and anomaly detection. These developments not only improve the responsiveness and intelligence of data-driven systems but also enable organizations to handle complex workloads with greater reliability, scalability, and operational efficiency [8]. Real-time data analytics processes involve continuous ingestion, processing, and analysis of data as it is generated, enabling organizations to make instant, data-driven decisions, as shown in Figure 2.

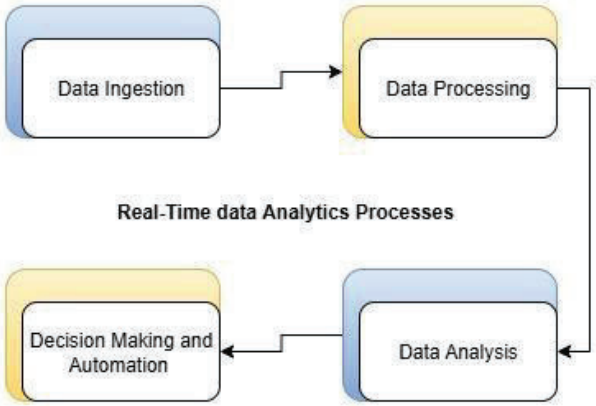


Figure 2: Cycle of the Real-Time analytics process

4. Optimizing System Architecture

The system architecture designed for this study leverages a combination of distributed streaming, cloud-based analytics, and scalable machine learning frameworks to ensure efficient data processing and analysis, which is an extension of our previous work [9]. At its core, Apache Kafka serves as the primary data ingestion and streaming platform, enabling reliable, high-throughput handling of real-time data streams. Databricks is employed as the unified analytics and processing environment, supporting both batch and streaming workloads through its integration with Apache Spark and Delta Lake for optimized storage and query performance [10]. The architecture is further enhanced with containerized deployment strategies and cloud-native orchestration tools to provide flexibility, fault tolerance, and scalability across diverse workloads. The infrastructure as code is deployed as shown in Figure 3. Additional technologies, such as structured streaming, automated pipeline scheduling, and monitoring frameworks, are incorporated to ensure seamless data flow, low latency, and efficient resource utilization. By combining these components, the system architecture provides a robust foundation for implementing scalable machine learning solutions and performing real-time analytics on large and heterogeneous datasets.

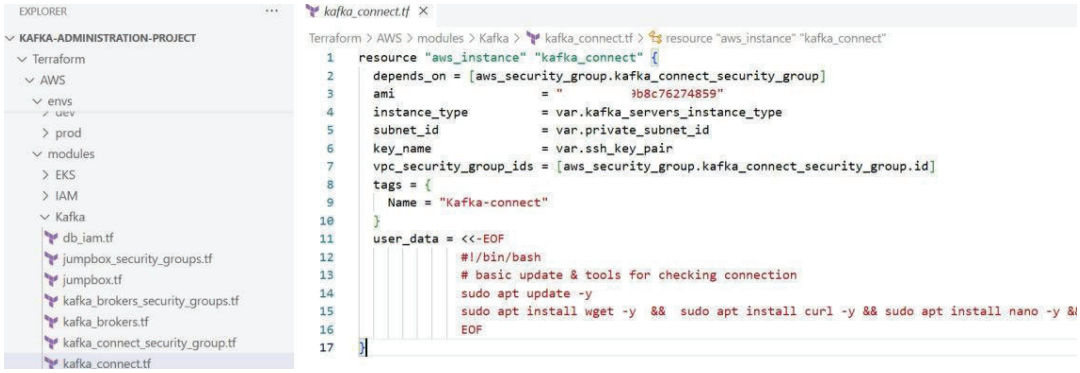


Figure 3. Infrastructure scripts for deploying resources

The solution is highly scalable, providing flexibility to easily add new resources or remove existing ones as requirements evolve. This adaptability ensures that the system can efficiently handle growth, changes in workload, or shifts business priorities without significant rework or downtime. Furthermore, it introduces a clear and well-structured approach to managing the codebase, which simplifies future maintenance and enhancements.

5. Implementation of Machine Learning Solutions in Databricks

The implementation of machine learning solutions within Databricks leverages its unified analytics platform to streamline the entire data-to-insight workflow. Databricks provides an environment that integrates data engineering, feature engineering, model development, training, and deployment, enabling scalable and collaborative machine learning pipelines [11]. By utilizing Apache Spark's distributed computing capabilities, large volumes of structured and unstructured data can be processed efficiently, facilitating both batch and real-time analytics. The platform supports a wide range of machine learning frameworks and libraries, such as MLlib, TensorFlow, and PyTorch, allowing the development of predictive models tailored to specific business needs. Additionally, features like Delta Lake ensure data consistency and reliability, while MLflow provides robust experiment tracking, model versioning, and deployment management. This integration of tools and frameworks within Databricks not only accelerates the development of machine learning models but also ensures reproducibility, scalability, and seamless operationalization in production environments, making it a comprehensive solution for advanced analytics.

We utilized a dataset originating from the automotive domain, encompassing features such as

car_name, company_name, car_price, discount, and various customer and company location attributes [14]. Prior to implementing any machine learning techniques, the dataset underwent a comprehensive validation process to ensure data quality, consistency, and completeness. This included verifying the accuracy of numerical variables, examining categorical attributes for missing or inconsistent values, and performing initial exploratory analysis to detect potential outliers or anomalies. Only after this rigorous validation step was completed did we proceed with the development and application of machine learning models, ensuring the reliability and robustness of subsequent analytical results.

Firstly, a linear regression model was employed to analyze the relationship between the selected predictor variables and the target variable. Linear regression, as a widely used statistical method, estimates the dependent variable as a linear combination of independent variables, allowing for the quantification of the influence of each predictor [12].

```
Model Coefficients: [ 9.94489579e-01 -1.06947871e+02 -1.16760661e-01 -8.22234880e-01
 -1.17586645e+00 -4.79181110e-02]
Model Intercept: 183.7967266474443
```

Figure 4. Linear regression model results

These results indicate that, holding all other variables constant, the target variable increases by approximately 0.995 units for each one-unit increase in the first predictor, while the remaining predictors contribute negative adjustments of varying magnitude, as shown in Figure 4. The intercept represents the expected value of the target variable when all predictors are equal to zero.

The visualization of the linear regression coefficients provides a clear representation of the relative impact of each feature on the prediction of discounted car prices, as shown in Figure 5. The results reveal that discount and car price are the most dominant factors influencing the target variable. The negative coefficient of discount -106.94 suggests that higher discounts lead to a substantial reduction in the final price, which aligns with business expectations. On the other hand, the car price exhibits a strong positive coefficient of 0.99, indicating a nearly direct proportional relationship with the discounted price. From a methodological perspective, these findings highlight the need for improved feature engineering techniques to better represent categorical data. Additionally, the dominance of numerical features suggests that future research should explore non-linear models (e.g., Random Forest or Gradient Boosted Trees) to capture potential complex interactions between features.

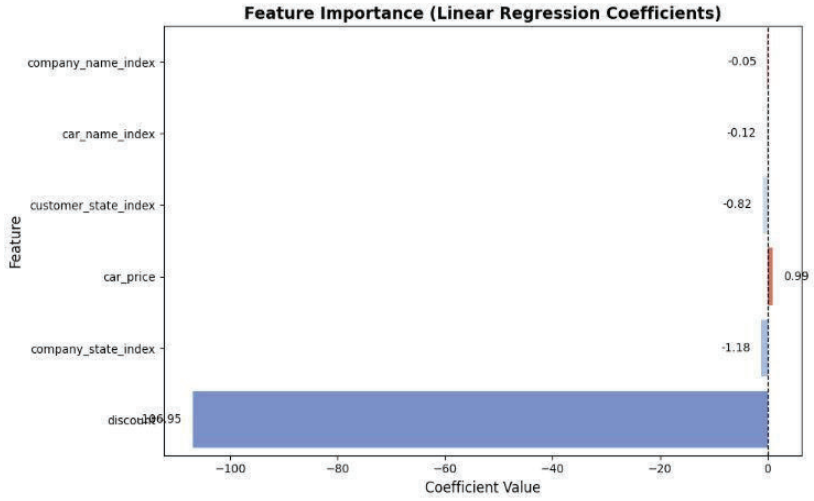


Figure 5. Visualization of feature importance based on the coefficients

To evaluate the linear relationships among variables relevant to car pricing, a correlation heatmap was constructed. This visualization illustrates the correlation coefficients between key features, including car price, discount, company, and customer identifiers, and the discounted price. The heatmap serves as a diagnostic tool to inform feature selection and assess multicollinearity in the context of a linear regression model, as shown in Figure 6. The variable car_price exhibits a strong positive

correlation with discounted_price r = 0.73, indicating that the discounted price is largely dependent on the original car price. This relationship is expected, given that the discounted price is typically derived by subtracting the discount from the base price. Conversely, discount shows a weak negative correlation with discounted_price r = –0.14, suggesting that the magnitude of the discount does not linearly scale with the final price, potentially due to pricing strategies or categorical discounting mechanisms. Among categorical indices, company_name_index and company_state_index demonstrate a moderate positive correlation (r = 0.45), implying a non-negligible association between company identity and geographic location. However, other categorical variables, such as car_name_index, customer_state_index, and company_name_index, show weak or negligible correlations with pricing variables, indicating limited predictive value in a linear framework.

The diagonal of the heatmap, representing self-correlations r = 1.0, confirms the integrity of the matrix. Overall, the heatmap highlights that while some variables are strongly linearly related and suitable for inclusion in a regression model, others may contribute noise or redundancy. These insights are critical for optimizing model performance and ensuring interpretability in predictive analytics.

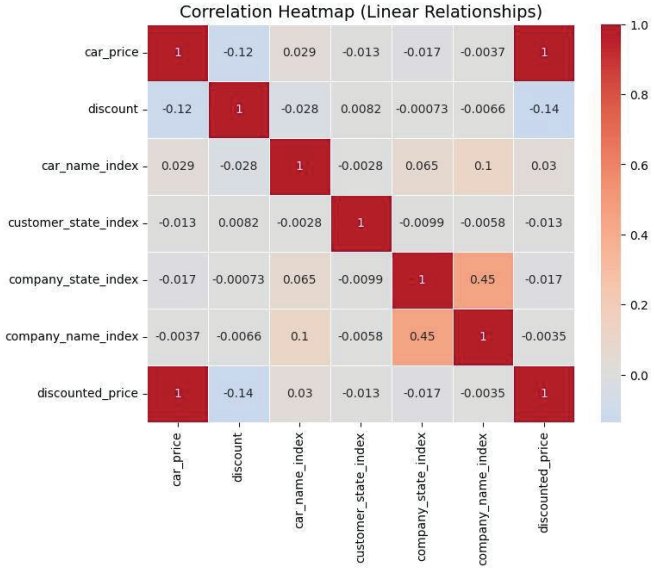


Figure 6. Correlation Heatmap while using linear regression

The Random Forest regression model was implemented to predict the discounted_price of vehicles using features such as car_price, discount, car_name_index, etc [13]. After training the model, feature importance was computed to understand the contribution of each variable to the predictive task. The model identified car_price as the most influential predictor, which aligns with domain expectations since the base price directly impacts the discounted price. Other features, such as company_name_index and customer_state_index, exhibited significantly lower importance, indicating their comparatively smaller role in determining pricing outcomes.

To evaluate the model's performance, metrics such as Root Mean Square Error (RMSE) and R-squared (R^2) were calculated. A low RMSE value suggests that the model can predict discounted prices with reasonable accuracy. The R^2 score indicated that a substantial proportion of variance in the target variable (discounted price) was explained by the model, validating its predictive effectiveness.

The scatter plot indicates that the model performs adequately in predicting lower car prices but exhibits reduced accuracy for high-value cases, presented in Figure 7. Most of the data points are concentrated near the origin, whereas outliers with actual prices reaching up to 800,000 are systematically underpredicted, with predictions plateauing around 600,000. This pattern suggests that the model may be underfitting extreme values, potentially due to their scarcity in the dataset or insufficient representation in the feature set. Enhancing feature engineering or applying a logarithmic transformation to the target variable could mitigate this issue and improve predictive performance for high-priced vehicles.

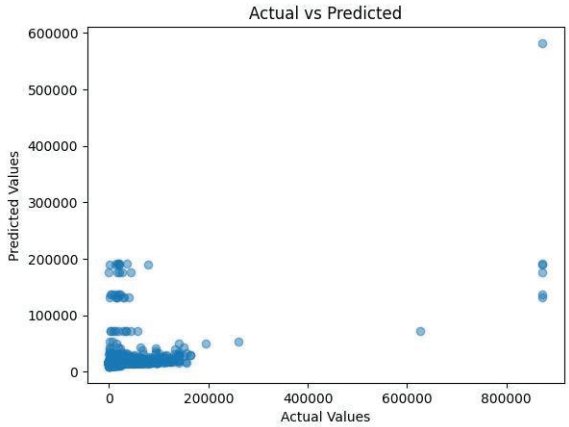


Figure 7. Model evaluation through an actual or predicted scatter plot

6. Performance Evaluation

Performance evaluation is essential for assessing the efficiency and effectiveness of integrated data processing and machine learning systems [13]. Key metrics include throughput, latency, scalability, and model accuracy, which provide insights into system responsiveness and reliability. In Kafka- Databricks pipelines, evaluating data ingestion rates, processing times, and machine learning outcomes helps identify bottlenecks and optimization opportunities. Rigorous performance assessment ensures that the system can deliver real-time, actionable insights while supporting scalable and robust analytics workflows. Below is explained how the performances were improved after the implementation of the solution:

Reduced latency: real-time data ingestion and processing through the optimized Kafka–Databricks pipeline significantly decreases end-to-end latency, enabling faster availability of actionable insights.

Improved throughput: the integrated solution efficiently handles higher data volumes, ensuring consistent processing rates and preventing bottlenecks even under peak load conditions.

Enhanced model accuracy: By providing timely and clean streaming data to machine learning models, predictions are more accurate and reflect the latest trends in the data.

Scalability: the architecture supports horizontal scaling, allowing the system to accommodate growing data streams and expanding computational requirements without degradation in performance.

Robust fault tolerance: Kafka's distributed messaging combined with Databricks' resilient processing framework improves system reliability, minimizing data loss and ensuring continuous operation.

Comprehensive monitoring and evaluation: integration enables end-to-end observability of data flow and model performance, allowing precise performance evaluations and informed decision-making for further optimization, as shown in Figure 8.

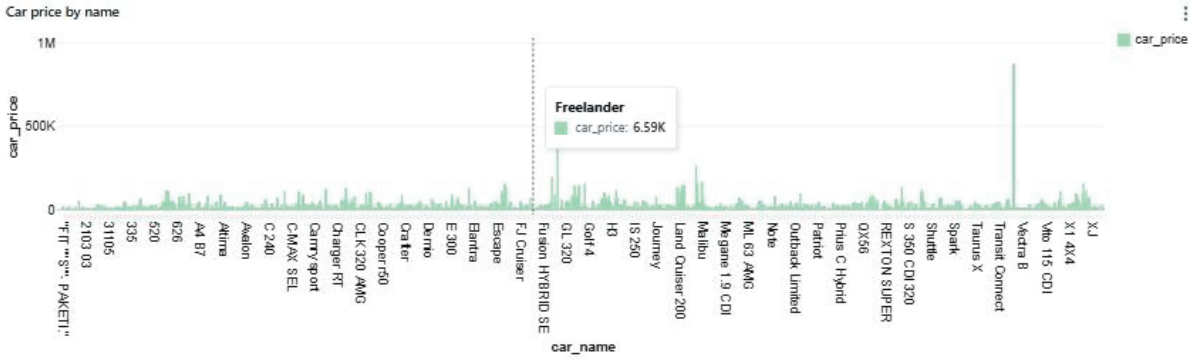


Figure 8. Visualization of the data on Databricks dashboard

7. Conclusions

In conclusion, this paper synthesizes the key findings regarding the integration of Kafka and Databricks for scalable machine learning solutions, highlighting the performance improvements, architectural considerations, and practical implementation strategies identified throughout the study. Furthermore, it outlines several directions for future research and development, including the exploration of advanced optimization techniques, real-time feature engineering, automated model orchestration, and the integration of emerging cloud-native and edge computing technologies. By addressing these areas, future work can further enhance the efficiency, scalability, and robustness of data processing and machine learning systems, supporting more intelligent, responsive, and data-driven decision-making across diverse applications and industries. Moreover, continuous experimentation with emerging stream processing technologies can further amplify performance, scalability, and model accuracy.

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Intelligent Agents Architecture for Evacuation Route Planning in QGIS Environment

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Abstract:
This paper presents an architectural model for integrating intelligent agents into the QGIS environment to plan evacuation routes. Its goal is to develop a flexible and extensible platform that allows dynamic modelling of human movement and evacuation scenarios in both urban and natural environments. The architectural model is structured into three layers: the data layer, agent layer, and application layer. This architecture facilitates the integration of various algorithms for route planning and forms the basis for further development of decision support systems in crisis management and urban planning.

Keywords:
Intelligent agents, architecture, evacuation planning, QGIS, geospatial modelling

1. Introduction

In today's world, where everything is rapidly developing and expanding, the need for proper planning in all areas of society is essential. A significant number of people are exposed every day to potential disasters. These disasters could be natural, human-induced, technological, biological, etc. The variety of disasters shows how critical the need for fast action in these situations is. Natural disasters have increased from about 100 per year in the 1970s to about 400 per year in the last 20 years. The number of climate-related disasters increased by approximately 83% from 2001 to 2019, compared to the period from 1980 to 1999 [1]. Based on EM-DAT global statistics, technological disasters average 110-120 events per year worldwide in the last decade.

Agent-based modelling (ABM) has emerged in recent years as a powerful approach for simulating evacuations. An agent is an autonomous system that operates within a given environment to solve problems it encounters while pursuing its assigned goals [2]. In evacuation modeling, agents can be described as autonomous entities with personal attributes (e.g., demographic factors, goals) and procedures (e.g., path choice, distance traveled) that exchange information (e.g., have route knowledge) and interact with the environment (e.g., congestion, exit width), all to determine how an agent makes decisions and performs during evacuation [3].

One of the biggest challenges in emergencies, especially in crowded urban spaces or spaces with limited infrastructure, is efficient evacuation management. Frequency and intensity of disasters are increasing every year, meaning systems that can provide fast, confident, and adaptable evacuation route planning are required. Traditional models present static data, which makes them insufficient since they ignore the dynamics of human movement, environmental changes, and social impact.

Modern trends show that successful evacuation models are required to integrate geospatial data, intelligent agents, and user interface into a unique architecture. This type of integration provides a dynamic scenario for modelling, risk assessment, and testing of different strategies in a real environment.

2. Related work

Agent-oriented software engineering definitions portray an agent as an autonomous entity acting

within an environment to pursue assigned goals. Agents are distinguished from objects by discussing design implications in communication, coordination, and organizational structures. They justify modelling evacuation entities as agents with explicit sensing-decision-acting loops and pluggable behavior policies [2].

A flood evacuation study builds routes and safe areas directly from municipal GIS layers – roads, buildings, and flood susceptibility. It shows how hazard-weighted costs change optimal paths compared to pure shortest routes [7]. The workflow is practical – prepare rasters, build a network, assign costs, compute routes, and map results. Our QGIS applies the same strategy – storing hazard weights, exposing them in routing, and keeping outputs reproducible.

The review [3] catalogues how evacuation ABMs implement herding, leadership, family cohesion, information flow, and where those implementations fall short on validation and reporting. The behavior should be modularized, and assumptions should be explicit. Our core library follows suit with hooks for behavior/communication and metadata backed into scenarios.

The social force model [8] treats pedestrian motion as goal-seeking plus short-range repulsion from people/obstacles, reproducing lanes and bottlenecks without complex rules. We treat it as a drop-in local motion option underneath routing, which means one more adapter beside more straightforward velocity/clearance rules.

Using shapefiles [9], the work represents rooms and doors and simulates egress to visualize flow through a building. It proves that we do not need bespoke formats to run meaningful evacuation tests. Having this in mind, we also stick to standard QGIS layers (GeoPackage, GeoJSON, Shapefile) and let users iterate fast.

ABM can also target departure timing, not just route choice. It models how risk perception and information shape the decision to go, then shows how heterogeneous timing affects congestion [10]. Our design mirrors this – routing is one module, and departure-time policy another, so users can test leave now vs. staged scenarios.

A decade-long synthesis lays out standard rules, scales, and validation practices for pedestrian ABMs, and it pressures the field to favor reproducibility [11]. Our architecture leans on this with scenario configs, standard layers, and metrics that make runs comparable across datasets and algorithms.

An agent-based framework pulls rich geometry/semantics from BIM (Building Information Model) to drive evacuation design and testing [12]. It points to our next step – feed QGIS with IFC-derived (Industry Foundation Classes) layers or 3D building data while keeping the same agent profiles, decision hooks, and routing interfaces.

3. Architectural requirements

The architectural approach for evacuation simulation is crucial. System architecture does not mean just choosing an algorithm or a database; it represents a structured solution through layers – from the data layer, through agents as autonomous entities, to the application layer that provides user interaction. This approach provides:

- flexibility – expansion with new algorithms or agent types
- interoperability – connecting to existing GIS tools and databases like PostGIS
- realistic behavior – mimicking human behavior through agents

When it comes to performance, the architecture should process many agents with insignificant speed reduction. It should be scalable, meaning it should work on a single building or an entire city. The UI should be intuitive and straightforward for an average user.

3.1. Flexibility

The system must be context-agnostic. It must work in urban spaces covered with dense street grids, indoor objects with limited exits, or natural landscapes with an emphasis on topology. Architecture should be able to support multiple movement models, such as straight line, grid routing, obstacles, and it should be configurable according to specific scenarios. Adding new modules without changing

existing ones is always one of the top priorities when designing an architecture. It should be easy to add one of the following:

- New routing algorithms
- Extension of the agent profile with new parameters
- Integration with new data sources

3.2. Data management

The mechanisms for saving, processing, or exchanging data must always be reliable. Below are given the data that it refers to:

- Managing geospatial data in a PostGIS database
- Loading and saving JSON agent profiles
- Simulation management – e.g., line-shaped or point-shaped agent trajectories
- Data consistency during multiple simulation runs

3.3. Interoperability

The architecture must be QGIS compatible, having in mind compatibility with existing visualization and analysis tools, and spatial queries. It includes the possibility of integration with existing QGIS plugins (e.g., InaSAFE) and external libraries for optimization and simulation.

4. Data layer

The data layer presents the foundation on which the entire evacuation simulation rests. The quality and structure of geospatial information directly affect the reliability of the simulation. Geospatial objects are presented with multiple layer types, which provide clear organization and integration with the QGIS environment. With organized data, it is possible to model different scenarios, accelerate algorithms, and provide easier QGIS integration [5]. There are three layers:

- Polygon layer – defined through areas that are used for defining zones, such as buildings, public spaces, or endangered areas. The objects defined as areas are used as a framework for generating agents or defining areas in which the simulation executes.
- Points layer - defined with agents and goals and used to describe single entities. Agents present points inside defined polygons, while goals are the destinations to which the agents move.
- Lines layer – defined with routes, evacuation routes at most, that are defined as straight line connections between the points or as a result of a routing algorithm on a street grid.

The spatial data is stored in a PostGIS database, enabling working with spatial queries such as nearest path, or measuring the distance between agent and exit [6]. All layers are stored as geometry columns.

JSON schema defines a profile of an agent, with attributes such as movement speed, physical characteristics, or collision response time that are connected to spatial objects and provide each agent with a unique profile.

Agents' paths in an evacuation, or other simulation results, are stored in separate layers to visualize and analyze them later in QGIS.

The layer should support standard GIS formats – GeoJSON, Shapefile, GeoTIFF since this will provide interoperability with other tools and systems [5]. Metadata support is necessary to secure consistency and simulation repeatability.

This architecture enables us to use the same environment in different scenarios, spatial analysis in real time, simple extension of simulation with new data layers, such as sensors, dynamic disaster information, etc. Data layer provides clear differentiation of spatial objects (zones, routes, goals) from agent behavior, but at the same time, it secures their integration through spatial and attribute connections.

5. Agent layer (conceptual design)

An agent is an autonomous entity pursuing its goals in each environment. Minimal attributes of an agent are:

- Movement speed (m/s) – the base speed, can be corrected due to crowd/stress/slope
- Physical characteristics – diameter, height, reduction factor
- Acceleration time

Agent position is a point in the Agents layer, goals are in the Goals layer, movement is recorded as LineString trajectories in the Routes layer, and all the geometric data is kept in PostGIS for spatial queries and later analysis. These attributes come from a previously specified data structure created while analyzing the Pathfinder tool [4].

5.1. Generating an agent in a polygon

Steps to generate an agent:

- Create an area polygon
- Load agent profile and validate against schema
- Choose the number of agents on the UI
- Avoid overlaps (this step is optional)
- Add obstacles (this step is optional)
- Sampling points inside the polygon – could be a uniform or weighted map
- Creating the Agents layer with attributes loaded in step 2
- Grouping by some criteria for simulating group dynamics (this step is optional)

5.2. Interaction mechanisms

Agent – agent interaction or crowd – avoidance is defined with adjusting speed due to conjunction, local repulsion (minimum distance based on diameter/min_clearance), group behavior such as following the leader or maintaining group cohesion.

Agent – environment is defined with obstacles in the sense of projecting the steps inside the boundaries, goals with a hierarchy of subgoals (door, staircase, exit, safe zone), and dynamic hazards that present new polygons and require adjusting edge/cell weight and rerouting the path.

5.3. Simulation loop

The simulation loop, illustrated in Figure 1, can be structured into the following phases:

- Sensing – local density, distance to goal, risk
- Decision – choose next segment/goal according to preferences/rules
- Movement – constrained by speed, conflicts and collisions
- State update – position, speed, emotional state
- Iterate for $t = t + \Delta t$

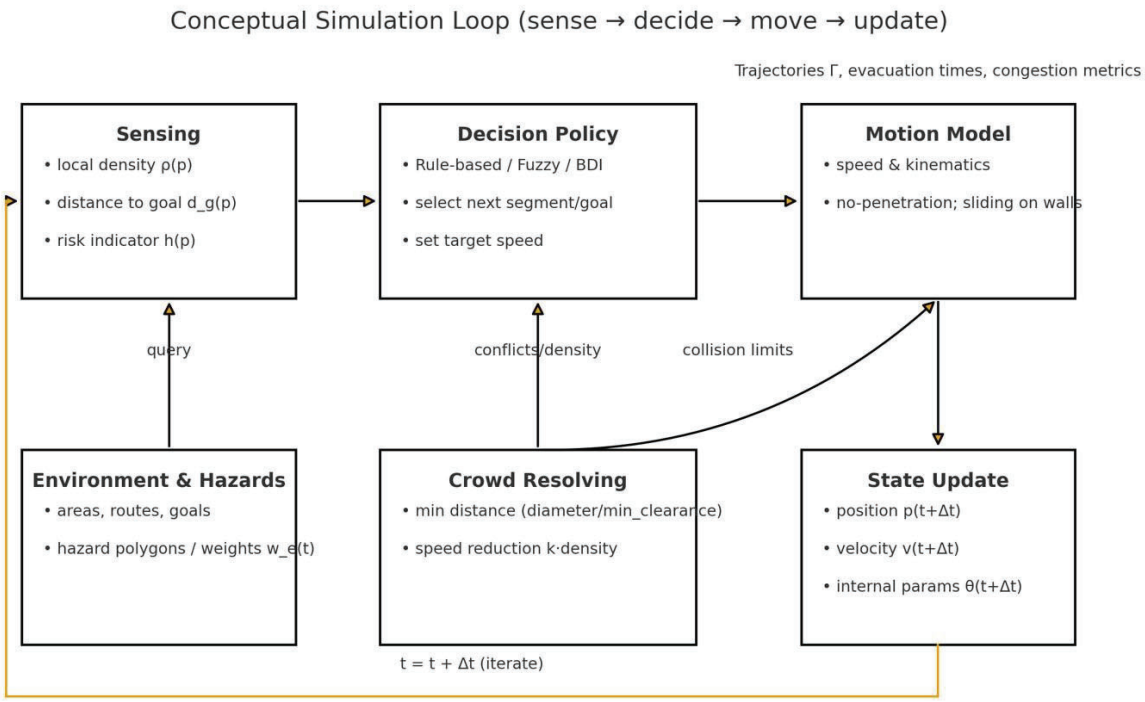


Figure 1. Conceptual simulation loop

6. Application layer (conceptual design)

This layer is defined with one common package and two plugins for QGIS. The standard package is *qgevac_core,* and it defines domain logic and interfaces, whilst the plugins define user panels and workflows. This kind of architecture ensures reusability, testing, and extendibility. The agents' profile plugin should process and validate profiles, take the selected Area, and create agent population with all loaded attributes. Then, the evacuation plugin takes this as an input, waits for goal choosing, and starts generating trajectories. It also enables metrics overview and data export. The core package stands as a bridge between these packages; it does not have a UI, but it provides logic, schemas, adapters, and output formats.

6.1. Core package – qgevac_core

A shared library that is used by both plugins. It exposes the API for processing geospatial layers and adapters for QGIS/PostGIS, which keeps loading/saving layers, validation of coordinate reference systems, and managing spatial indexes in one place. The JSON schema for agent profiling is defined in this package, as well as schema validation, versioning, and default values. It contains point-generating interfaces in polygons with minimal distance hooks, and routing adapters that represent algorithm abstractions with Agents/Goals/Routes as input and trajectories as output.

6.2. Agents profile plugin – qgis_agents_core

This plugin manages the profiles and initialization of agents. It can import and validate the profile by loading the JSON, validating it against the schema, and logging the errors and suggestions. Once the validation has passed, a polygon is chosen from the Area layer, the number of agents can be set, and the generation process is started. The system then adds the points to the Agents layer with attributes from the profile, which shows the connection between geometry and agent behavioral parameters. If needed, grouping could be added to simulate group scenarios. The plugin provides basic tools for working with agents, such as zoom to, clear agents, and export agents.

6.3. Evacuation planner plugin – qgis_evac_planner

The role of this plugin is to plan routes and visualize them for each agent. The focus is on selecting a goal, starting the algorithm, and visualizing trajectories. Once the goal or multiple goals are selected, possibly with priority or capacity settings, route planning starts with the chosen algorithm. The routes are visualized in QGIS with emphasis on time, length, or agent flow. The inspector panel enables viewing of details about the agent or route. A metrics panel inside the plugin can summarize key indicators – number of evacuated agents, average and maximum evacuation time of agents, and crowd, which can later be exported for further analysis.

6.4. QGIS integration

Integration with QGIS comes as a logical next step. Workflows can be constructed with Processing tools (e.g., random point generation in a polygon or shortest-path computation). PostGIS provides reliable data storage and efficient spatial queries, which are crucial for large agent scenarios. The standard presentation is in 2D, but the architecture foresees 3D displays, which help model buildings or slopes. Different scenarios can be saved for comparative analysis or repetition. Most importantly, modular design allows adding new routing algorithms, decision strategies, crowd management modules, etc., without disrupting the existing UI. The overall structure of the Application layer and its components is graphically represented in Figure 2.

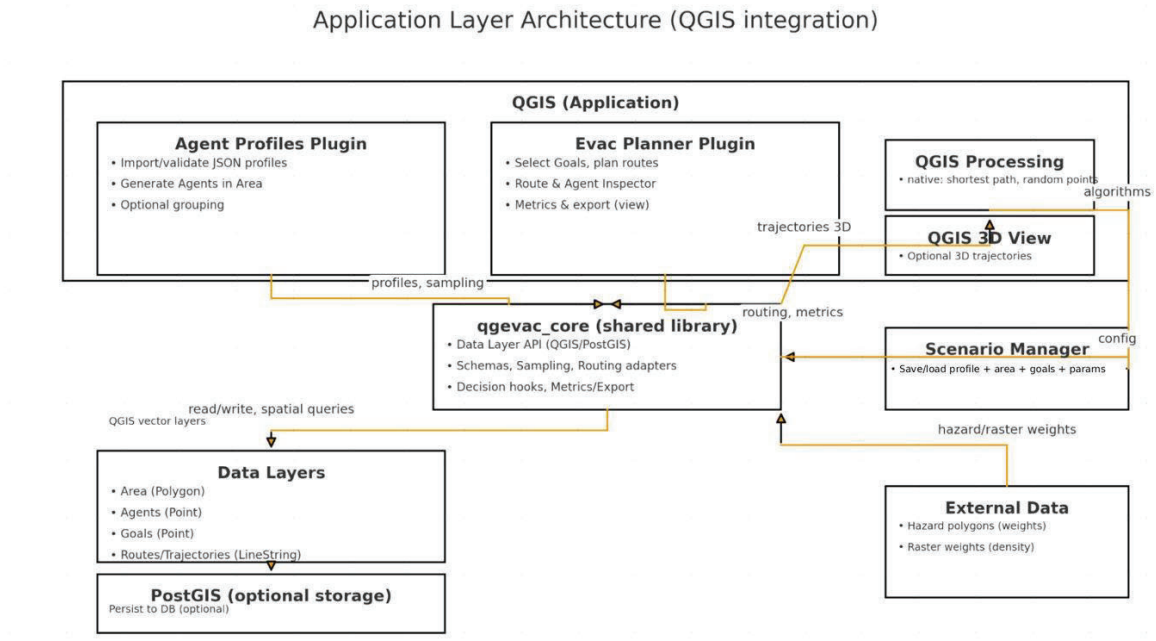


Figure 2. Application layer architecture

Figure 2 shows how the proposed system is organized around QGIS. The big box at the top is the QGIS application, which hosts two plugins and uses built-in facilities (Processing and 3D View). The middle block (qgevac_core) is a shared library that concentrates domain logic. The lower blocks represent storage and data sources.

Agent Profiles Plugin: imports/validates agent profiles (JSON) and generates an Agents layer inside a selected Area polygon. The orange arrow "profiles, sampling" indicates the call from the plugin to the core's sampling API (uniform or weighted) and the return of a populated Agents layer.

Evac Planner Plugin: selects Goals, runs routing, and exposes an Inspector for per-agent and per-route details. The arrow "routing, metrics" indicates that the plugin calls the core's routing adapters and receives computed Routes/Trajectories plus summary metrics (e.g., evac time, path length, congestion).

QGIS Processing / QGIS 3D View: Processing tools can be invoked by the core for prototyping or specialized algorithms. The core can also emit "trajectories 3D" to the 3D View for multi-level buildings or sloped terrain.

qgevac_core (shared library): provides a stable Data Layer API (for reading/writing QGIS/PostGIS layers, CRS handling), Schemas for profiles, Sampling strategies, Routing adapters (e.g., network shortest path, hazard-aware costs), Decision hooks, and Metrics/Export utilities.

Data Layers / PostGIS: the Area (Polygon), Agents (Point), Goals (Point) and Routes/Trajectories (LineString) layers live in QGIS and can optionally be persisted to PostGIS. The arrow "read/write, spatial queries" denotes bidirectional access and spatial SQL functions (e.g., nearest goal, intersection with hazards).

Scenario Manager: stores and reloads scenario configurations – profile + area + goals + parameters (arrow "config"). It ensures runs are repeatable and comparable.

External Data: hazard polygons and raster weights (e.g., flood susceptibility, density) feed the core via "hazard/raster weights", altering link/cell costs used during routing.

6.4.1. End-to-end workflow (process view)

- Load profile & area. In the Agent Profiles Plugin, load a JSON profile and select an Area polygon.
- Generate agents. Call the core's sampler ("profiles, sampling"): either uniform acceptance–rejection (optional min spacing) or weighted by a raster/vector weight field. The plugin writes an Agents layer.
- Set goals. In Evac Planner, pick one or more Goals (optionally with priority/capacity).
- Plan routes. Evac Planner calls the core ("routing, metrics"). The core reads Data Layers, applies hazard/raster weights from External Data, and computes Routes/Trajectories.
- Inspect & visualize. Trajectories appear on the map; the Inspector shows per-agent/per-route details and summary metrics. Optionally send "trajectories 3D" to QGIS 3D View.
- Persist & repeat. Save the scenario config via Scenario Manager ("config") and, if needed, persist layers to PostGIS. The same configuration can be rerun on new data or with different sampling/routing options.

7. Conclusions

This paper presents the conceptual architectural model for integrating intelligent agents into QGIS for planning evacuations. The proposed solution divides architecture into three layers: data layer, agent layer, and application layer. This separation ensures reusability and clear separation of responsibility. It allows modelling of different scenarios to connect geospatial layers and agent parameters. The key feature of this architecture is flexibility, especially in terms of sampling strategies, routing adapters, and crowd management. All these modules are easily replaceable. PostGIS and QGIS integration provides efficient data storage, fast analysis, storage for different scenarios, and most importantly, scalability. With a 3D display, it is easy to analyze multi-layered objects and slopes.

The model does come with limitations – movement and interaction assumptions are not yet calibrated. Output data accuracy depends on the input data's truthfulness. There is no simulation data with many agents for performance analysis.

In the future, a computational simulation loop could be implemented, including crowd and collision management, and graph-based routing with multiple criteria. The plan is to calibrate and exercise on real-world scenarios, provide early-warning system integration and real-time sensor integration, and improve the UI.

This type of route planning is widely applicable – fire evacuations, floods, earthquakes, mass events, industrial complexes, critical infrastructure, training, etc. The architecture is designed to provide easy knowledge transfer, scenario replacement, and gradual introduction of advanced algorithms.

Acknowledgment:

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Artificial Intelligence for Assisting People with Sensory and Cognitive Disabilities

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Abstract:
This paper explores and compares various applications of artificial intelligence (AI) to support people with sensory and cognitive disabilities. A detailed analysis and classification of existing intelligent solutions were conducted according to their primary functions. Furthermore, a convolutional neural network (CNN) for image classification was implemented and evaluated. The results indicate that appropriately selected AI technologies can provide functional support, and significantly improve the quality of everyday life for individuals with diverse disabilities. The study highlights both the potential and practical value of integrating AI-based systems in assistive technologies, emphasizing their role in enhancing accessibility, autonomy, and inclusion.

Keywords:
Artificial intelligence, assistive technologies, sensory disabilities, cognitive disabilities, convolutional neural networks

1. Introduction

In recent decades, artificial intelligence has opened new opportunities for the integration of people with disabilities into all spheres of life. A particularly important role in this transformation is played by intelligent systems, which enable automation, adaptation, and personalization of services and content. The term *intelligent systems* (IS) *[1]* refers to software and hardware solutions based on algorithms from artificial intelligence, machine learning (ML), and natural language processing (NLP), designed to improve user interaction and increase functional independence.

This paper focuses on intelligent systems aimed at supporting individuals with sensory and cognitive disabilities. Sensory disabilities include impairments of vision, hearing or sensory integration while cognitive disabilities involve conditions that affect learning, memory, communication, and decision-making. These difficulties often create significant barriers to accessing educational resources (e.g., the unavailability of braille textbooks or challenges in following digital lectures), communication tools (such as speech or visual applications without alternative modes of expression), and daily activities (including mobility, device management, or performing tasks at home and in public spaces).

Therefore, there is a growing need for inclusive intelligent systems that apply adaptive interfaces, multimodal interactions, and personalized algorithms to meet the diverse cognitive and sensory needs of these individuals. Such challenges can be significantly mitigated through the application of appropriate technological solutions that leverage the advantages of modern artificial intelligence.

2. Intelligent Systems Supporting People with Disabilities

Intelligent systems play an increasingly important role in facilitating the daily lives of people with disabilities by providing innovative technological solutions based on artificial intelligence. These systems offer practical tools that enhance communication, navigation, access to information, and the performance of everyday tasks. A classification of such systems according to their primary functionality is presented below. There are scientific studies that underline the importance of collaboration among several disciplines in order to create IS that promotes equity and empowerment, such as: AI specialists,

technologists, policymakers, healthcare providers, and also, end-users [2]. Some of the scientists take into account services that can improve life quality, minimize environmental impacts, improve health service, improve security and accessibility for People with Disabilities, and therefore they propose a Model for Assistive Smart Cities [3], or implement identity recognizer, facial expression recognizer, gesture recognizer, vocalization recognizer as part of IS [4]. There are IS where AI holds transformative potential in advancing equitable and inclusive healthcare, promoting autonomy, accessibility, and well-being for people with disabilities and at the same time addressing ethical challenges, overcoming limitations, and fostering user-centered design [5, 6, 7], at the same time having in mind disability – friendly AI implementation according to the "rules to ensure that artificial intelligence systems are used safely and ethically, with a particular focus on protecting human rights" [8].

2.1. Classification of IS by Function

IS supporting people with disabilities can be classified into several categories according to their primary function. In order to research their way of work and perform comparative analysis of IS we use the most important implementations of those systems already applied across North and South America, Europe, South Africa, Asia, and Australia [9, 10]. They can be classified into the few categories:

Communication support IS are a category that consists of applications and devices designed to facilitate communication for individuals with various cognitive and motor impairments. These systems provide alternative methods of expression and interaction by employing advanced technologies such as speech processing, brain–computer interfaces (BCI), augmented reality (AR), and text-to-speech (TTS) synthesis. Some of the systems in this category include [11]:

- *Expressia* – facilitates communication for non-speaking individuals
- *TelepatiX* – generates speech through blinking control
- *Voiceitt* – recognizes non-standard speech
- *Cognixion ONE* – enables communication using brain signals and augmented reality
- *Prometheus* – translates brain signals and facial expressions into digital commands

Visual support IS are a category of IS designed for individuals with partial or complete visual impairment. These solutions rely on advanced sensory and cognitive technologies to enable improved orientation, object recognition, text reading, and safe navigation in the environment [12, 13, 14]. By combining artificial intelligence, computer vision, spatial audio, and mobile or wearable devices these systems provide practical support for daily living. Some of the systems in this category include:

- *Seeing AI* – describes the environment and text through the camera
- *Be My Eyes* – video assistance from volunteers
- *Aira* – navigation and spatial description via remote operators
- *Microsoft Soundscape* – audio navigation with 3D spatial sound
- *OrCam MyEye* – reads text and recognizes objects through a camera

Hearing support IS are a category of IS that provide inclusive communication through automatic translation, speech transcription, visual notifications, and digital sign language interpreters. Modern solutions leverage technologies such as automatic speech recognition (ASR), animated avatar generation, natural sign language synthesis, and mobile applications for real-time interaction. Some of these systems are based on machine learning algorithms and computer graphics, enabling highly accurate and context-aware translations that are essential for daily communication, and educational activities. Some of the systems in this category include:

- *ProDeaf* – translates speech into sign language (LIBRAS)
- *HandTalk* – automatically converts text and speech into sign language
- *Ava* – provides real-time speech transcription for deaf individuals

Motor support and accessibility IS are a category of intelligent solutions that provide innovative systems that enable interaction through alternative methods such as eye-tracking, voice control, head movement tracking, or direct brain–computer communication [15]. To overcome the challenges faced by individuals with motor impairments in using traditional devices and physically managing their

environment these systems integrate computer vision, voice interaction, BCI technology, and personalization algorithms. Some of the systems in this category include:

- *eSSENTIAL Accessibility* – navigation through head movement or voice;
- *Tobii Dynavox* – device control via eye-tracking
- *Polly (Parrots Inc.)* – AI assistant for wheelchair users

Spatial and infrastructure support – this category of intelligent systems is of particular importance for individuals with disabilities, as the physical environment can directly facilitate or hinder their mobility, participation in public life and access to resources. These solutions support spatial orientation and accessibility awareness, representing a vital component in the creation of inclusive societies:

- *Wheelmap* – identifies wheelchair-accessible public spaces

3. Comparative analysis

3.1. Communication support systems

The intelligent solutions included in this category (Expressia, TelepatiX, Voiceitt, Cognixion ONE, and Prometheus) exhibit significant variation in their technological approaches, the complexity of their implementation, and the degree to which they adapt to the individualized needs of users. In Table 1 comparative analysis of these type of intelligent systems is shown.

Table 1:
Comparative analysis of communication support systems

System	Expressia	TelepatiX	Voiceitt	Cognixion ONE	Prometheus
Interaction method	Symbols, Icons, Touch	Eye blink	Speech (non-standard)	Brain signals + AR	EEG (electroencephalogram) + facial expressions
Technologies	TTS, Cloud Sync, AI adaptation	Eye tracking, Blink detection, TTS, AI	Custom ASR, ML, Internet of Things integration	Eye tracking, TTS, AR, EEG, Edge AI	EEG, AI, Eye tracking
Required level of Motor Control	Low	Very low	Average	None	None
Personalization	High	Average	High	High	High
Works offline	Yes	Partial	Yes	Yes	Yes
Platform	Android/iOS/ Web applications/ CRM solutions	Android/iOS	Android/iOS	Independent device	Cloud-based (Azure, Amazon)/ Local servers/ Internet of Things devices

All of the analyzed solutions incorporate some form of intelligent data processing, and provide alternative channels of communication, yet they differ in terms of technical sophistication and adaptability. Expressia and Voiceitt emerge as the most accessible options for broader user groups, whereas Cognixion ONE and Prometheus integrate advanced technologies that require more specialized configurations. TelepatiX represents a balanced compromise, particularly suitable for users with highly limited motor abilities.

When personalization and offline functionality are considered, the systems demonstrate an orientation toward individual needs, though the extent of adaptation, and the required initial setup vary. Consequently, the selection of a particular solution often depends on the type and degree of disability, as well as the availability of technical support, and the user's budget.

3.2. Visual support systems

The intelligent solutions in this category (Seeing AI, Be My Eyes, Aira, Microsoft Soundscape, and OrCam MyEye) take different approaches to supporting independence and spatial orientation for people with visual impairments. They combine mobile apps, wearable devices, and 3D audio technologies to provide information about the surrounding environment through sound or human guidance (shown in Table 2).

Table 2:
Comparative analysis of visual support systems

System	Seeing AI	Be My Eyes	Aira	Microsoft Soundscape	OrCam MyEye
Interaction method	Camera + Touch	Video call+ Speech	Video call + Smart glasses	3D audio navigation	Gestures + Pointing
Technologies	Computer vision, Optical character recognition, TTS	WebRTC, GPT-4, Push notifications	Cloud streaming, GPS, Smart glasses	Head Related Transfer functions (HRFT), Bluetooth	Edge AI, Optical character recognition, Computer vision, Gesture recognition
Required level of Motor Control	Low	Low	Low	Low	None
Personalization	Average	Low	Average	Low	Average
Works offline	Partial	No	No	Partial	Yes
Platform	iOS	Android/iOS	Android/iOS	iOS	Independent device

OrCam MyEye operates entirely offline, ensuring both privacy and uninterrupted availability, while Seeing AI offers partial offline functionality. In contrast, Be My Eyes and Aira rely on live human assistance, which can be highly effective but requires a stable internet connection. Microsoft Soundscape stands apart by adopting a unique navigation approach through 3D audio cues rather than visual or video-based interaction.

Systems that employ on-device intelligence (such as OrCam MyEye) provide the greatest autonomy, while human-assisted platforms (Be My Eyes and Aira) may be more advantageous in situations where contextual interpretation and accuracy are paramount.

3.3. Hearing support systems

The intelligent solutions in this category (ProDeaf, HandTalk, and Ava) use different technological approaches to enhance access to communication and information. They illustrate three practical solutions in this area: automatic transcription, sign language translation, and the use of visual interfaces.

All analyzed systems require only minimal motor control, which makes them accessible to a wide range of users. As shown in Table 3, ProDeaf and HandTalk primarily support visual communication via sign language, whereas Ava provides a textual channel through real-time speech transcription. HandTalk stands out for its level of personalization thanks to customizable avatars and web integrations. The main distinction lies in the communication medium: visual (ProDeaf and HandTalk) versus textual (Ava).

Table 3:
Comparative analysis of hearing support systems

System	ProDeaf	HandTalk	Ava
Interaction method	Text/Speech → Sign language	Text/Speech → Sign language	Speech → Text
Technologies	Text-to-Sign,3D avatar, TTS, STT	Text-to-Sign, Speech-to-Sign, 3D avatar, Cloud SDK	ASR, Speaker diarization, Cloud synchronization, Bluetooth
Required level of Motor Control	Low	Low	Low
Personalization	Average	High	Average
Works offline	Partial	Partial	Partial
Platform	Android/iOS	Android/iOS/Web	Android/iOS

All systems offer partial offline functionality, giving users a degree of flexibility. However, certain advanced features (such as cloud synchronization and group interactions) require an internet connection.

3.4. Motor support and accessibility systems

The intelligent solutions in this category (eSSENTIAL Accessibility, Tobii Dynavox, and Polly (Parrots Inc.)), are designed for users with limited or entirely absent hand function but they differ in their technological approaches, level of autonomy, and target user group. The comparative analysis is shown in Table 4.

Table 4:
Comparative analysis of motor support and accessibility systems

System	eSSENTIAL Accessibility	Tobii Dynavox	Polly (Parrots Inc.)
Interaction method	Voice, Head movement	Eye movement	Voice, Head movement
Technologies	Virtual Keyboard, Voice input, Head-tracking	IR eye-tracking, Augmentative and Alternative communication, TTS, ML	AI assistant, Computer vision, Head-tracking
Required level of Motor Control	Low	Very low	Low
Personalization	Average	High	High
Works offline	Partial	Partial	Partial
Platform	Android/iOS/Web	Independent device	Android/iOS

Tobii Dynavox employs highly precise eye-tracking technology, enabling direct device control without physical touch, while Polly combines mobility, artificial intelligence, and environmental

interaction via IoT devices. eSSENTIAL Accessibility is the easiest to implement and serves as a software-based alternative accessible through existing devices.

Regarding personalization, Polly and Tobii Dynavox offer the greatest flexibility through adaptive algorithms and individual profiles, whereas eSSENTIAL Accessibility provides basic configuration options. Offline functionality is limited across all systems due to reliance on cloud services or remote communication.

4. Fundamental IS Architecture for Supporting People with Disabilities

Based on the previously analyzed intelligent solutions, it can be observed that assistive systems for individuals with diverse disabilities have fundamental architecture where several interrelated components manage data acquisition, processing, and feedback delivery, enabling the system to adapt to the specific needs of each user [16]. Regardless of their particular application, these systems typically feature a layered architecture, consisting of: an input layer, a processing layer, an adaptation and personalization layer, and an output layer. The in-depth analysis of the architecture shows that the input layer is responsible for receiving sensory, speech, visual, or textual data. Depending on the system, this may include cameras, microphones, eye-tracking devices, EEG sensors, or touch interfaces. The processing layer encompasses the intelligent logic of the system. It is typically based on artificial intelligence (AI), machine learning (ML), deep learning (DL), or natural language processing (NLP) algorithms. This layer performs tasks such as speech recognition, object classification, intention prediction, translation, or response generation. The adaptation and personalization layer enables the system to adjust based on the user profile, usage history, and contextual information. Techniques commonly applied in this layer include reinforcement learning, content-based filtering, or rules defined by caregivers or therapists. Finally, the output layer generates visual, auditory, or mechanical feedback (e.g., speech, text, or signals to IoT devices). It may include screens, speakers, haptic vibrations, or synchronization with other devices.

4.1. Key Technologies and Frameworks Utilized in the Reviewed Systems

The analysis of intelligent systems developed to support individuals with cognitive and sensory disabilities highlights a number of widely adopted technologies and software frameworks. Presented below are some of the most prominent technologies along with their respective applications in the design of assistive intelligent systems:

- *TensorFlow* and *PyTorch* – these frameworks are extensively utilized for implementing machine learning and deep learning algorithms
- *OpenCV* – a computer vision library applied in applications such as facial recognition, eye-tracking, and gesture analysis
- *Speech Recognition (ASR) libraries* – used for converting spoken language into text (such as Google Speech-to-Text, Mozilla DeepSpeech and Whisper (OpenAI))
- *Text-to-Speech technologies* – applied to generate synthesized speech (such as Google Text-to-Speech, Amazon Polly and Microsoft Azure TTS)
- *Natural Language Processing (NLP) tools* – libraries utilized for natural language understanding (such as Hugging Face Transformers and spaCy)
- *Internet of Things (IoT) and edge computing platforms* – facilitate the management of connected devices (e.g., in smart home environments) and enable real-time data processing close to the user (as exemplified in systems like Polly)
- *Brain–Computer Interface (BCI) SDKs* – applied for the analysis of EEG signals to support interaction based on brain activity (such as with Emotiv or OpenBCI)

5. Practical Implementation of ANN for Assisting People with Visual Disabilities

We would like to highlight the importance of protecting and ensuring the safety of people with visual disabilities (PVD). Devices typically used in IS for helping PVD include sensors like infrared, ultrasonic, and imagery to gather environmental data, which is then processed by machine learning techniques [17]. During the research an artificial neural network (ANN) model was created to perform image classification aiming to support assistive solutions for individuals with visual difficulties.

5.1. Model: Image Classification and Class Interpretation

The model performs image classification using a moderately complex Convolutional Neural Network (CNN) built with Keras and TensorFlow. It consists of three convolutional blocks with batch normalization, pooling, and dropout, followed by fully connected layers mapping features to output classes. The model was trained on the CIFAR-10 dataset for 30 epochs with validation on the test set. The evaluation included both accuracy and a confusion matrix to evaluate class-specific performance.

Accurate class interpretation is essential for assistive systems for individuals with visual impairments, as it provides the basis for generating accessible outputs, such as synthesized speech or haptic feedback.

The model was implemented in Python using the Jupyter environment via Google Colab. This setup facilitates straightforward access to the required libraries, GPU resources for accelerated computation and easy sharing of results.

5.1.1. Results of the CNN model for image classification

The CNN model, designed for image classification, was trained on the CIFAR-10 dataset and it was evaluated twice. In the first evaluation, the model was tested over 25 epochs, achieving a test accuracy of 83.17%. In the second evaluation, the model was tested over 30 epochs achieving a test accuracy of 84.17%.

The model correctly predicted the class of the examined image as dog in both cases, which matches the true label.

This demonstrates the model's capability to accurately interpret visual input, confirming its suitability as a foundational component in assistive systems for individuals with visual impairments, where reliable image classification can support the generation of meaningful output information.

Figure 1 shows the confusion matrix for the model for different objects and as seen, the confusion between cat and dog is observable. This is somehow understandable, taking into account the similarity of appearance of these two animals.

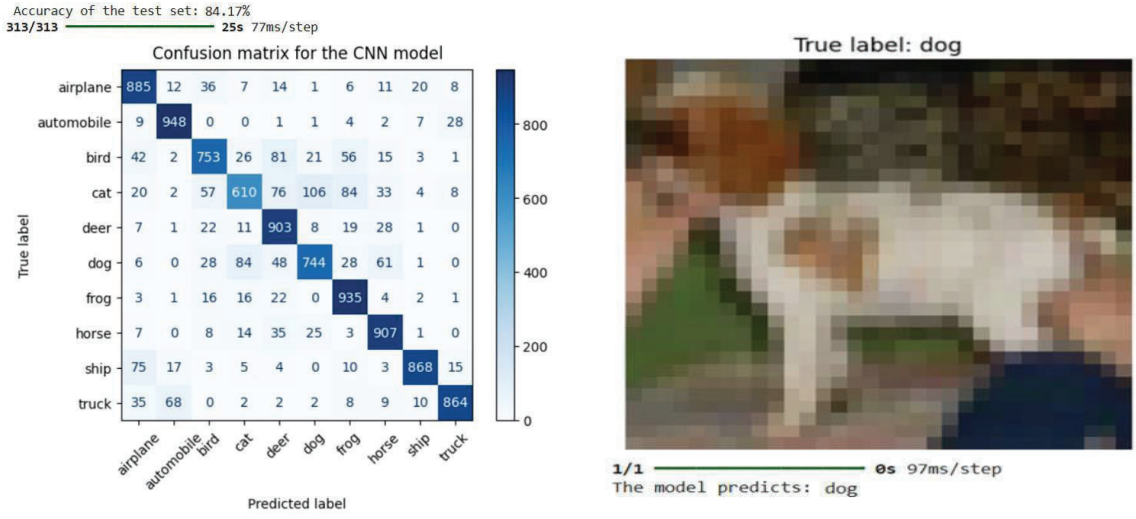


Figure 1: Result for the CNN model (after 30 epochs of the training process)

6. Conclusion

This paper presents a comprehensive investigation, analysis, and practical demonstration related to artificial intelligence aimed at supporting individuals with sensory and cognitive disabilities. By reviewing existing solutions, the main types of intelligent systems, including applications, devices, and platforms, were identified and categorized according to their functionality.

As a result of the comprehensive analysis, a generalized architecture for intelligent systems was proposed, informed by the current solutions. This architecture consists of multiple interconnected layers: an input layer, a processing layer, an adaptation and personalization layer, and an output layer, each serving a distinct role in facilitating interaction and responsiveness.

The practical component involved the implementation of a CNN model addressing visual impairments. Trained on the CIFAR-10 dataset, the model demonstrated robust image classification capabilities with an accuracy of 84.17%, providing a reliable foundation for integration into assistive technologies.

As a conclusion it is evident that the theoretical insights and practical results underscore the pivotal role of intelligent systems in fostering inclusive technological environments. The findings indicate that even relatively straightforward approaches, such as the CNN-based image classifier can deliver tangible support in everyday activities. Looking forward, the adoption of more advanced models, larger datasets, and greater personalization holds considerable promise for enhancing the quality of life for diverse users, contributing to a society where technology serves the needs of all individuals equally.

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Comparative Study of Depth-Search Algorithms: DFS, DLS, and IDDFS in Undirected Unweighted Graphs

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Abstract:
Depth-search algorithms are among the key algorithms for exploring graph structures, with wide applications in the fields of artificial intelligence, computer networks, and information systems. In practice, various variants exist that differ in their implementation methods and evaluation criteria. The aim of this study is a comparative analysis of three depth-search algorithms: DFS (Depth-First Search), DLS (Depth-Limited Search), and IDDFS (Iterative Deepening Depth-First Search). The experimental comparison was conducted on generated unweighted graphs of varying sizes, assessing algorithm performance according to completeness, optimality, time complexity, and space complexity criteria. The results showed that, although it requires more time due to repeated exploration of shallower levels, the IDDFS algorithm stood out as the most stable and reliable solution, as it ensures both completeness and optimality, unlike DFS and DLS. The findings provide insight into the practical implications of algorithm choice and can serve as a basis for further research in optimizing depth-first search algorithms and their applications across various domains.

Keywords:
Graphs, depth-search algorithms, DFS, DLS, IDDFS, completeness, optimality, time complexity, space complexity

1. Introduction

Search algorithms hold a special place in computer science when it comes to solving various problems that involve exploring and finding solutions within graph structures. Their universality is reflected in the fact that they are applied across numerous domains, serving as a foundation for solving complex problems that require a systematic approach. Regardless of whether the structures are small or consist of thousands of entities, search algorithms can serve as powerful tools for finding specific data or performing a comprehensive search.

A particularly significant group within search algorithms consists of algorithms based on deep search. They are characterized by simple implementation and wide applicability in complex systems such as artificial intelligence, computer networks, and information systems. However, their practical value largely depends on specific application conditions, data structures, and the goals to be achieved. For this reason, choosing the appropriate algorithm is not merely a technical decision but a strategic one, directly affecting the quality and efficiency of the obtained solutions.

In practice, different scenarios require different approaches. For example, in applications where time is a critical factor, preference may be given to an algorithm that quickly finds any solution, even if it is not optimal. On the other hand, in areas where finding the shortest path or ensuring search completeness is crucial, it is necessary to use algorithms that guarantee accuracy and reliability, even if this entails higher consumption of time or memory resources. This demonstrates that there is no universally best solution for all situations and the choice of algorithm depends on balancing completeness, optimality, execution time and memory usage.

For this reason, understanding the behavior of different algorithms under controlled research conditions is of crucial importance. Comparative analysis enables the identification of the strengths and weaknesses of individual approaches and allows for well-founded decisions in practical applications. Such analysis not only contributes to a better theoretical understanding of algorithms but also provides

concrete guidelines for their use in real-world systems, where requirements are often complex and multi-layered.

Based on this, the aim of this study is to provide a comprehensive comparative analysis of the DFS, DLS, and IDDFS algorithms.

The structure of the paper is designed to establish a clear relationship between the theoretical framework, the experimental procedure, and the analysis of the obtained results. The theoretical section presents the fundamental concepts related to search algorithms, defines the evaluation criteria, describes the depth-search algorithms, and includes an analysis of relevant previous research. Following this, the research section explains the experimental procedure, including details related to graph generation and performance measurement. The results are then presented, followed by their analysis and discussion, upon which conclusions and guidelines for future research are formulated.

Thus, by comparing depth-search algorithms according to the evaluation criteria (completeness, optimality, time complexity, and space complexity), this paper lays the groundwork for a deeper understanding of the behavior of search algorithms and their practical implications, as well as for selecting the most appropriate algorithm depending on the specific requirements and nature of the problem being solved.

2. Background

In this section the theoretical foundation will be presented with appropriate literature calls.

2.1. Search algorithms

Search is one of the fundamental operations in data structures and, as such, is intended for finding a specific element in a sorted or unsorted list of data [1]. As one of the key tools of artificial intelligence, it forms the basis for solving complex problems through the exploration of the state space [2]. Within graphs, search algorithms are used for both general and targeted exploration [3]. In [4] and [5], the authors defined the basic terminology related to search algorithms, which is presented in Table 1. A comprehensive literature review can be found in the book [4].

Table 1:
Terminology for search algorithms

Term	Explanation
Search	A step-by-step procedure for solving a search problem in a given search space
Search space	A set of possible solutions that the system may have
Start state	The state from which the agent begins the search
Goal state	A state in which all formulas evaluate to true
Goal test	A function that observes the current state and returns whether the goal has been achieved or not
Search tree	A tree that represents the search problem
Root of the search tree	The root node that corresponds to the initial state
Actions	A description of all possible actions available to the agent
Transition model	A description of what each action does
Path cost	A function that assigns a numerical cost to each path
Solution	A sequence of actions that leads from the start node to the goal node
Optimal solution	A solution that has the lowest cost compared to all other solutions
Graph traversal	The process of visiting all nodes in a graph

2.2. Evaluation criteria for selecting a search algorithm

Since there are many available search algorithms, the choice of the appropriate one depends on the specifics of the problem. When selecting a search algorithm, special attention should be paid to the evaluation criteria [2, 4, 5, 6, 7, 8]:

- Completeness – the ability to find a solution if one exists.
- Optimality – the ability to find the best solution among all possible solutions.
- Time complexity – the time required to find a solution.
- Space complexity – the maximum amount of memory required at any point during the search.

2.3. Depth-search algorithms

A special group of search algorithms is made up of depth search algorithms which, as the name itself suggests, perform the search of data structures (trees and graphs) in depth. This group includes the basic form of the depth-first search algorithm – DFS, as well as the modifications of this algorithm – DLS and IDDFS.

2.3.1. Depth-First Search algorithm

DFS (Depth-First Search) is an algorithm for traversing a graph that relies on the stack principle (LIFO – "Last In, First Out"), meaning that the last inserted node is the first one to be removed [2, 4, 5, 6, 7, 10, 11]. The algorithm starts from the root of the structure and explores one branch to its end, after which it backtracks and proceeds to the next branch [4, 6, 7, 10, 12, 13]. The advantage of the depth-first search algorithm over other types of search algorithms is that it requires little memory because only the stack of nodes on the path from the root to the current node is stored, which makes it particularly suitable for situations with limited memory or when there is a large number of possible solutions with potentially long paths, especially in cases where almost all paths lead to a solution [2, 4, 7, 11]. On the other hand, DFS does not guarantee that the shortest path will be found [2, 4, 5, 7, 10, 11, 12]. Due to its characteristics, DFS is often used for identifying cycles and strongly connected components in a graph, as well as solving puzzles with a unique solution [2].

2.3.2. Depth-Limited Search algorithm

DLS (Depth-Limited Search) represents a variant of DFS in which the maximum search depth is predefined [2, 4, 5, 6, 7, 10, 11, 13]. A node located at the depth limit of this algorithm is treated as if it has no successors, so the search terminates once the specified depth limit is reached [4, 6, 7, 10, 11]. The main advantages of this approach are lower memory and time consumption [2, 4, 7, 11]. However, DLS is incomplete because it will not find a solution if it lies below the defined limit, and even if a solution is found, it may not be optimal [2, 4, 6, 7, 11]. DLS is applied when it is known that the solution lies within a certain depth or when it is desirable to limit memory usage, which is why it also finds application in the field of game theory [2, 7].

2.3.3. Iterative Deepening Depth-First Search algorithm

IDDFS (Iterative Deepening Depth-First Search) combines the characteristics of depth-first search and breadth-first search algorithms [2, 4, 5, 11, 12]. The algorithm repeatedly runs DLS with a gradually increasing depth limit until the goal is found, starting from depth 0, then 1, 2, and so on, until a solution is discovered [2, 4, 5, 6, 7, 10, 11, 13]. The advantage of this approach lies in the fact that it combines the speed of BFS with the memory efficiency of DFS, while also ensuring completeness and optimality when all edge costs are equal [2, 4, 7]. The drawback of the algorithm is the repeated processing of

previously explored nodes, which may lead to exponential execution time depending on the depth of the solution [2, 4, 7]. IDDFS is particularly suitable for searching game trees and problems with unknown solution depth, and it is applied in network analysis, solving puzzles with a unique solution, cycle detection in graphs, topological sorting of directed acyclic graphs, and N-queens problems [2, 7].

2.4. Related works

Previous studies comparing depth-search algorithms have reached significant conclusions:

- The authors in [9] found that among all uninformed search strategies, Iterative Deepening Depth-First Search (IDDFS) achieves the best performance in large state spaces, particularly when the solution depth is not known in advance.
- Results of experimental research in a two-dimensional grid environment indicate that IDDFS provides by far the best performance in terms of overall execution time, although it requires a significantly larger number of expanded nodes compared to DFS and DLS [10].
- In the study [11], aimed at developing didactic interactive software for understanding and applying uninformed state space search strategies, it was established that Iterative Deepening Depth-First Search (IDDFS) offers an advantage in terms of space complexity compared to Depth-Limited Search (DLS).

3. Research description

As the research problem relates to examining the performance of different variants of depth-search algorithms, and the research subject involves the comparison of depth-search algorithms, this study was conducted with the aim of comparing the performance of depth-search algorithms: DFS (Depth-First Search), DLS (Depth-Limited Search), and IDDFS (Iterative Deepening Depth-First Search). The evaluation was carried out according to standard criteria for assessing search algorithms: completeness, optimality, time complexity, and space complexity.

The experiment was implemented by coding the algorithms in Python, which enabled the generation of graphs, execution of searches, and precise performance measurement. For the implementation of the DFS, DLS, and IDDFS algorithms, standard approaches described in the previous chapter were used. The goal of the experiment was to traverse the graphs. Randomly generated undirected and unweighted graphs with 100 and 5000 nodes were used. As output data, upon executing the experiment, the metrics necessary for comparing the algorithms are obtained, which were recorded during the experiment and saved in the corresponding CSV file, and which include information on whether the target node was found (Found), the path from the start node to the target node (path) and its length (PathLen), the number of visited nodes (Visited_Nodes), the algorithm's execution time in milliseconds (Time (ms)), and the maximum memory used (Max_Memory (KB)). For the DLS algorithm, the depth limit used (DLS_Limit) was additionally recorded.

Since the DLS algorithm requires setting a search depth, the experiment examined the impact of different depth limits:

- less than the optimal path length (shortest – 1);
- equal to the optimal path length (shortest);
- greater than the optimal path length (shortest + 2).

The shortest path, labeled as "shortest", was obtained using the shortest_path_length() function, respectively, the BFS algorithm, which was used solely for the purpose of determining the shortest path. This value, therefore, was used as a reference for setting the aforementioned experimental cases, enabling a precise assessment of the DLS algorithm’s performance.

The evaluation criteria were determined as follows:

- Completeness – the algorithm started the search with the intention of traversing the entire graph. The parameter "Found" would be set to "True" if the traversal was successfully completed. If the algorithm finished the search without traversing the entire graph, "Found" would be set to "False".
- Optimality – the function shortest_path_length() was used to calculate the length of the shortest path. The length of the path found by the algorithm was then compared with this value. If they

matched, the solution was considered optimal; otherwise, it was deemed non-optimal.

- Time complexity – at the start of each search, a timer was triggered (time.perf_counter()), and upon completion, the measured value was recorded in milliseconds as "Time (ms)".
- Space complexity – before each search, the tracemalloc module was activated to monitor memory usage. During execution, the maximum allocated value (tracemalloc.get_traced_memory()[1]) was recorded, converted into kilobytes, and saved as Memory (KB).

4. Research results

In this chapter, the research results are presented using tabular and graphical representations, which illustrate the performance of the compared algorithms according to the defined evaluation criteria. For clarity and ease of visualization, two graphical representations are provided for each of the two complexity criteria (time and space): one for graphs with 100 nodes and one for graphs with 5,000 nodes. The completeness and optimality of the algorithms are summarized in a single table to concisely and clearly present the relevant algorithm characteristics, which remained unchanged for both the 100-node and the 5,000-node graph examples.

The analysis of algorithm completeness showed that DFS and IDDFS successfully performed graph traversal in all experiments, regardless of the size of the generated graphs. In contrast, DLS exhibited certain deviations, which were directly dependent on the set depth limit. In cases where the specified limit was insufficient to traversal of the entire graph, DLS proved to be incomplete.

Regarding optimality, DFS did not prove to be an optimal algorithm. DLS achieved optimality only when the depth limit was set precisely to match the depth required to traverse the entire graph. In all other cases, DLS was not optimal. Unlike these two algorithms, IDDFS consistently generated optimal solutions in the analyzed scenarios.

The results regarding the completeness and optimality of the DFS, DLS, and IDDFS algorithms are presented in Table 2.

Table 2:
Algorithm completeness and optimality

Algorithm	Completeness	Optimality
DFS	Yes	No
DLS (shortest – 1)	No	No
DLS (shortest)	Yes	Yes
DLS (shortest + 2)	Yes	No
IDDFS	Yes	Yes

The time complexity of the algorithms was negligible for graphs with 100 nodes, where all algorithms completed the search in less than 1 milliseconds. However, the differences became significant for large graphs with 5000 nodes, where the algorithms demonstrated varying execution speeds. Overall, DFS proved to be the most efficient, consistently exhibiting the shortest execution times across all graph variants. In contrast, DLS and IDDFS tended to require significantly longer execution. It was shown that DLS can cause particularly high time consumption if the depth limit is set too high. Figures 1 and 2 show the comparison of the execution times of the DFS, DLS, and IDDFS algorithms.

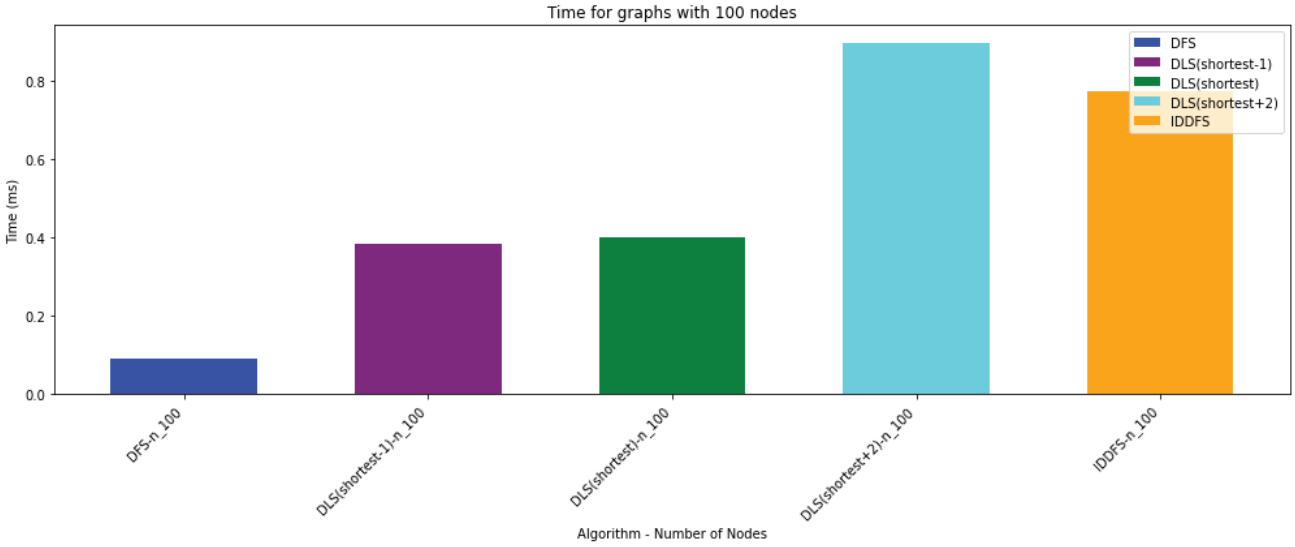


Figure 1: Algorithm time complexity for graphs with 100 nodes

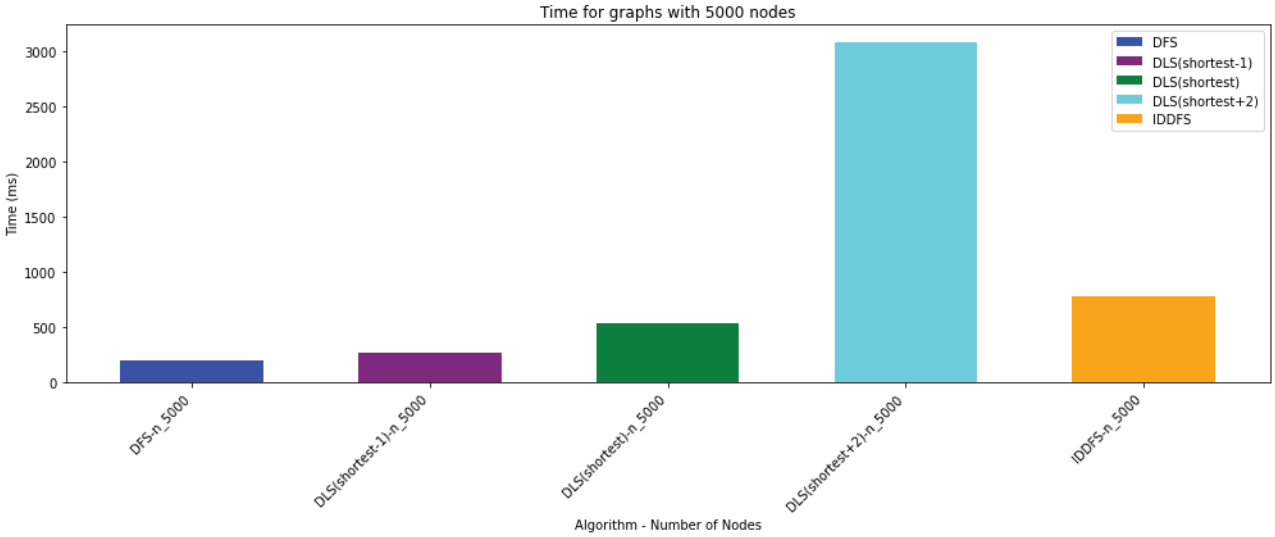


Figure 2: Algorithm time complexity for graphs with 5000 nodes

The analysis of memory usage on a small graph with 100 nodes and a large graph with 5000 nodes showed that the DFS algorithm consumed significantly more memory compared to DLS and IDDFS. On the smaller graph, the differences in memory usage were roughly double, but numerically relatively small due to the small number of nodes. Traversing the large graph with 5000 nodes demonstrated that the memory requirements of the DFS algorithm increase, reaching almost four times the usage of the DLS and IDDFS algorithms. A comparison of the algorithms in terms of space complexity is presented in Figures 3 and 4.

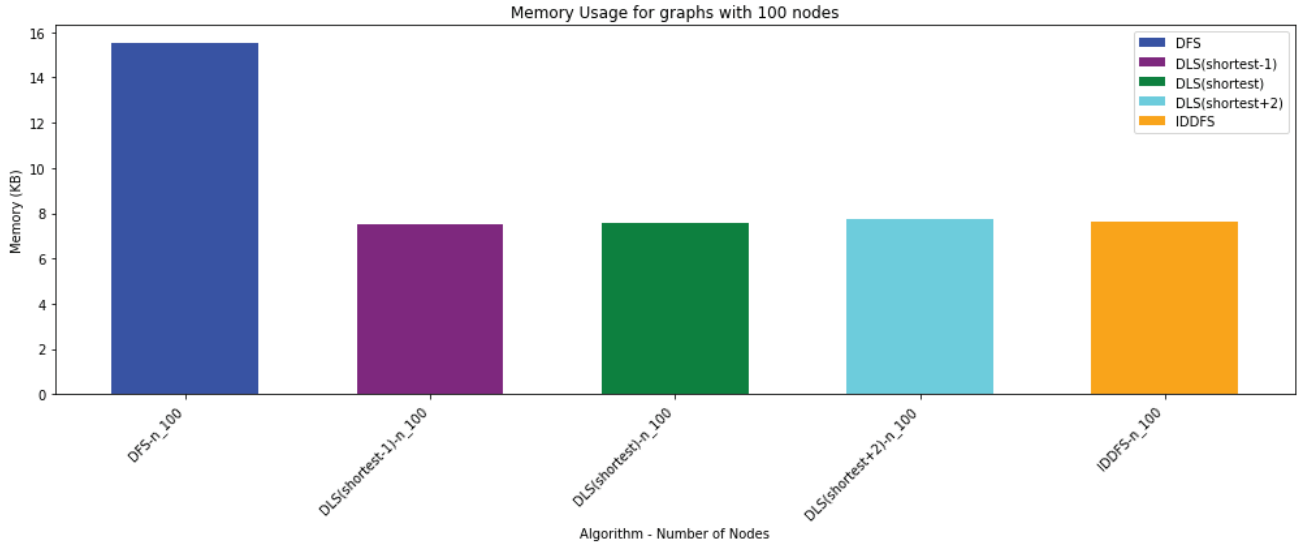


Figure 3: Algorithm space complexity for graphs with 100 nodes

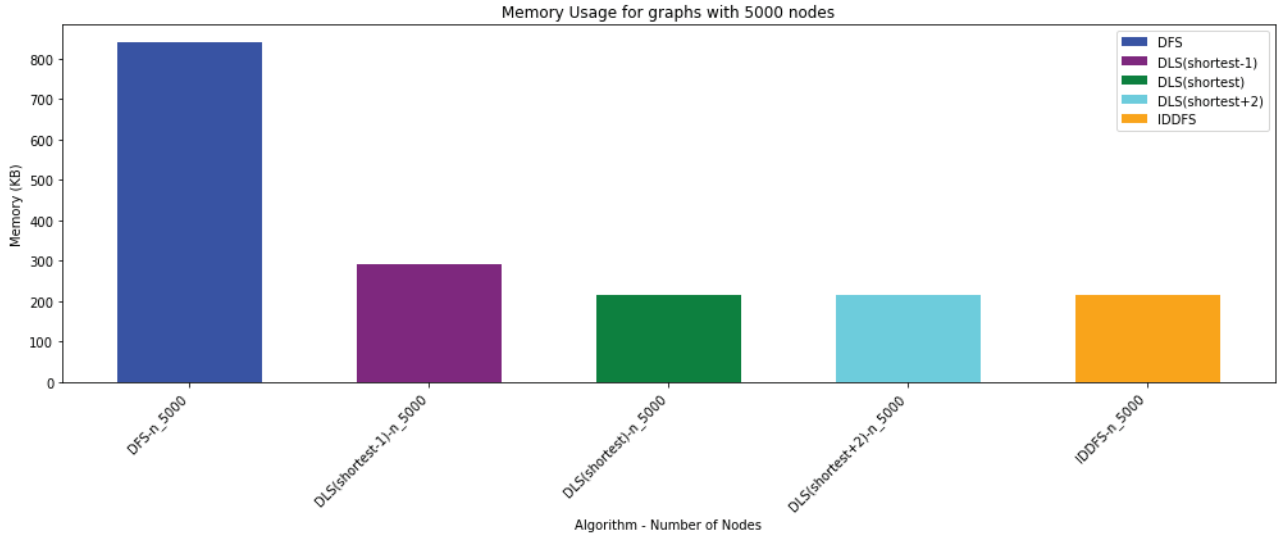


Figure 4: Algorithm space complexity for graphs with 5000 nodes

5. Discussion and conclusion

The conducted research enabled a comparison of the depth-search algorithms DFS, DLS, and IDDFS according to the criteria of completeness, optimality, time complexity, and space complexity. The results demonstrate clear differences among these algorithms.

It was found that DFS and IDDFS successfully performed graph traversals in all cases, while DLS failed to meet the completeness criterion whenever its depth limit was set too low. DFS is complete because it explores all available branches until the entire graph is traversed, while IDDFS expresses this property through iterative deepening, also ensuring traversal of the graph. DLS, on the other hand, is not complete when the depth limit is insufficient, as nodes beyond the predefined limit are not considered.

The DFS algorithm did not prove to be optimal. The reason for this is that DFS follows a single path as deep as possible, which can lead to longer paths. It was also found that DLS can be optimal only when the depth limit is properly set. Therefore, in general, the DLS algorithm has not demonstrated optimality. In contrast, IDDFS proved to be an optimal algorithm, thereby confirming its stability and reliability in all cases. IDDFS achieves this because, by combining iterative deepening with a complete traversal at each level, it eventually successfully finds the shortest path.

The analysis of time complexity showed that DFS was the most efficient in terms of speed, while DLS and IDDFS required more time on graphs with a large number of nodes. DFS has an advantage in speed over the other two depth-search algorithms, as it follows a single path without repeating the search. DLS can be slower when the depth limit is high, while IDDFS requires more time due to repeated executions of DFS with increasing depths.

On the other hand, DLS and IDDFS consumed significantly less memory compared to the DFS algorithm. This is because DFS can have a larger number of nodes on the stack, as it stores all nodes along the current path, whereas DLS and IDDFS limit the search depth and reset the stack at each iteration.

Based on these findings, it can be concluded that IDDFS represents the best choice among the analyzed algorithms in terms of accuracy and reliability. Although it requires longer execution time due to multiple iterations (which is not a burden in the case of smaller graphs), IDDFS provides complete and optimal solutions, while also being efficient in terms of memory consumption. The DFS algorithm may offer faster execution, but it does not guarantee an optimal solution and requires substantial memory resources for large graphs. DLS can be useful in specific situations when the solution depth is known, but otherwise represents a very risky option, particularly in terms of completeness and optimality.

The limitations of this study lie in the fact that the research was conducted exclusively on randomly generated undirected and unweighted graphs with predefined sizes. The results obtained in this study provide practical guidelines for selecting an algorithm depending on specific conditions and requirements, while also opening space for further research that would enable the application of depth-search algorithms in different and more complex scenarios. Recommendations for future work could include extending the analysis to directed and weighted graphs, examining evaluation criteria on even larger graphs, as well as considering hybrid approaches that could combine the strengths of different algorithms.

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Digital School in Transition: Overcoming Resistance Through Mental Models and Organizational Learning

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Abstract:
This theoretical paper explores cognitive and organizational barriers that slow down digital school transformation. Starting from the assumption that the technical implementation of digital tools is not sufficient for sustainable change and transition of a school into a digital learning community, the paper analyzes the interrelations between resistance, mental models, and organizational learning. In addition to the natural inertia of the system and the mismatch between existing processes and new demands, misaligned mental models of school community members further hinder collective understanding and coordinated action. In this context, organizational learning represents a key mechanism for overcoming these obstacles, enabling the harmonization of perspectives, reflection on existing practices, and the systematic adoption of new digital solutions. The paper offers systematized recommendations in the form of an e-guide, aiming to support schools in building a strategic, emotionally intelligent, and inclusive approach to digital transformation. Although theoretically grounded, the paper lays the foundation for further empirical research and practical interventions in education.

Keywords:
digital transition, organizational learning, mental models, resistance, school as a learning organization, digital transformation, e-learning

1. Introduction

The digital transformation of education is a complex, multilayered process that extends far beyond the mere implementation of digital tools and infrastructure. In fact, rather than being limited to technology adoption, it requires profound changes in organizational culture, professional identities, cognitive frameworks, and interpersonal relationships within schools [1,2]. As such, successful transformation depends not only on technical competence but largely on the readiness of community members to engage with and adapt to change [3,4].

A key challenge in this process is resistance to change, which emerges from both structural and functional constraints within schools. Misalignments in organizational structures and mental models further exacerbate these challenges. Mental models—deeply ingrained thought patterns that shape perception, information interpretation, and behavioral responses—play a critical role in determining attitudes toward change, technology adoption, and one's perceived role within the educational system. When mental models are incongruent, they can lead to communication breakdowns, misunderstandings, and fragmented implementation of digital practices [5,6,7,2]

Moreover, the inherent inertia of educational systems, coupled with varying interests and competencies among organizational members, represents an additional barrier to digital transition [8,9]. Such resistance often reflects the difficulty of adapting established routines, professional authority, and institutional values to align with emerging digital practices.

In response to these challenges, organizational learning is widely recognized as a critical mechanism for overcoming barriers and fostering alignment within school communities. Through systematic reflection, collaborative learning, and structured dialogue, schools can cultivate openness, trust, and a culture of continuous improvement. These processes facilitate not only the technical integration of digital solutions but also sustainable transformation of organizational and cognitive structures [10,11,4].

Building on these theoretical foundations, this study examines how process misalignments, mental models, and organizational learning interact during schools' digital transformation. The focus is on understanding organizational and cognitive barriers that hinder effective integration of digital technologies, as well as identifying strategies to overcome them. Based on existing literature, the study proposes the following hypotheses:

Process misalignments significantly slow the digital transition of schools. Incongruence of mental models within the school community hinders the development of the school as a digital learning community. Organizational learning serves as a key mechanism for overcoming barriers and aligning mental models during digital transition.

By analyzing these relationships, the study aims to advance understanding of the organizational and cognitive challenges inherent in digital transformation and provide a foundation for empirical research and strategy development that strengthens schools as digital learning communities.

2. Organizational Learning through Reflection and Dialogue: The Path to Sustainable Digital School Transformation

Sustainable digital transformation in schools requires systematic reflection and open dialogue among community members. Reflection fosters higher-level organizational learning by examining not only pedagogical practices but also underlying mental models and beliefs about teaching, learning, and technology [10,7]. Tools such as digital portfolios, learning analytics, and collaborative platforms support monitoring, personalized feedback, and knowledge sharing [2]

This approach exemplifies double-loop learning, in which organizations question not only strategies and procedures but also the fundamental assumptions, norms, and values guiding their actions [12]. Unlike single-loop learning, which corrects errors within existing frameworks, double-loop learning enables deeper transformation through redefinition of goals, beliefs, and practices. In schools, this underpins the concept of the learning organization, where digital transformation challenges ingrained mental models and fosters a culture of collaboration and continuous improvement [4,11].

Dialogue complements reflection by aligning mental models, reducing resistance, and building shared vision. This is due to the fact that unlike discussion, dialogue emphasizes joint exploration and reshaping assumptions through open exchange [13]. Therefore, structured dialogue strengthens collective intelligence, trust, and strategic decision-making, supporting adoption of digital innovations and mitigating emotional resistance [6,3,9].

Without reflection and dialogue, digital transformation risks remaining a technical change rather than a shift in learning, collaboration, and work practices. Schools that cultivate joint reflection and open communication establish digital learning communities, where knowledge is shared, change is collectively shaped, and resistance becomes a driver of development [4,11]. This approach enhances both individual competencies and collective capacity, enabling sustainable innovation and adaptation.

3. The Influence of Mental Models on Digital School Transformation

Mental models are internal, often unconscious cognitive structures that individuals use to make sense of the world around them [14]. They shape expectations, decision-making processes, and the interpretation of new information. In educational and professional contexts, mental models determine how individuals perceive their roles, authority, change, and technology. Senge emphasizes that mental models are frequently unspoken and implicit, yet they exert a strong influence on behavior, communication, and the emotional responses of staff [15]. These patterns of thinking guide how people interpret changes—including the digital transformation of schools— and how willing they are to embrace them. When new organizational practices, such as the implementation of digital tools and learning platforms, conflict with existing mental models, strong emotional resistance and reluctance to learn may emerge [5,4].

Digital transitions are often perceived as a threat to established ways of working, particularly when mental models are rooted in values of stability, routine, and experience-based expertise. Such models can generate feelings of loss of control, professional insecurity, anxiety, and frustration, further hindering the acceptance of change [16,9,15,5].

Since mental models are shaped over time through experience and interaction with the environment, they are resistant to change but not static. Contemporary theoretical frameworks emphasize their plasticity which means the capacity to adapt to new contexts through processes of dialogue and reflection [11]. This highlights the importance of organizational learning as a means of identifying, mapping, and aligning diverse mental models within the educational community [6].

In digital educational settings, misaligned mental models among teachers, students, and leadership can lead to fragmented practices, misunderstandings, and ineffective technology implementation. Therefore, recognizing and raising awareness of these mental models is essential for developing school as a functional, digitally competent learning community.

4. Overcoming Emotional Resistance in Digital Transition

Emotions, moods, personality traits, and mental models are central to how individuals perceive and respond to change. While emotions are short-term reactions to stimuli, mental models are relatively stable but adaptable patterns of thinking, feeling, and behaving that evolve over time, enabling psychological resilience and influencing decision-making, collaboration, and technology adoption [11,6,17,4].

Responses to digital change are shaped by personality traits, mental models, learning orientation, and intrinsic motivation. Individuals with openness to learning more readily adopt new competencies and embrace digital innovations, whereas those with rigid mental models may experience insecurity and frustration [8,2]. For example, a teacher accustomed to traditional methods may initially resist digital collaboration tools, while a more open colleague may integrate them quickly to enhance student engagement.

Emotional resistance—conscious or unconscious reactions to change that provoke discomfort, uncertainty, or fear—can manifest cognitively (skepticism, doubt), behaviorally (disengagement, reduced cooperation), and emotionally (anxiety, frustration, insecurity) during digital transitions [18,9,16]. It often stems from fears of losing status, security, or being overwhelmed by new technologies.

Addressing emotional resistance requires cultivating organizational climates that promote continuous learning, reflective practice, and emotional intelligence. Leaders' emotional literacy, opportunities for self-development, and participatory decision-making reduce resistance and facilitate adoption of digital practices [4,8]. By empowering members and pacing change to align with their needs, schools strengthen collective capacity, foster knowledge sharing, and build sustainable digital learning communities.

5. The Importance of Aligning Mental Models in Developing Digital School Communities

According to Schaffernicht and Groesser, mental models are dynamic processes that shape how actors perceive causal relationships, temporal sequences, and interconnections within an organization or school [6]. This concept is critical for understanding the formation and structuring of schools in digital environments. In virtual schools and digital learning communities, different stakeholders—teachers, students, principals, and parents—often hold misaligned mental models regarding how educational processes function, which can result in confusion, poor digital practices, and fragmented pedagogical solutions [2].

It is essential to detect, compare, and adjust the mental models of stakeholders to reveal deficiencies in processes, guide dialogue toward systemic causes of problems, and systematically redesign educational practices. This methodological framework requires continuous communication and reflection, often supported by digital tools for visualization and mapping of understanding [4]. A concrete example of this approach is the mental model alignment framework for schools illustrated in Figure 1.

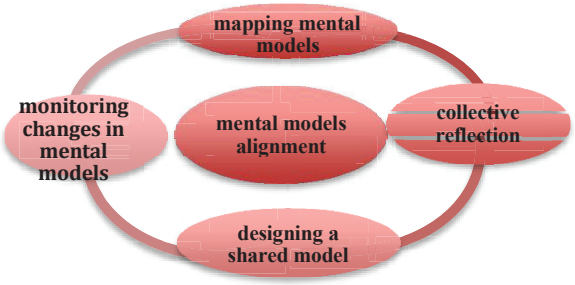


Figure 1. Alignment of Mental Models in Schools

Applying this approach enables schools to operate more coherently in digital spaces, develop a shared pedagogical logic, and accelerate the transformation into a functional digital learning community. The effectiveness of a virtual school community largely depends on the alignment, mapping, and sharing of mental models among educational stakeholders. Such integrated practices contribute to greater organizational clarity, transparency, and cohesion—key prerequisites for successful digital learning in the 21st century.

6. Digital Strategies for Developing a Digital Learning Organization

Recent research emphasizes that digital transformation requires not only technology implementation but also a redefinition of how an organization learns. Volberda, Foss, and Lyles propose the concept of the "new learning organization," which leverages digital tools to continuously detect environmental changes and adapt resources and processes [1]. In this paradigm, technology complements learning, enabling faster development of competencies, experimentation, and adaptation to societal challenges [11,2].

Volberda et al. identify three core dimensions of the new learning organization: digitally mediated learning, organizational agility, and the cultivation of a new culture [1]. Digital tools and data accelerate individual, team, and organizational learning, supporting rapid detection, analysis, and response to change. Emphasizing experimentation and viewing mistakes as learning opportunities aligns with double-loop learning, where assumptions and norms are continuously questioned [12]. Thus, developing a learning organization in the digital age depends on both individual competencies and the organization's capacity to create, share, and apply knowledge through digital platforms, fostering collective learning and accelerating adaptation [1,4].

Based on this, three key digital strategies can be identified for developing a learning

organization:

a) **Digital collaboration platforms** (e.g., Microsoft Teams, SharePoint, Confluence) enable real-time access to information and collaborative learning regardless of location. Knowledge is no longer confined to individuals but is dynamically shared and enhanced through digital infrastructure [9].

b) **Artificial intelligence (AI)** allows organizations to tailor learning content to the individual needs of employees, predict competency development requirements, and provide diagnostic insights into organizational knowledge [9,3]. This facilitates personalized learning, significantly increasing engagement and relevance of educational content. AI is regarded as a system that continuously adjusts and optimizes learning processes based on user feedback and behavior [1,2].

c) **Knowledge management systems (KMS)** enable the formalization and structuring of organizational knowledge, preventing its loss during employee turnover. These systems involve creating spaces for sharing experiences and reflection, strongly supported by digital tools [16].

6.1. The School as a Digital Learning Community: Benefits and Challenges

In the context of accelerated digital transformation, schools are becoming spaces where all stakeholders participate collectively in continuous development. When a school integrates digital technologies not only as instructional tools but also as instruments for collaborative learning and reflection, it becomes a digital learning community [10]. The characteristics of such a community are reflected in digitally competent and active students, professional communities with shared purpose, openness to changing mental models, transparent communication, knowledge sharing, remote learning, and digital connectivity with other schools and experts [15,1,4].

Key elements of a school as a digital learning community include digital infrastructure for knowledge sharing (e.g., Google Workspace for Education, Microsoft Teams, Yammer, and e-Diary), student progress analysis (e.g., School Portal, Loomen), and knowledge management at the school level through sharing best practices, evaluation, and reuse (e.g., Padlet, Wakelet, OneNote Staff Notebooks). Potential challenges include insufficient digital competencies among staff, resistance to change, and unequal access to infrastructure. To mitigate these issues, it is recommended to develop a school digital strategy aligned with the learning vision, promote guided learning through reflective practices and micro-education, use teaching data to improve instruction, and engage parents and the local community in shaping the school's digital vision [20,9].

In the context of organizational learning in the digital age, Ifenthaler and Yau highlight the benefits of applying so-called *learning analytics*, which involves the processing, interpretation, and application of digital learning data to provide real-time insights into learning processes [7]. Collecting and analyzing learning data—such as grades, prior educational outcomes, and activity on digital platforms—enables a better understanding of learning patterns and facilitates timely, personalized, and targeted support for students. It allows identification of learning stages that require intervention and supports informed decision-making regarding curriculum and pedagogical approaches. Beyond improving academic performance, motivation, and student engagement, the primary benefits of learning analytics include better alignment of instructional activities with individual needs and a reduced risk of student dropout or failure.

The following table illustrates three key ways learning analytics is applied in e-education to inform pedagogical and strategic decisions at all levels—from individuals to the organization as a whole.

Table 1

Applying learning analytics in e-education

Application	Data Examples	Benefits
Informed instructional practice	- Analysis of access to materials (who, when, how often)	- Enables adaptation of teaching methods to actual student

	- Tracking time on tasks - Identifying challenging parts of the curriculum	behavior - Promotes reflective practice among teachers
Strategic decision-making	- Identification of vulnerable student groups - Evaluation of the effectiveness of tools and approaches - Management of instructional resources	- Evidence-based decision-making - Improvement of support systems for students and teachers

7. Recommendations in the Form of an E-Guide

Based on the theoretical framework and analysis of key factors in the digital transformation of schools, the following guide provides a synthesized overview of recommendations in the form of an e-guide. The table presented below can serve school teams, decision-makers, and researchers as a reference for planning and implementing organizational changes, with a focus on overcoming emotional resistance, aligning mental models, and strengthening a learning-oriented organizational culture.

Table 2:

Recommendations for Transforming a School into a Digital Learning Community

Thematic Area	Recommendation	Focus of Action
Emotional Resistance	Recognize and normalize emotions associated with change; provide psychological support and spaces for dialogue; monitor emotional responses during digital transformation	Psychological support, guided discussions, reflective workshops, regular satisfaction surveys, and stress monitoring
Mental Models	Map existing thought patterns and encourage dialogue among stakeholders; promote critical examination of assumptions; foster collective learning	Group discussions, simulations, digital concept maps, workshops to identify implicit assumptions
Organizational Learning	Establish systems for reflection, collaborative decision-making, and knowledge sharing; implement double-loop learning; document best practices	Professional learning communities, micro-training sessions, mentoring, knowledge repositories, post-project reflective sessions
Learning Analytics	Introduce data analysis to improve instruction and personalize learning; monitor student progress and identify risk areas; use data for evidence-based decision-making	Dashboards, student progress tracking tools, data visualizations, personalized interventions, periodic evaluations
Vision and Strategy	Develop a clear digital school strategy aligned with broader learning goals; ensure compliance with school and national policies; communicate the vision to all stakeholders	Participatory planning, parent and community involvement, strategic plans, public forums, regular meetings with school teams
Digital Culture	Cultivate openness, experimentation, and flexibility as school values; promote idea-sharing, innovation, and tolerance for mistakes	Guided learning, recognition of initiative, tolerance for errors, creative thinking workshops, mentoring, and peer coaching

8. Discussion

The aim of this theoretical study was to examine how emotional resistance and mental models influence the process of organizational learning and interact within the context of a school's digital transformation. Based on a review of contemporary literature and a synthesis of key concepts, three hypotheses are considered in light of the theoretical insights obtained.

Hypothesis 1: There is a significant relationship between emotional resistance and a slowed digital transition in schools. The findings support this hypothesis—numerous studies [18,8,16] indicate that emotional reactions such as fear, uncertainty, and frustration act as major barriers to adopting new digital practices. These emotions are often linked to perceived threats to professional identity, competencies, and status within the organization. Insufficiently addressed emotional resistance can lead to passive opposition, reduced engagement, and unsuccessful technology implementation.

Hypothesis 2: Misaligned mental models within the school community hinder the development of a digital learning school. This claim is also supported by the literature. Misalignment of mental models among teachers, administration, students, and parents creates communication barriers and prevents a collective understanding of digital transformation goals [6,4]. Under such conditions, digital practices remain fragmented, and the learning process is impeded due to differing expectations and perceptions of change.

Hypothesis 3: Organizational learning represents a key mechanism for overcoming resistance and aligning mental models during digital transition. Insights from [1,11,7] suggest that organizational learning is essential for the transition to a digital learning community. Through processes of reflection, dialogue, knowledge sharing, and the use of digital tools for mapping understanding and learning analytics, organizations can actively identify problems, adapt strategies, and build a shared vision for development.

Furthermore, the use of digital platforms, personalized learning tools (AI), and knowledge management systems (KMS) enables learning processes to extend beyond individual actors and become part of the collective knowledge of the school. This strengthens the resilience of the school as a system and allows continuous adaptation to changing digital conditions [2,9]

Although this study is theoretical in nature, the findings have clear practical potential—the proposed model can serve as a foundation for designing empirical research and interventions in schools seeking to transform into digital learning communities.

9. Conclusion

The digital transformation of schools extends far beyond the technical implementation of innovations and digital tools—it requires changes in mindset, professional culture, and interpersonal relationships. This study highlights that emotional resistance, mental models, and organizational learning are key factors determining the success of a school's digital transition.

Analysis of contemporary literature suggests that emotional resistance is often overlooked but constitutes a strong barrier to change, particularly when digital innovations are perceived as threats to professional identity. At the same time, entrenched mental models influence how individuals interpret change, and misalignment among school stakeholders further complicates the implementation of innovations.

Organizational learning, especially when supported by digital tools, reflective strategies, and data analysis, emerges as a crucial mechanism for overcoming these challenges. Schools that successfully integrate these dimensions can develop into digital learning communities—flexible, connected, and collectively oriented toward growth.

Although theoretically grounded, this study provides a framework that can inform future empirical research and intervention models. In practice, emphasis should be placed on emotional support, mapping of mental models, and strategic development of a digital culture within schools.

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Enhancing Digital Competencies Through Visual Programming in Education

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Abstract:
This paper provides a comparative analysis of Scratch, Snap!, Blockly, and App Inventor, highlighting their educational philosophies, technical features, and classroom applications. The results indicate that Scratch and Blockly are most suitable for beginners due to their accessibility and ease of use, while Snap! and App Inventor provide pathways toward more advanced and applied skills. In addition to fostering computational thinking, these tools enhance engagement, selfefficacy, and digital creativity, making them valuable assets in formal and informal learning environments. The analysis concludes that visual programming environments not only serve as effective entry points into programming but also contribute significantly to the development of broader digital competences, thus supporting the long term goals of digital education.
Keywords:
visual programming, computational thinking, digital competences, Scratch, Blockly, Snap!, App Inventor, education technology

1. Introduction

In today's more digitalized world, the acquisition of digital competences has become one of the primary objectives of modern education. Besides common ICT literacy, students are supposed to express critical thinking, creativity, problem solving skills, and the capacity to employ digital technologies in meaningful and effective manners. Implementing block based and visual programming environments: such as Scratch, Blockly, and Snap!, has become a trend to assist in these purposes, especially at the K–12 and introductory higher education levels.

Block based programming, by sacrificing heavyweight syntax for visually manipulated code blocks dragged and dropped into place, lowers programming barriers. In the process, it allows students to focus on logic, structure, and creativity. Numerous studies over the past decade have demonstrated these environments to be successful at building computational thinking skills, increasing student engagement, and promoting selfefficacy, especially for students with no or minimal prior programming experience.

Block based programming, which exchanges cumbersome syntax for visual, drag and drop code blocks, lowers the threshold to programming and allows students to focus on logic, structure, and creativity. An extensive body of research in the past decade has shown that such environments are effective at building computational thinking skills, student engagement, and self efficacy, especially for students with little prior experience in programming.

In order to form an in depth analysis of the role of visual programming environments within contemporary education, this paper will provide a comparative analysis of three preeminent block based environments: Scratch, Snap!, and Blockly. Despite these three environments sharing a common philosophy of accessibility to beginners through drag and drop blocks, they differ in design principles, levels of complexity, pedagogical emphasis, and educational practice application. Scratch has been used most intensively in schools, but Snap! and Blockly offer unique affordances that broaden the range of learning options: anything from advanced programming concepts to adaptable uses across numerous subjects. By looking at their educational theory, features, and classroom integration, this critique aims to give an ordered summary of how these resources promote computational thinking and digital literacy.

2. Scratch as a Visual Programming Environment

2.1 What is Scratch?

Scratch is a block based visual language that has been developed by the Lifelong Kindergarten Group of the MIT Media Lab. It is an environment that is primarily aimed at children and novice programmers, and it enables the users to design interactive stories, games, and animations by merely combining code blocks which have rudimentary programming concepts, like loops, conditional statements, variables, and events [1]. The user friendly interface of Scratch eliminates the writing of advanced syntax, thereby reducing the mental barrier to use and enabling students to think more on the logic, creativity, and problem solving fronts.

2.2 Educational Philosophy and Pedagogical Value

The structure of Scratch is built on constructionist learning theory that emphasizes learning by creating, exploring, and by collaborative activity. Students learn not just by accessing digital materials but by creating content by themselves, often by working on issues that are personally relevant and meaningful. Scratch cultivates an experimental culture, iterative development, and sharing of projects that perfectly complements the modern learning goals like active learning, collaborative learning, and project based learning [10].

In addition, Scratch facilitates the development of computational thinking—a set of skills widely acknowledged as valuable transdisciplinarily. As identified by Brennan & Resnick, Scratch projects can illustrate three main aspects of computational thinking:

- Basic computational concepts (e.g., sequences)
- Coding practices (e.g., coding style)
- Computational perspectives (such as explaining ideas, interacting with humans) [2][4].

2.3 Integration into Educational Contexts

Scratch has been incorporated into various learning environments internationally during the last ten years, spanning primary school classrooms to pre service teachers' study rooms at the undergraduate level. It has been proved by studies that it not only enhances programming abilities, but also digital abilities on a larger scale like information literacy, digital creativity, and communication [3][6][8].

Teachers appreciate Scratch because it is versatile; it is not merely a medium of teaching of elementary computer science concepts, but also utilized to enhance fields such as mathematics, language arts, and social studies through interdisciplinary initiatives [9][16]. Additionally, the platform's online community (scratch.mit.edu) facilitates collaborative learning as students can share, remake, and comment on projects of their peers [13].

3. Snap! as an Advanced Visual Programming Environment

3.1 What is Snap!?

Snap! is a visual, block based programming language developed at the University of California, Berkeley, as an extended reimplementation of Scratch [17]. While it keeps the intuitive drag and drop environment that users of Scratch are familiar with, Snap! introduces additional advanced features such as first class procedures, lists, first class continuations, and the definition of custom blocks. This makes Snap! not just suitable for children and beginners but also for advanced learners who would like to explore higher level programming concepts in a simplified graphical setting.

3.2 Educational Philosophy and Pedagogical Value

Snap! takes a constructionist and exploratory approach, but its learning potential is broader than Scratch in that it completes the gap between beginner focused programming and higher level computer science. Harvey and Mönig state that Snap! allows one to experiment with higher order abstractions, and this allows

for deeper computational thinking [10]. Pedagogically, Snap! provides a learning environment whereby students can eventually transition from elementary programming concepts into more advanced ones without necessitating a switch to text based coding too soon. The scaffolding fosters creativity, problem solving, and ease with complexity, and Snap! is thus the ideal tool for secondary school and even introductory university courses [14].

3.3 Integration into Educational Contexts

Although less ubiquitous than Scratch, Snap! has seen increasing use in formal and informal learning environments. For instance, it is consistently integrated into AP Computer Science Principles (AP CSP) courses in the United States, where it helps students explore introductory computing principles [7]. Snap! has also been employed in STEM outreach programs, coding boot camps, and summer camps as a bridge between recreational programming and more advanced subject matter [12]. Its web based and open source character allows teachers to adopt it flexibly, and its compatibility with various libraries and extensions (e.g., robotics) facilitates cross disciplinary teaching in a flexible way [15].

4. Blockly as a Customizable Visual Programming Framework

4.1 What is Blockly?

Blockly, developed by Google (Fraser, 2015), is a web based visual programming Blockly, developed by Google, is a web based visual programming framework that allows developers and educators to design customized block based environments [17]. Unlike Scratch or Snap!, Blockly is not primarily an end user programming platform but rather a library that can be embedded into websites or applications. The drag and drop block structure provides support for programming constructs such as loops, conditionals, variables, and functions, with the additional capability of generating code in multiple languages (e.g., JavaScript, Python, PHP). This feature makes Blockly an especially powerful tool for contexts where the goal is to provide a transitional path from visual to text based coding [11].

4.2 Educational Philosophy and Pedagogical Value

Blockly's educational philosophy is rooted in accessibility and adaptability. Because it is not tied to a single platform, it empowers educators and developers to design block based tools for specific curricula or domains, such as mathematics, robotics, or data science [11]. Pedagogically, Blockly promotes scaffolding in learning: students can start by assembling blocks and then gradually view or modify the equivalent text based code. This dual representation fosters computational thinking, helps demystify syntax, and supports learners in making the transition to professional programming languages [2][5].

4.3 Integration into Educational Contexts

Blockly has been widely integrated into coding applications such as Code.org, MIT App Inventor, and Tynker, making it one of the most influential frameworks for early programming education globally [15]. It is used in schools, after school programs, and coding competitions as a stepping stone toward textual programming. Studies have shown that Blockly helps learners grasp both algorithmic logic and syntax conventions more effectively, thereby improving programming self efficacy [13]. Its adaptability to different educational contexts and disciplines makes it a powerful ally for teachers seeking customized digital learning environments [9].

5. App Inventor as an Advanced Visual Programming Environment

5.1 What is App Inventor?

App Inventor is an open source, web based, block based visual programming environment developed by MIT to design and build Android and iOS device apps. Rather than writing code, users of App Inventor create apps by dragging and dropping graphical blocks within the built in app builder interface, which is more accessible to beginners, students, and those who don't have experience in any form of programming. It provides tools for designing the app's user interface and programming its behavior, besides ways to test apps either in real time on a phone or using an on computer emulator [18].

5.2 Educational Philosophy and Pedagogical Value

The educational philosophy of App Inventor is based on constructivist and constructionist learning theories, which emphasize the active creation of meaningful digital products as the best way in which students learn. With its visual, block based programming environment, App Inventor reduces the threshold to engage with computer science education and lets learners focus on logical thinking rather than syntax, thereby supporting the learning of core computational thinking skills, including abstraction, decomposition, problem solving, and debugging. Its design encourages creativity, experimentation, and iterative learning by providing students with immediate feedback through real time testing on mobile devices. It also fosters collaborative and project based learning organically, matching modern pedagogical paradigms in the fields of STEM and STEAM that privilege hands on practice, collaboration, and innovation[18][19].

5.3 Integration into Educational Contexts

App Inventor can be integrated into a wide range of educational contexts, from early introduction to programming in primary schools to more advanced project based work in secondary and higher education. In early grades, it is often used to teach basic programming concepts through simple, engaging app building activities, while in secondary education, it enables students to design more sophisticated applications connected to real world problems or community needs. Teachers can incorporate App Inventor into informatics, technology, or interdisciplinary curricula, using guided tutorials, independent projects, or team challenges. At the university level, it provides an accessible entry point for students new to programming, bridging the way before transitioning into text based languages and more complex software development. Its flexibility, ease of use, and ability to quickly prototype ideas make it a valuable tool for fostering digital literacy, creativity, and problem solving across educational environments[18][19].

6. Comparison of Visual Programming Environments

Table 4:
Comparison of Visual Programming Environments

Feature	Scratch	Blockly	Snap!	App Inventor
Difficulty Level	Basic	Basic	Intermediate	Intermediate
Target Group	Pupils	Pupils	Older pupils	Students
Platform	Web	Web	Web	Web / Android
Support for Advanced Concepts	Limited	Moderate	High	High
Developed by	MIT Media Lab	Google	UC Berkeley + SAP	MIT + Google
Type	Visual, block programming	Block programming library	Advanced Scratch	Visual, Android app development

Target Audience	Children(7 16), beginners	Programmers, educators, children	Older pupils, advanced users	Teenagers, beginners in mobile development
Interface	Intuitive, user friendly	Can be integrated into other apps	Similar to Scratch, but more advanced	Mobile app oriented
Project Types	Animations, games, stories	Depends on implementation (e.g., games, quizzes)	Advanced animations, OOP concepts	Mobile apps (Android)
Connection to Real Code	No direct export to text code	Generates JavaScript, Python, etc.	Focus on concepts, not export	Generates Java code for Android
Cloud / Local Work	Online (scratch.mit.edu), offline editor	Can be integrated online and locally	Online and local	Online (browser) with emulator
Advanced Concepts (e.g., recursion, parameterized functions)	Limited	Depends on integration	Yes, supports advanced functions and recursion	Limited compared to real IDEs
Advantages	Very accessible for kids, large community, easy to learn	Easy integration into projects, generates code	Suitable for CS teaching, more freedom and power	Enables quick Android app development
Disadvantages	Limited for advanced concepts	Depends on usage context	May be too complex for younger users	Limited to Android, no iOS support
Code Export	No	Yes	Yes	No (blocks only)

6.1 Short Conclusion from the Comparison

The comparison shows that Scratch and Blockly are best suited for beginners, offering simple and accessible entry into programming, while Snap! and App Inventor provide more advanced opportunities. Snap! supports deeper computer science concepts such as recursion, making it appropriate for older learners, whereas App Inventor connects programming to practical mobile app development. In essence, Scratch and Blockly serve as introductory tools, while Snap! and App Inventor enable progression toward advanced and applied skills.

6.2 Recommendations by User Profile

- For younger children and absolute beginners: Scratch is the best choice due to its simplicity and playful interface.
- For developing a basic understanding of code in other environments: Blockly is a good option because it allows generating real code (e.g., JavaScript, Python).
- For high school students and those who want to learn CS principles: Snap! is excellent as it supports more complex concepts (e.g., recursion, lists, functions).
- For learners interested in creating mobile applications: App Inventor is specialized for Android apps and enables quick learning of app development.

7. Conclusions

The analysis of Serbian learning institutions illustrates that even though there is an absence of massive

deployment of fully autonomous intelligent agents, present platforms such as Petlja, electronic coursebooks, as well as MozaBook, already contain attributes related to interactivity and adaptivity. Such projects reveal promising avenues for expanding intelligent systems into local learning paradigms.

Nonetheless, challenges remain, primarily with addressing moral problems, maintaining data privacy, and promoting transparency among decision structures. Educators play an irreplaceable role because human monitoring is necessary to ensure fairness, kindness, and pedagogically relevant.

Intelligent Educational Agents should not be perceived as a replacement for teachers but as a highly effective tool that can.enhance learning experience, overcome inequality in accessibility and customization, and contribute to a future development of fair and effective distance education.

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Understanding User Acceptance of Technology: A Theoretical Review of Behavioral Intention Models

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Abstract:
This paper provides a theoretical analysis of key models that explain user acceptance of technology, emphasizing their conceptual foundations, evolution, and interrelations. The discussion begins with the Theory of Reasoned Action (TRA), which posits that behavioral intention is shaped by attitudes and subjective norms. It then explores the Theory of Planned Behavior (TPB), which extends TRA by incorporating perceived behavioral control as an additional determinant of intention and behavior. The Technology Acceptance Model (TAM) is examined next, focusing on perceived usefulness and ease of use as predictors of technology adoption. Finally, the paper analyzes the Unified Theory of Acceptance and Use of Technology (UTAUT), a comprehensive model that consolidates constructs from previous theories and introduces performance expectancy, effort expectancy, social influence, and facilitating conditions. By systematically comparing these models, the paper highlights their theoretical contributions and practical relevance in understanding technology adoption. The findings underscore the importance of integrating psychological and contextual factors in modeling user behavior, providing a foundation for future empirical research and applications in diverse domains where digital technologies are increasingly embedded.

Keywords:
technology acceptance, user behavior, UTAUT, theoretical models

1. Introduction

The rapid evolution of information and communication technologies has fundamentally reshaped the ways individuals interact with digital systems, particularly in domains such as e-education, e-government, and internet-based services. As the integration of these technologies deepens across sectors, understanding user acceptance becomes critical for successful implementation. Rooted in behavioral psychology, theoretical models such as the Theory of Reasoned Action (TRA) [3], Theory of Planned Behavior (TPB) [1], and the Technology Acceptance Model (TAM) [11] have long provided insights into technology adoption behavior. These models emphasize the role of attitudes, subjective norms, and perceived control in shaping behavioral intentions. Building on these frameworks, the Unified Theory of Acceptance and Use of Technology (UTAUT) [29] offers a consolidated approach, introducing performance expectancy, effort expectancy, social influence, and facilitating conditions as key determinants of user acceptance. This paper presents a theoretical overview and comparative analysis of these models, contributing to the broader discourse on technology acceptance and its implications for applied internet and information technologies in diverse human activities.

1.1 The theory of Reasoned Action (TRA)

The Theory of Reasoned Action (TRA), developed by Ajzen and Fishbein [3], originates from the field of social psychology and is recognized as one of the most influential frameworks for understanding human behavior. Its broad applicability has enabled researchers to predict a wide array of behavioral intentions and actions [16]. Davis et al. [12] extended the application of TRA to the context of individual acceptance

of technology, demonstrating that the explanatory power of the model was consistent with previous studies employing TRA across various behavioral domains [29]. According to TRA, an individual's behavioral intention is the primary determinant of actual behavior. This intention is shaped by two key constructs: the individual's attitude toward the behavior and the perceived social pressures, or subjective norms, associated with performing the behavior [15]. Within this theoretical model, attitude toward behavior is defined as an individual's overall evaluative disposition—either favorable or unfavorable—toward engaging in the target behavior (Fishbein & Ajzen, 1975, as cited in Venkatesh et al. [29]). Subjective norms refer to an individual's perception of social expectations, specifically the belief that important others approve or disapprove of the behavior in question (Fishbein & Ajzen, 1975, as cited in Venkatesh et al. [29]). Authors specify three conditions that can affect the relationship between intentions and behavior: the level to which the measure of intention and the behavioral criterion correspond, the stability of intentions from the moment of measuring to the moment of the behavioral manifestation, and the level to which realization of the intention is under the person's volitional control. TRA is most successful when used in behaviors that are under an individual's volitional control [16].

There is considerable empirical support for the effectiveness of the Theory of Reasoned Action (TRA). As noted by Hagger [13], TRA has been extensively employed across a wide range of behaviors, settings, and populations, underscoring its strong predictive capacity. Its application spans various disciplines, including health psychology, marketing, and the social sciences [17]. Despite its strengths, TRA was subsequently extended into the Theory of Planned Behavior (TPB) to better account for actions that are not entirely under an individual's volitional control [20]. Subsequently, Davis [11] introduced the Technology Acceptance Model (TAM) as an extension of the Theory of Reasoned Action to better predict user acceptance of information systems. TAM posits that two primary factors—perceived usefulness and perceived ease of use—are critical determinants of an individual's willingness to adopt and utilize technology [26]. Although the original TRA did not explicitly incorporate the influence of user experience, Davis et al. [12] empirically explored its role through a large-scale cross-sectional study, which revealed no significant variation in the underlying constructs. However, subsequent studies indicated that as users gain experience, the influence of attitude on behavioral intention tends to increase, while the impact of subjective norms diminishes [29].

1.2. The Theory of Planned Behavior (TBP)

Ajzen [1] introduced the Theory of Planned Behavior (TPB) as a theoretical advancement following the development of the Technology Acceptance Model (TAM). TPB extends the original Theory of Reasoned Action (TRA) proposed by Ajzen and Fishbein [3], offering a more comprehensive framework for understanding human behavior. Similar to its predecessor, TPB emphasizes the central role of behavioral intention in predicting actual behavior. However, TPB enhances TRA by incorporating a third antecedent—perceived behavioral control—alongside attitude and subjective norms. This additional construct accounts for an individual's perceived ease or difficulty in performing a given behavior. According to TPB, behavioral intentions are shaped by attitudes toward the behavior, subjective norms, and perceived behavioral control, all of which serve as direct predictors of both intention and behavior [16, 26, 2, 19].

Within the Theory of Planned Behavior (TPB), behavioral intention is considered the most salient predictor of actual behavior. Ajzen [1] posits that the strength of one's behavioral intention reflects the degree of effort an individual is willing to exert to engage in a specific behavior. Attitude toward the behavior is conceptualized as the individual's evaluative disposition—either favorable or unfavorable—toward performing the behavior, such as adopting new technology. This construct captures the degree to which a person views the behavior positively or negatively. Subjective norms refer to the perceived social pressure exerted by significant others—such as family members, peers, supervisors, and colleagues—regarding whether the behavior should be enacted. An individual is more likely to form an intention to engage in a behavior if they believe that important referents endorse that behavior.
Perceived behavioral control, analogous to the concept of perceived ease of use in the Technology

Acceptance Model (TAM), represents the individual's assessment of their ability to execute the behavior. This construct reflects one's beliefs about the presence of necessary resources, opportunities, and competencies to perform the behavior. It is shaped by two components: control beliefs (perceptions about factors that facilitate or hinder behavior) and perceived power (the perceived impact of those factors). Perceived behavioral control influences motivation by shaping expectations regarding the difficulty of the behavior and one's confidence in successfully performing it. Unlike locus of control, which is considered a stable, generalized trait across situations, perceived behavioral control is context-specific and may fluctuate depending on the behavior and setting. Ajzen [1] argues that the more favorable the individual's attitude and subjective norm, and the stronger the perceived behavioral control, the greater the likelihood of forming a strong behavioral intention, thereby increasing the probability of performing the behavior [16, 26, 29].

The Theory of Planned Behavior (TPB) was developed to predict and explain deliberate human behavior across specific contexts, and its validity is supported by a substantial body of empirical research [1]. Empirical findings have demonstrated that intentions to engage in various behaviors can be reliably predicted by three antecedents: attitudes toward the behavior, subjective norms, and perceived behavioral control. These predictors, in conjunction with perceived behavioral control, collectively explain a significant proportion of the variance in actual behavior. Moreover, each of these constructs—attitude, subjective norm, and perceived behavioral control—is grounded in corresponding belief systems: behavioral beliefs, normative beliefs, and control beliefs, respectively [1].
TPB has been widely applied in the domain of technology acceptance, offering robust explanatory power for individuals' adoption and use of technological innovations. A notable extension of TPB is the Decomposed Theory of Planned Behavior (DTPB), which modifies the original model by disaggregating the core constructs—attitude, subjective norm, and perceived behavioral control—into more granular belief dimensions. This approach aligns with the structure of the Technology Acceptance Model (TAM) and provides a more detailed understanding of user intentions in the context of technology adoption [29].

2. The Unified Theory of Acceptance and Use of Technology (UTAUT)

The Unified Theory of Acceptance and Use of Technology (UTAUT), introduced by Venkatesh et al. [29], emerged from a comprehensive synthesis of eight prominent theoretical models previously utilized to explain user behavior in the context of information system adoption. This integrative framework aims to capture the influence of individual differences on technology usage behaviors [18]. UTAUT identifies four core determinants of behavioral intention and actual system use: performance expectancy, effort expectancy, social influence, and facilitating conditions. These constructs collectively explain users' acceptance and continued use of technology. Moreover, the model posits that the influence of these four constructs is moderated by key demographic and situational factors, namely age, gender, experience, and voluntariness of use. Notably, the UTAUT framework accounts for approximately 70% of the variance in behavioral intention to use technology—a predictive strength that surpasses the explanatory power of any of the eight individual models it consolidates [4, 26]. The eight foundational models integrated into UTAUT include: the Theory of Reasoned Action (TRA), the Technology Acceptance Model (TAM), the Motivational Model (MM), the Theory of Planned Behavior (TPB), a combined TPB-TAM framework (C-TPB-TAM), the Model of PC Utilization (MPCU), the Innovation Diffusion Theory (IDT), and Social Cognitive Theory (SCT) [29]. Seven constructs appeared to be important direct determinants of intention or usage in one or more of the examined models. Authors hypothesized that four constructs would play a significant role as direct determinants of user acceptance and usage behavior: performance expectancy, effort expectancy, social influence, and facilitating conditions, whereas attitude toward using technology, self-efficacy, and anxiety were hypothesized not to be direct determinants of intention [29].

Venkatesh et al. [29] developed a measurement model to empirically test the Unified Theory of Acceptance and Use of Technology (UTAUT), incorporating seven direct determinants of behavioral intention. Each construct was measured using its associated item set, with all constructs—except for actual system use—modeled as reflective indicators. The model demonstrated robust psychometric properties,

with internal consistency reliabilities exceeding the recommended threshold of 0.70 for all constructs. The empirical findings provided substantial support for the UTAUT framework, which identifies three core determinants of behavioral intention—performance expectancy, effort expectancy, and social influence—and two primary determinants of actual usage behavior—behavioral intention and facilitating conditions. Additionally, significant interaction effects were observed, particularly concerning the moderating roles of gender and age. The UTAUT model accounted for approximately 70% of the variance in usage intention, offering a more comprehensive and integrative framework than any of the preceding models, and serving as a foundational reference for future research in technology adoption [29]. In subsequent longitudinal studies, the model explained 77% of the variance in behavioral intention and 52% in actual technology usage [32]. Building on this foundation, Venkatesh, Thong, and Xu [31] proposed an extended model, UTAUT2, which incorporates additional constructs such as hedonic motivation, price value, and habit to enhance explanatory power in consumer technology use contexts.

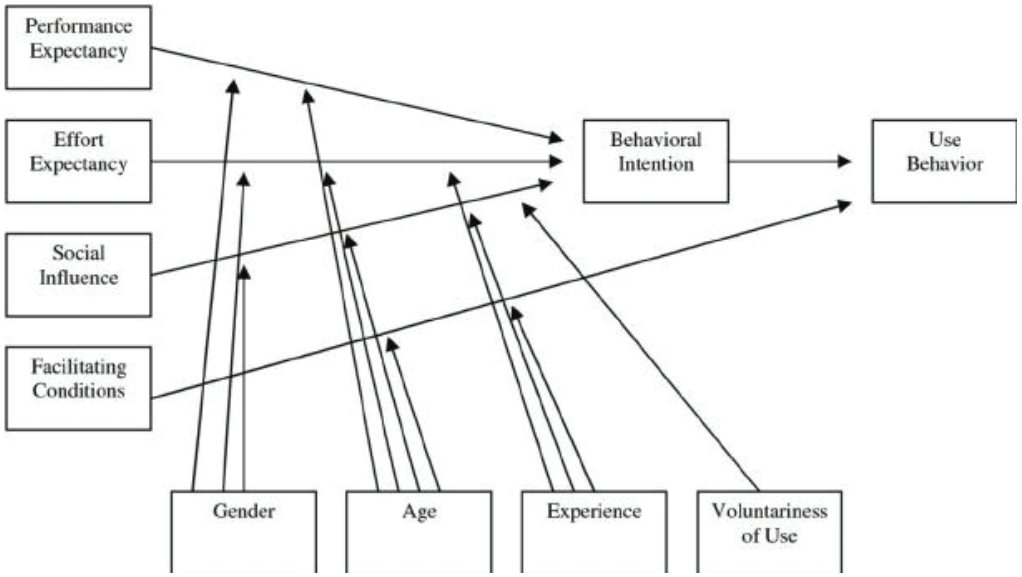


Figure 1: UTAUT model [29]

The Unified Theory of Acceptance and Use of Technology (UTAUT) has been widely employed as a theoretical framework in both its original and extended forms across numerous empirical studies spanning diverse domains and cultural contexts [6, 7, 9, 8, 4, 10, 15, 18, 22, 23, 24, 25, 20, 30, 32, 33]. The findings of these studies consistently support the reliability of the measurement instruments used for UTAUT constructs and validate the hypothesized relationships among them [4, 18, 23]. Moreover, the model's generalizability has been substantiated across various technological applications and settings. While interrelationships among some predictors—namely effort expectancy, social influence, and facilitating conditions—exhibit modest correlations over time, these are typically weaker than the longitudinal consistency observed for performance expectancy [29, 30]. Nevertheless, a limitation in the existing literature is that relatively few studies have applied the full UTAUT framework, incorporating all proposed constructs and moderating variables. This suggests a need for further empirical validation of the complete model in diverse contexts [15, 31].

In a broader evaluative study, Samaradiwakara and Gunawaedena [23] conducted a comparative analysis of fourteen prominent technology acceptance models and concluded that UTAUT offers an enhanced theoretical framework, particularly well-suited for assessing the likelihood of successful technology adoption. Supporting this view, Williams et al. [33], through a systematic literature review of 174 published articles on UTAUT, reported that performance expectancy and behavioral intention were the most robust predictors of technology acceptance across empirical studies. However, a meta-analytic study by Taiwo and Downe [25], synthesizing data from 37 empirical investigations, yielded more nuanced findings. The analysis revealed that the relationship between performance expectancy and

behavioral intention was consistently strong, while associations involving effort expectancy, social influence, and behavioral intention were comparatively weaker. Furthermore, the links between facilitating conditions, behavioral intention, and actual usage behavior were found to be weak. Importantly, the statistical robustness of the associations between facilitating conditions and use behavior, as well as between behavioral intention and use behavior, did not meet the criteria set by the fail-safe test, indicating limitations in the strength and generalizability of these relationships. Researchers continue to refine the model, suggesting extensions and context-specific adaptations for different technological environments [21, 34].

3. Conclusions

The evolution of technology acceptance theories—from TRA and TPB to TAM and UTAUT—reflects a growing recognition of the complex interplay between individual, social, and contextual factors in shaping user behavior. Each model has contributed unique insights, with UTAUT offering a comprehensive framework that integrates and extends previous approaches. This theoretical analysis demonstrates that no single model can fully capture the dynamics of technology adoption across all contexts, but together they provide a robust foundation for understanding user acceptance. As digital technologies continue to permeate various domains, these models remain essential tools for researchers and practitioners seeking to enhance the effectiveness of technology implementation. Future research should focus on empirically validating and refining these frameworks in specific settings to ensure their continued relevance and applicability.

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Towards Standardized Quality Practices for Custom Game Development Tools: A Contextualization of ISO/IEC 25010 Standard

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Abstract:
Modern game engines increasingly support the creation of extensions such as custom editors, inspectors, and workflow tools that extend engine functionality to accomplish, automate, or accelerate specific development tasks. Since general-purpose engines are used not only for games but also for virtual reality, simulations, and other interactive applications, such extensibility has become essential for adapting workflows to diverse production and research contexts. These tools are created by studios or independent developers and are often shared publicly through asset stores. Their number continues to grow, particularly with the emergence of AI-assisted tools that integrate into the engine's editor environment to streamline development. Studies show that developers prefer AI asset generators and authoring tools integrated directly within the engine, and given the long-standing use of natural language as primary tool in game design, a rise in extensions leveraging natural language to generate assets or code is expected. This paper explores how the ISO/IEC 25010 software quality standard, combined with engine documentation, best practices, and academic insights, can serve as a reference framework for developing consistent, efficient, and user-centered custom game engine extensions and tools across engine ecosystems.

Keywords:
game development tools, custom editor tools, game engines, software quality, standardization

1. Introduction

Game engines have evolved into powerful, general-purpose development environments used not only for video games but also for virtual reality (VR) experiences, simulations, and interactive applications in general. They provide a unified ecosystem that combines rendering, physics, scripting, asset management, and other core subsystems, enabling developers to build complex real-time systems efficiently. Due to their versatility, game engines such as Unity, Unreal Engine, and Godot are increasingly adopted across entertainment, industry and academic research.

To accommodate the wide range of production needs, modern engines offer extensibility through custom editor tools, add-ins, and inspectors. These extensions allow developers to modify or extend the editor interface to automate repetitive tasks, streamline workflows, or introduce entirely new functionalities. As a result, users can tailor the development environment to the specific requirements of their projects, improving efficiency and productivity. For example, Volkovas [1] presented a Godot engine plugin that allows designers to visualize and explore the states of a game system and their relations during active development, reducing the need for repeated play-testing. Murphy-Hill et al. [2] found that game developers in large-scale triple-A studios heavily rely on in-house tools, a domain notably underrepresented in academic research. A decade later, systematic studies on their use, design, quality, and standardization remain scarce.

The number of such engine extensions has grown rapidly, supported by online asset stores and open-source communities. Recent trends show an increasing number of tools integrating artificial intelligence (AI) to assist in providing inspiration, exploring ideas, generating placeholder assets and creating variations of existing assets [3], character creation [4], code prototyping [5], design of gamepad rumble

patterns [6], and general content creation through natural language input. These developments have further expanded the role of editor tools beyond traditional game development, reinforcing their importance across multiple domains.

However, because these extensions are created by a wide variety of contributors, from individual developers to large studios, their quality, usability, and maintainability vary significantly. Unlike the engines themselves, which follow well-defined design and testing processes, extensions often lack standardized guidelines or quality assurance mechanisms. This results in inconsistent user experiences, interoperability issues, and limited long-term support.

This paper addresses this gap by exploring how the ISO/IEC 25010 software quality standard can be interpreted and applied in the context of development and evaluation of custom game engine extensions. Building on existing documentation from major engines and insights from academic research, it provides a contextualized framework aimed at improving the standardization, consistency, and overall quality of these custom tools.

The remainder of this paper is organized as follows. The second section provides an overview of related work, including documentation and extensibility practices in major game engines. The rationale for adapting the ISO/IEC 25010 standard to this context and the contextual interpretation of the standard's quality characteristics for custom game engine tools are presented in section three, while section four discusses limitations and future research directions. The fifth section concludes the paper.

2. Related Work

When it comes to tools, most papers and scientific studies focus on video game design tools, which belong to the pre-production phase of video game development. The general conclusion across these works is that natural language remains the primary medium used by game designers and that the majority of existing approaches to game design tools, whether developed in commercial or academic contexts, are not sufficiently flexible or practical for supporting the game design process [7], [8]. However, this finding also offers an important perspective for custom tool development within game engines. With the rapid progress of artificial intelligence, users can now generate an increasing amount of content through natural-language input. Consequently, it is reasonable to expect a rise in game engine extension tools that leverage natural-language processing to generate not only various types of assets but also functional code usable in prototyping and further development. Already, several tools exist that can generate narratives, characters, assets, terrains, environments, and even scripts defining object behavior and properties based solely on user input in natural-language form. As a result, even users without programming or technical expertise can potentially provide game design documents written in natural language, or in slightly adapted formats, as input and obtain a prototype of a smaller or larger portion of a game through one or more AI-assisted tools.

Research conducted by Fukaya et al. [3] on generative tools for graphical assets has demonstrated that designers and developers prefer such tools to be integrated in existing design and development environments (e.g., game engine editors). The study emphasized the importance of producing outputs in common, manipulable data formats that can be seamlessly integrated into existing workflows. It also highlighted the ability to configure or modify such a tool and the need for a stronger focus on user requirements to ensure these tools can be effectively incorporated into existing production pipelines. These findings align with those of Walton et al. [9] and Kasurinen et al. [10].

Chamusca et al. [11] conducted a systematic literature review (2018–2021) that distilled fourteen concrete design guidelines that address how authoring tools should be structured and standardized to reduce the learning curve for users without programming or 3D-modeling expertise and to promote sustainable VR development. These guidelines are: Adaptation and Commonality, Automation, Customization, Democratization, Metaphors, Movement Freedom, Optimization and Diversity Balance, Documentation and Tutorials, Immersive Authoring, Immersive Feedback, Real-time Feedback, Reutilization, Sharing and Collaboration, and Visual Programming. Building on this taxonomy, Chamusca et al. [12] later evaluated the operational reliability of these guidelines by having six engineering students with no prior VR-authoring experience assess NVIDIA Omniverse Enterprise. Using Likert-scale questionnaires and focus-group interviews, they found that the majority of guidelines received ratings consistent with their

intended purpose, confirming that the checklist provides a curated set of editor-level requirements and repeatable, measurable framework for evaluating tool intuitiveness.
On the other hand, several studies compare game engines for various purposes. These comparisons typically acknowledge that some engines support extensibility and the development of custom tools, but they do not examine in detail the specific differences in implementation or the degree of standardization across them in terms of custom editor tool development and related guidelines.

Regarding support for extensions and modification of the engine functionality, the three most popular game engines, Unity, Unreal Engine, and Godot, all allow the development of custom tools that can be integrated into their editors. Godot is fully open-source, enabling users to even modify the core engine code and contribute to its development, while Unreal Engine is "source-available", providing access to its code on GitHub after creating an Epic account. Unity, in contrast, is the most closed, offering only partial access to the C# API wrappers, without exposing the main C++ engine code.

All three engines provide submission guidelines for their respective marketplaces [13], [14], [15], ensuring that published assets and editor extensions meet specific technical and organizational requirements. They also offer guidance for extending their editors, covering terminology, error handling, documentation, usability, accessibility, among other aspects. The level of detail in both the marketplace submission guidelines and the editor extension guidance varies across engines. Among them, Unity offers the most comprehensive editor extension guidelines, including detailed documentation, best practices, terminology styles, and highly visual resources such as the Figma design system, which enables rapid prototyping of custom tool interfaces before implementation [16]. Godot also provides documentation and style guidelines [17], but the level of detail and visual support is more limited, reflecting that it is a younger engine with a smaller, community-driven, open-source development model.

While platform-specific frameworks and guidelines support internal consistency, they also highlight the absence of a common heuristic for custom authoring-tool design that can guide development across different engines. Existing documentation remains fragmented, and there is no overarching structure for creating or evaluating such tools that could inform consistent practices. This gap motivates the present work, which proposes a foundational, user-centered framework for authoring tools that can serve as a backbone onto which future refinements, engine-specific guidelines and detailed requirements can be overlaid.

3. Interpretation of ISO/IEC 25010 Standard for Game Engine Editor Tools

This section interprets the ISO/IEC 25010:2023 — Systems and software engineering — Systems and software Quality Requirements and Evaluation (SQuaRE) — Product quality model [18] software quality standard in the context of custom game development tools. It connects the standard's quality characteristics with practical considerations derived from official engine documentation, best practices of major engines (Unity, Unreal Engine, Godot), and insights from academic and industry research on developer experience, tool design, usability, and integration. The aim is to establish a structured framework for understanding how quality principles can be applied to improve the consistency, maintainability, and user-centeredness of custom tools across different engines and contexts.

As a theoretical foundation, the ISO/IEC 25010 software quality standard was adopted as the primary reference model due to its broad acceptance in both academic and industrial software engineering and its ability to systematically describe software quality through well-defined characteristics and their subcharacteristics. Although this standard is originally designed for general-purpose software systems, its comprehensive structure and terminology provide a flexible and robust framework that encapsulates the key dimensions of software quality. Since these dimensions are fundamental and generally applicable, this standard could be adopted for evaluating the product-level quality of interactive development tools, including those integrated within game engines.

The quality model defines which characteristics are considered when evaluating a software product. The quality of a system reflects the extent to which it fulfills the stated and implied needs of its stakeholders, thereby providing value. These needs are represented within the quality model, which organizes product quality into a hierarchy of characteristics and subcharacteristics [18]. The product quality model defined in ISO/IEC 25010:2023 comprises the nine quality characteristics that collectively

describe software product quality. To adapt these concepts to the context of custom game engine tools, each characteristic was examined to determine its relevance and possible interpretation in relation to the development of game engine editor extensions and custom editor-integrated authoring tools.

Functional suitability in this context concerns how effectively a custom editor tool fulfills the creative or technical purpose for which it was intended. This characteristic reflects how the tool's available functionalities support users in achieving the goals and actions relevant to its intended task (*functional completeness*), whether it produces correct and reliable outcomes that align with user inputs and parameters (*functional correctness*), and how efficiently it enables users to reach the desired results without unnecessary steps or workflow complications (*functional appropriateness*).

Performance efficiency in this context is the ability of a custom editor tool to execute its intended functions within acceptable time and resource limits under specific conditions, ensuring responsiveness and optimized use of hardware and software resources. In the context of game engine editor tools, performance efficiency can be understood through the tool's ability to maintain smooth interaction and responsiveness during operation (*time behaviour*), to use processing power and memory economically (*resource utilization*), and to remain stable and scalable when handling complex scenes, many objects or large projects (*capacity*). Major game engines include built-in performance profiling tools, provide documentation and community resources on optimization practices such as using caching, reducing unnecessary user interface redraws, rendering only visible elements, and avoiding complex calculations during redraw methods to ensure efficient performance of custom editor tools [19].

Compatibility represents the ability of a custom editor tool or extension to integrate, exchange information and operate effectively in a shared environment. A compatible extension should coexist with the core editor and other plugins without causing performance degradation or conflicts (*co-existence*), while also enabling consistent data exchange and mutual understanding through shared interfaces, data structures and formats (*interoperability*). Unity, Unreal, and Godot provide guidelines and best practices for ensuring compatibility, including adherence to API boundaries, use of supported data formats, respecting engine data structures, and testing extensions in diverse project setups to verify smooth coexistence with other editor components. Use of common and expected data formats, as well as integration with application programming interfaces (APIs) to ensure compatibility, have also been identified as important characteristics of such tools in previous research [3] [11].

Interaction capability is defined by how effectively users can engage with a tool through its user interface to accomplish intended tasks within the editor environment. In the context of game engine editor tools, this means that extensions should be immediately recognizable as suitable for developers' needs (*appropriateness recognizability*) and present sufficient contextual cues and labels so that their functions and usage are obvious without excessive exploration (*self-descriptiveness*). Tools should also be easy to learn by leveraging users' existing knowledge of the engine's interface and language conventions (*learnability*), and intuitive to control without confusion or redundant steps (*operability*). The tool should also prevent common mistakes and reduce the likelihood of destructive actions by implementing validation and confirmation mechanisms, such as input validation, undo support, or confirmation prompts (*user error protection*). Maintaining visual clarity, smooth interaction flow, and responsive feedback encourages sustained engagement (*user engagement*), while supporting color contrast, scalable UI, localization, and assistive input ensures accessibility across diverse users (*inclusivity* and *user assistance*). Major engines emphasize these principles to varying degrees in their documentation. Unity's Editor Foundations design system [16], Unreal's Scriptable Tools System [19] and Editor Utility Widgets [20], and Godot's Editor Plugin API [21] all promote consistent and inclusive interface design. Unity's design system and accompanying Figma resources further enable developers to prototype and evaluate their tools before implementation, facilitating usability testing and heuristic evaluation in early stages of development. Previous studies have also identified matching the design language of the environment and ensuring user interface usability [3], as well as the use of metaphors and good documentation [11], as important characteristics of such tools.

Reliability corresponds to a product's capability to perform its specified functions under defined conditions over a set period without interruptions or failures. For game engine editor tools, reliability ensures that custom extensions and authoring tools operate consistently during development sessions, avoiding crashes, freezes, or loss of work. They should function stably under normal operation without crashing (*faultlessness*), remain responsive and ready to use whenever required within the editor

(*availability*), provide robust error handling (*fault tolerance*), and allow users to undo or reload previous states if a failure occurs (*recoverability*). Major game engines provide guidance and examples supporting reliability: Unity's editor extensions emphasize error handling, safe undo operations, and autosave mechanisms [16]; Unreal recommends structured exception handling and replication strategies [19]; Godot offers signals and error reporting APIs to prevent disruptions [21].

Security stands for product's capability to protect information and data, ensuring that access is appropriately restricted and resistant to malicious or unintended interference. For custom game engine editor tools, this includes prevention of unauthorized access to project or user data (*confidentiality*), ensuring project files and settings remain unaltered (*integrity*), verifying that scripts, plugins, and extensions come from trusted sources (*authenticity*), tracking user actions such as asset imports (*accountability*), and providing proof of actions or events so that they cannot be denied later (*non-repudiation*). Extension should continue to operate safely even when confronted with corrupted input, malformed files, or maliciously crafted data (*resistance*). In AI-assisted tools that connect to external APIs, API keys and credentials must be securely stored and managed to prevent unauthorized access. It should be noted that the security of custom editor tools largely depends on the underlying game engine, since these tools typically rely on engine APIs for programming and execution. Users also play a critical role by ensuring they only load trusted plugins, scripts, and assets into the engine editor.

Maintainability signifies product's capability to be modified effectively and efficiently by its intended maintainers. In the context of custom game engine editor tools, this includes updating features, correcting bugs, and adapting to changes in project requirements or new engine versions. Changes in one tool component should not unintentionally affect others (*modularity*), and components or scripts should be reusable across multiple projects (*reusability*). The tool should also support understanding the impact of changes or diagnosing issues (*analysability*), enable safe updates without introducing defects (*modifiability*), and allow verification that modifications meet requirements (*testability*). Engine documentation and resources, such as Unity's Editor tooling guidelines, Unreal's Editor utility best practices, and various community tutorials, provide concrete recommendations for modular design, coding standards, and testing strategies that improve maintainability. Ensuring maintainability in custom tools facilitates long-term usability, supports iterative development, and reduces the effort required for updates and bug fixes.

Flexibility indicates product's capability to adapt to changes in requirements, usage contexts, or system environments. For custom game engine editor tools, this involves adapting to different project types, hardware or software configurations, user workflows, and evolving development needs. A flexible tool should be efficiently transferable or customizable for different environments (*adaptability*), capable of handling projects of varying size or complexity (*scalability*), easy to install or remove without disrupting existing projects (*installability*), and able to be replaced or updated with alternative modules or solutions while minimizing dependency or lock-in (*replaceability*). Engine documentation and best-practice resources offer recommendations for modular architecture, standardized file formats, and configuration flexibility that enhance the flexibility of editor tools [13].

Safety refers to a product's capability, under defined conditions, to avoid states that could endanger human life, health, property, or the environment. In the context of custom game engine editor tools, safety concerns are mostly not relevant to physical hazards but can be discussed in terms of projects or critical data. Tools should be able to identify potential risks or conflicts in their operation (*risk identification*), restrict unsafe actions or operations that could compromise data integrity (*operational constraint*), provide clear alerts or warnings before performing potentially destructive actions (*hazard warning*), and revert to a stable or previous state in the event of a failure (*fail safe*). They should also maintain stability and data integrity when integrated with other extensions or scripts (*safe integration*). Engine documentation and community resources emphasize backup mechanisms, validation routines, and safe API usage as practical ways to implement these safety measures.

It should be acknowledged that the applicability of software quality standards such as ISO/IEC 25010 varies across different types of custom extensions. The relevance and applicability of individual characteristics depend strongly on the tool's purpose, design goals, and context of use. For example, editor extensions focused on automation or batch processing (e.g., importers, converters, or build pipelines) may be primarily evaluated in terms of their compatibility, support for different file formats, performance efficiency, and reliability. In contrast, tools designed for interactive use within the editor, such as custom

inspectors, visual node editors, or interactive layout tools, would require stronger emphasis on usability, accessibility, and overall user experience. This means that a flexible interpretation of the standard is required, because not every quality attribute is equally important for every use case, and the evaluation framework should allow context-sensitive prioritization of quality aspects.

4. Discussion

The presented framework serves as an interpretive model for understanding and improving the quality and consistency of custom game engine extensions through the lens of the ISO/IEC 25010 software quality characteristics. Its primary contribution lies in providing a structured perspective for evaluating functionality, usability, maintainability, and other relevant aspects of editor tools, which are often overlooked in practice. This interpretation establishes a conceptual foundation for future standardization discussions and can serve as a starting point for both academic and industrial validation practices.

The rapid evolution of technology, both in general and specifically within the domains of game development, virtual reality, simulations, and interactive applications, presents a moving target that demands flexibility and continuous adaptation. Game engines and their supporting tools evolve rapidly, introducing new workflows, APIs, and design paradigms. Consequently, the proposed contextualization should be continually evaluated, maintained, and expanded to remain relevant. Furthermore, as ISO/IEC standards themselves undergo revision, certain criteria or terminology may also require updating to preserve alignment, compatibility, and interoperability with broader software quality frameworks. Establishing a feedback loop between game engine development teams, end users (including tool creators), and standardization bodies would help ensure the long-term validity and practical applicability of the proposed approach.

In the case of internal or in-house tools, some of the quality aspects highlighted through this contextualization of the ISO/IEC 25010 standard may appear less critical, as such tools are typically developed for a narrower user base within a company rather than for a global audience through asset stores. Internal users are often already familiar with the tool's functionality or may have directly contributed to its development. However, this can also introduce certain risks. Once the tool achieves its intended functionality, developers may move on to other projects, leaving behind incomplete documentation, unoptimized or unrefactored code, and limited quality assurance. Over time, this can result in technical debt, reduced maintainability, and difficulties in extending the tool for future needs. Nevertheless, since these tools are likely to be maintained, reused, and adapted in subsequent projects or by other teams within the organization, it remains highly beneficial to invest in their quality, documentation, and adherence to best practices. This proactive approach ensures sustainability, knowledge transfer, and long-term efficiency across development cycles. In such cases, these aspects should be carefully considered, and a thorough assessment of the required degree of compliance with each quality standard should be conducted in order to achieve an appropriate compromise.

However, several limitations must be acknowledged. The proposed framework has not yet been empirically validated through systematic evaluation or user studies on real-world examples of custom editor tools, and its applicability may vary across different game engines due to differences in architecture, development workflows, and asset store submission requirements. Furthermore, certain quality attributes, such as usability and reliability, remain partially subjective and may require adapted assessment methods within the context of interactive development environments and concrete use cases.

Future work could focus on empirically validating the proposed framework through practical case studies and user evaluations. Applying it to a selection of existing editor extensions across the most popular game engines such as Unity, Unreal, and Godot would help assess its effectiveness in improving usability, maintainability, and interoperability. In addition, surveys and interviews with both platform developers (game engine and asset store teams) and end users (engine users and tool creators) could provide valuable insight into the practicality and perceived benefits of standardized quality criteria. Further research should also explore ways to potentially automate parts of the evaluation process, for example through static analysis tools or AI-assisted quality assessment systems. In terms of documentation, resources, and guidelines for developing custom tools and integrating them with the game engine editor, Unity provides

a particularly detailed and structured design system. This level of guidance serves as a strong reference model that other engines could follow to improve their own documentation and support for custom tool development. Finally, collaboration with game engine communities, industry partners, and standardization organizations could facilitate the establishment of shared evaluation practices and lightweight certification processes, supporting broader adoption and long-term sustainability of high-quality custom game development tools. Of course, the proposed approach could also be applied to standalone development tools created independently of any specific game engine, with appropriate modifications to accommodate differences in technology, architecture, and use context.

5. Conclusions

This paper highlighted the growing importance of custom game engine extensions for adapting general-purpose game engines to increasingly diverse commercial and academic contexts, including games, virtual reality, simulations, and interactive applications in general. Although these tools greatly improve flexibility and productivity, their rapid, decentralized development can lead to inconsistent quality, limited interoperability, and varying levels of functionality and usability. By contextualizing the ISO/IEC 25010 software quality standard, this paper proposed a framework that can be used to guide the design, development and evaluation of such extensions. Presented interpretation encourages a more systematic approach to tool development by addressing functionality, reliability, maintainability, and user experience, while aligning with existing documentation and best practices from most popular game engines. The adoption of standardized quality principles can support developers, studios, and asset store curators in producing more robust and sustainable tools. Future work will focus on validating the proposed framework through empirical evaluation on practical examples, refining measurable quality indicators, and collaboration with the developer community to discuss, adapt, and iteratively improve the framework for development of custom tools that can be integrated into the game engine, but potentially also in case of standalone tools that are developed outside of game engine in different technologies.

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Artificial Intelligence and Critical Thinking in Foreign Language Learning: From Theory to Practice

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Abstract:
In recent years, Artificial intelligence (AI) has been increasingly utilized in educational contexts to improve student learning outcomes. This technology offers instant feedback, foster interactive and engaging learning experiences, and contributes to the development of critical thinking skills by allowing students to engage with content in dynamic ways. Critical thinking is the ability to evaluate, analyze and synthesize information, helps students assess the vast amount of information, make informed decisions, and solve complex problems that arise from rapid technological advancements, including AI innovations. While AI cannot replace human thought, it has the potential to enhance students thinking when used wisely. Similar to an effective teacher, AI can challenge assumptions, present alternative viewpoints, pose provocative questions, and provide structured feedback. Employing AI as a tool for critical thinking offers significant value: it compels students to exercise judgment, critically evaluate the system's responses, and ultimately take responsibility for their own decisions. The present paper provides a theoretical perspective on AI technology and critical thinking in the context of foreign language education. Furthermore, the paper presents selected prompt templates that are very illustrative as to how both teachers and students can use AI to develop critical thinking skills.

Keywords: Artificial intelligence, critical thinking, students, foreign language

1. Introduction

The rapid advancements in Artificial Intelligence (AI) technology in educational settings has emerged as a transformative trend, redefining the landscape of learning and teaching foreign language (FL). AI tools, such as ChaGPT, DeepSeek, Perplexity, Gemini, Copilot, etc. provide new opportunities in addressing the critical need to develop higher-order thinking skills, such as critical thinking, which are essential for students to navigate the complexities of the modern world [1]. Today, critical thinking helps students assess the vast amount of information and solve complex problems that arise from rapid technological advancements, including AI innovations [2,3].Critical thinking is a fundamental skill that enables individuals to analyze, evaluate, and make informed decisions[4,5,6]. It is a crucial aspect of learning and problem-solving in many educational systems. Foreign language classes are a proven medium for fostering critical thinking through activities that require evaluation of multiple interpretations, deep analysis, and synthesis of concepts and themes [7,8]. Critical thinking in foreign language classes involves questioning underlying assumptions, individual biases and evaluating the credibility of arguments [9]. By integrating AI tools into foreign language classes, these cognitive processes can be further enhanced. AI provides individualized feedback and support, encouraging students to engage with complex texts in deeper, more analytical ways[10]. The present paper provides a theoretical perspective on how AI tools can enhance critical thinking skills in foreign language classes at tertiary level. Furthermore, the paper presents some examples of prompt templates

proposed by Nik Peachey in his book "Developing Critical Thinking Skills with AI: A Guide For Teachers" illustrating how teachers and students can use AI to develop critical thinking skills. These examples demonstrate the efficacy of AI in promoting critical thinking skills in teaching foreign language. Nik Peachey is an experienced educator, author, and consultant specializing in educational technology, digital learning materials, and teacher development in the field of English Language Teaching (ELT). Peachey's work was selected for this paper because his latest book "*Developing Critical Thinking Skills with AI: A Guide For Teachers*" published in August, 2025 deals explicitly with how AI can be employed in language classrooms, and how prompt-design and digital tools can promote higher-order thinking. Peachey does not just theorize but offers concrete prompt templates, teaching materials, classroom tasks, and frameworks that teachers can adapt. This makes his work especially useful for empirical studies or classroom applications.

2. Literature review

2.1 Critical thinking in foreign language context

Critical thinking (CT) is the ability to think clearly, logically, and independently. It involves questioning ideas, analyzing information, and making reasoned judgments. According to [12], critical thinking is reflective thinking that is focused on deciding what to believe or do. While [13] described CT as the art of analyzing and evaluating thinking with a view to improving it. Briefly, CT helps individuals make more informed decisions by considering different perspectives and carefully evaluating evidence. There are several key components of CT skills such as analysis, reasoning, evaluation, explanation, and self-regulation. Analysis enables individuals to break down complex ideas into smaller components to understand them better [14]. Reasoning allows individuals to connect pieces of information logically to form sound conclusions [15]. Evaluation enables individuals to assess the quality and reliability of information before accepting it [16]. Explanation and elaboration involve clearly expressing ideas and the reasoning that supports them [17]. Self-regulation allows people to reflect on their thinking, recognize biases, and improve their judgment [18]. Together, these skills enable learners to think in a structured, logical, and rational way. To think critically, students have to want to think. They need motivation, curiosity and interest in the topic. Without these basic things, no amount of assignments, AI assisted or not, are likely to help them [11].In language learning, particularly in English as a Foreign Language (EFL) education, CT plays an essential role, especially in writing, reading, and speaking. In English writing course, students need to organize their ideas logically, construct strong arguments, and consider opposing viewpoints [19]. In English reading, CT ability helps learners analyze texts, recognize biases, and differentiate facts from opinions [20,21]. In English speaking, it enables learners to express their thoughts clearly, support their ideas with evidence, and engage in meaningful discussions [22]. Thus, through developing CT skills, foreign language learners become more independent thinkers who can communicate effectively and evaluate information critically.

2.2 The impact of artificial intelligence on critical thinking in foreign language context

Learning foreign language (FL) is not only about using correct grammar and expanding vocabulary it also requires analyzing texts, developing arguments, and thinking critically [23] AI can't think for students, but it can help them think more efficiently, if they use AI wisely. AI can be used to stimulate, and enhance the thinking process. It can prompt questions, spark curiosity, provide new perspectives, and help students explore complex ideas more deeply[11].Engagement with AI-generated discussions exposes learners to diverse perspectives, thereby fostering their capacity to critically evaluate ideas and conduct deeper analyses of arguments[24]. AI can contribute to the development of logical reasoning by providing feedback on reasoning processes [25]. When learners ask AI to explain a concept, they can evaluate the logic behind the response and refine their own thinking. Additionally,

AI tools support reflective learning by offering instant feedback on speaking, writing and problem-solving [26], which helps FL learners improve their CT skills over time. A number research studies have revealed the significance of AI in fostering critical thinking, confirming its role as a facilitator of higher-order cognitive skills within 21st-century education. The authors [27] highlight that attributes such as trust and self-confidence can be strengthened through AI-assisted learning, influencing not only language acquisition but also the development of critical thinking skills. These insights align closely with [28] literature review (2022), which outlines a structured approach to using technology to foster critical thinking, indicating that effective technological integration can significantly impact educational outcomes. An integrative literature review by [29] explored the integration of ChatGPT into English language teaching as a means to enhance critical thinking and cognitive development. Also, [29] also proposed a framework for "Critical AI Literacy" to guide educators in the effective use of generative AI while addressing its limitations. Moreover, a systematic review by [30] examined the impact of generative AI on critical thinking skills in higher education. The review found that ChatGPT can support the development of students' analytical abilities by offering diverse perspectives, aiding in argument construction, and facilitating information analysis. Additionally, a systematic review by [31] investigated the influence of AI on students' critical thinking (CT) skills. In this context, the findings of the use of AI in French and Spanish foreign language education highlight that AI applications, particularly chatbots and automated writing tools, are primarily used to enhance writing skills and critical thinking [32].

In sum, although the literature reviews provide valuable insights into how AI tools such as ChatGPT influence students' critical thinking, inconsistencies remain in theoretical frameworks, assessment methods, and pedagogical applications—especially within FL education. Future research should aim to reconcile these perspectives by examining CT as both a cognitive skill and an attitudinal disposition, while also exploring contextual and motivational factors that shape learners' capacity for critical engagement.

3. Prompt templates useful for developing critical thinking

As mentioned before, in this paper we refer to some practical prompt templates developed by [11] in his latest book "*Developing Critical Thinking Skills with AI: A Guide For Teachers*". This specific publication has been selected as, to the best of our knowledge; it pioneers ideas as to how AI can be harnessed to develop critical thinking in the context of foreign language acquisition. More specifically, it offers classroom-ready examples that explicitly integrate artificial intelligence tools into tasks designed to develop learners' critical thinking skills. For the purposes of this study, we chose to discuss three selected prompt templates (*AI Critical Thinking Friend, Role Play Simulations, Brainstorming Feedback*) which are part of Section 8 in the book and are intended to inspire practical classroom innovation using AI tools that encourage active learning and creativity on the part of both teachers and students. In other words, Nik Peachey's idea with these prompt templates is to demonstrate how AI gives opportunities to explore ideas more deeply and refine the critical thinking skill. In the discussion bellow, we have included Peachey's interactions with AI, based on the above-mentioned prompts.

3.1 AI critical thinking friend

The "AI Critical Thinking Friend" prompt template to create an AI critical thinking friend that can discuss any issue or opinion students express [11]. The huge benefit of inputting this prompt is that students can express an opinion and the AI will act as a calm and rational critical thinker who will attempt to challenge and rebut the opinion.

In acting as a "critical thinking friend", AI, in fact, supports critical thinking by providing a safe space for open dialogue, encouraging self-reflection, and offering constructive challenges. It helps students spot gaps in their reasoning, consider new perspectives, and grow more open-minded, confident, and thoughtful over time, Figure1.

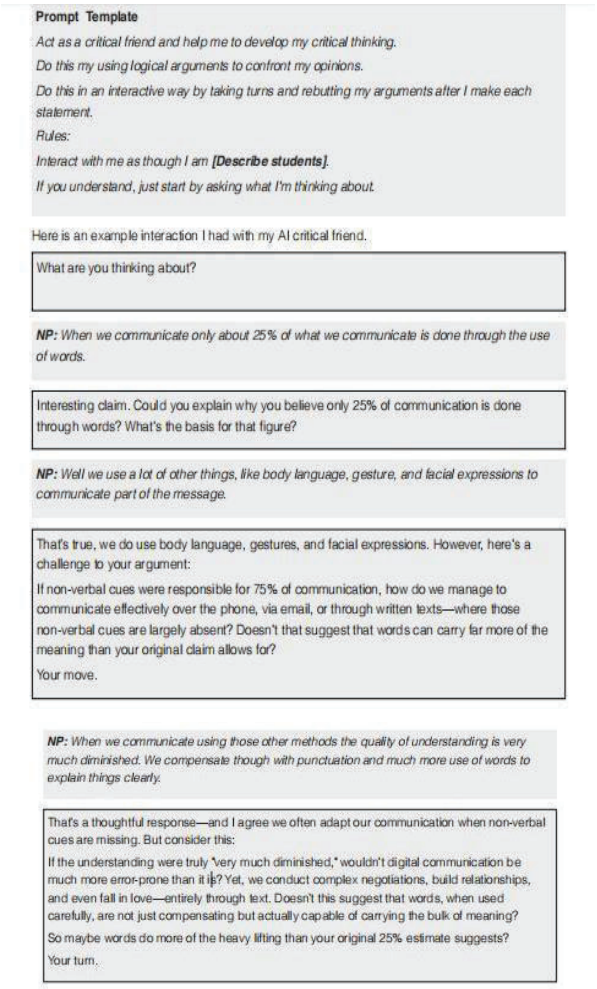


Figure 1: The "AI Critical Thinking Friend" prompt template

3.2 Role play simulations

The "Role-playing Problem Solving" prompt, according to [11] enables students/learners to engage with real or simulated situations, adopt specific roles, and analyze complex problems from multiple perspectives. This approach to active learning fosters critical thinking by encouraging learners to evaluate information, reflect on diverse perspectives, and make well-reasoned decisions within dynamic contexts.

This prompt helps students explore complex situations from multiple perspectives. It builds critical thinking by promoting analysis, creativity, collaboration, and decision-making in realistic scenarios where there is no single correct answer, Figure 2.

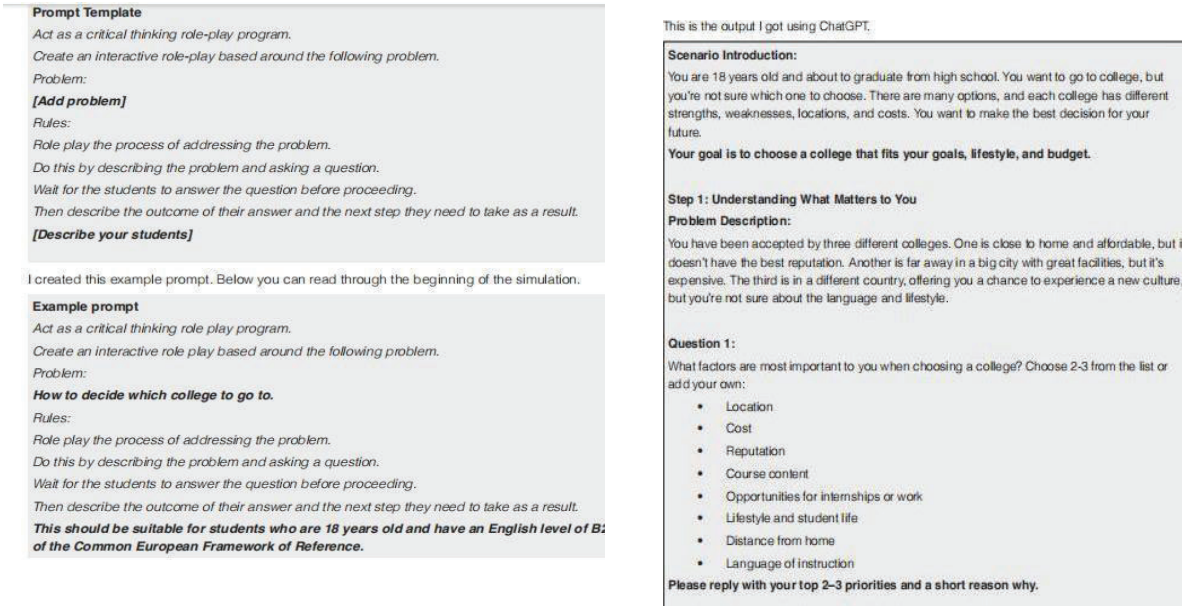


Figure 2: The "Role Play Simulations" prompt template

3.3 Brainstorming feedback

The "Brainstorming feedback" prompt template, according to [11] can be utilized by students to evaluate and get feedback on their ideas. They start by brainstorming ideas to solve a problem and then use the AI to get feedback on the ideas and suggestions for improving them, Figure 3.

Brainstorming solutions and receiving critical feedback gives students a valuable chance to build their thinking and communication skills. Since AI can respond instantly and objectively, students can quickly identify strengths and weaknesses in their reasoning, arguments, or writing. This feedback highlights gaps in logic, encourages considering alternative perspectives, and helps refine ideas, which are key aspects of developing critical thinking.

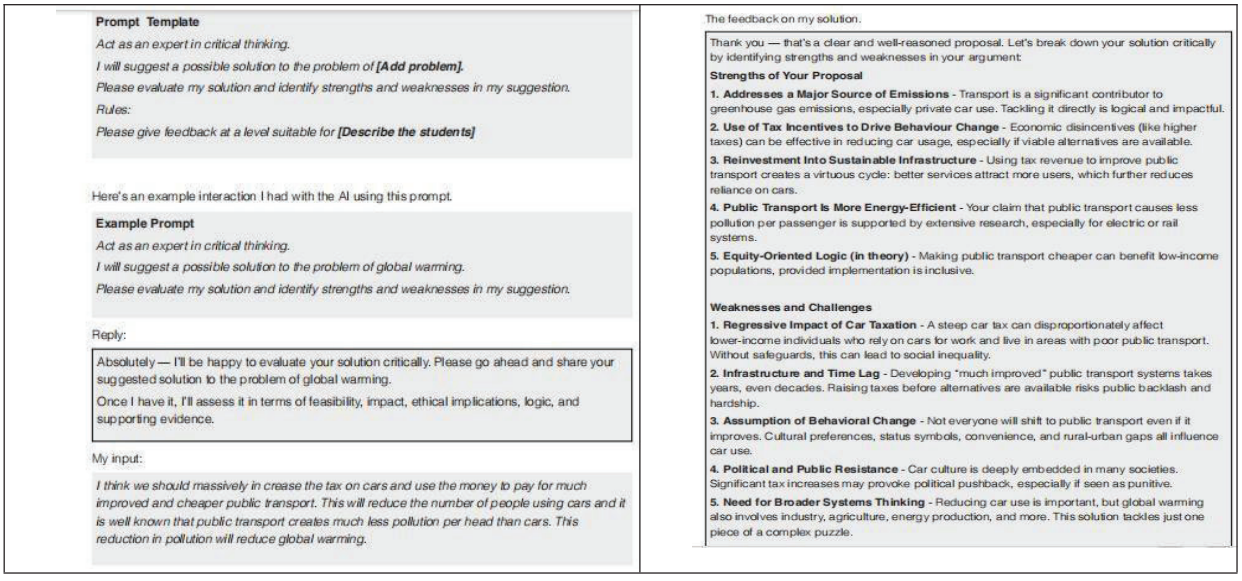


Figure 3: The "Brainstorming Feedback" prompt template

What is significant regarding the structure of all the above proposed prompt templates is that they start with "*Act as...*".This clarifies the AI's role and the knowledge domain it should utilize. Next,

instructions are provided to specify what it should generate, (e.g. "*Identify strengths and weaknesses in my suggestion").* Then, in many cases, there are rules that define the output's parameters, including the intended audience and any specific requirements to include or exclude. This structure generally works well, and understanding and following it should allow both teachers and students to create a number of their own prompts.

Although Peachey's approach provides an innovative conceptual foundation, empirical validation remains limited. Future research should aim to test and refine this framework through systematic classroom-based experiments and longitudinal studies. Specifically, three key research directions emerge: 1. Empirical validation of AI-supported CT frameworks -researchers could design quasi-experimental or mixed-method studies comparing traditional CT instruction with AI-enhanced approaches using Peachey's templates. Variables such as learners' CT skills, engagement, language proficiency, and reflective depth could be measured through pre- and post-intervention assessments. 2. Cross-modal transfer of CT skills in FL contexts - further studies could explore whether CT developed through AI-supported writing or speaking tasks transfers to other domains (e.g., reading comprehension, listening analysis). 3. Motivational and affective dimensions of AI-Based CT learning - since motivation and curiosity are essential for critical engagement; further empirical work could investigate how AI prompt templates influence students' affective responses such as confidence, curiosity, and persistence in critical thinking activities.

4. Conclusion

The integration of Artificial Intelligence (AI) into foreign language learning marks a transformative shift from traditional approaches toward more dynamic, personalized, and interactive pedagogies. Beyond its role as a technological tool, AI fosters an environment where students are not only exposed to authentic linguistic input but are also encouraged to engage in higher-order thinking processes. At the same time, AI-supported environments encourage students to question, analyze, and reflect on both content and process, moving them beyond rote memorization into meaningful communication and problem-solving. This alignment of AI's capabilities with the goals of critical thinking prepares students for the complexities of intercultural communication in real-world contexts. Nevertheless, the transition from theory to practice requires thoughtful pedagogical design. Teachers remain central in framing AI not as a replacement, but as a catalyst for deeper learning experiences. Ethical considerations, such as data privacy, equity of access, and the potential for overreliance on technology, must also be carefully addressed. Despite the promising potential of AI to enhance learners' critical thinking (CT) skills, several disadvantages and limitations have been noted in recent literature and practical applications: overreliance on AI feedback; superficial engagement and lack of deep processing; quality and bias of AI responses; limited contextual and emotional understanding; ethical and privacy concerns and teacher competence and instructional integration.

In conclusion, the integration of AI into foreign language learning offers significant opportunities to merge linguistic development with critical thinking. When implemented responsibly and guided by sound educational principles, AI can empower students to become not only proficient speakers of a foreign language but also reflective, autonomous, and critical thinkers – skills essential in a globalized and digitally mediated world.

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A Comparative Analysis of Locomotion Techniques in Virtual Reality for Architectural Visualization

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Abstract:
This paper presents a systematic analysis and comparison of locomotion techniques in virtual reality as applied to architectural visualizations. Synthesizing key reviews and empirical studies, it examines how motion-based, room-scale, controller-based, and teleportation methods affect spatial perception, sense of presence, and VR-induced symptoms. The analysis shows that room-scale and real-walking approaches yield the most accurate spatial cognition and strongest presence but are constrained by physical tracking space; controller-based techniques enable efficient exploration of large interiors and exteriors but increase the risk of cybersickness (also referred to as VRISE - *Virtual Reality Induced Symptoms and Effects*); teleportation greatly reduces it yet disrupts spatial continuity and orientation. A comparative overview (Table 2) summarizes the suitability of these locomotion techniques for interior and exterior architectural spaces, forming one of the paper's key contributions. Based on this analysis, the paper offers practical recommendations for selecting appropriate locomotion methods depending on spatial scale, presentation goals, and user profile. Hybrid schemes (local natural movement + long-distance teleportation or controller movement) are advised to balance immersion, comfort, and efficiency. The work concludes with considerations for future development of hybrid locomotion systems and the potential impact of emerging technologies such as full-body tracking and omnidirectional treadmills on architectural VR practice.

Keywords:
locomotion, virtual reality, architectural visualization, spatial cognition, cybersickness, teleportation, room-scale, hybrid locomotion

1. Introduction

Virtual reality is becoming a key tool in architectural practice and education, allowing clients, designers, and other stakeholders to intuitively explore unbuilt spaces. Navigation within these environments, or VR locomotion, is crucial because movement directly affects perceptions of size, proportions, spatial relations, and presence. This connection between locomotion and presentation quality raises the question of which technique best supports specific architectural scenarios [1, 2].

Choosing a locomotion method is not merely technical. It must balance spatial realism, user comfort, and accurate spatial cognition. Real-movement techniques (room-scale) offer high immersion and support mental map formation, improving distance and orientation judgments, but are limited by available physical space and tracking requirements [3, 4]. Artificial methods, such as controller-based or teleportation locomotion, allow rapid navigation through large interiors and exteriors where real walking is not feasible, though they may increase simulator sickness and reduce spatial coherence [5, 6, 8, 10].

Hybrid approaches combining real walking for local movement with teleportation or controller-based travel for longer distances provide the best balance between comfort and spatial perception. They enable detailed inspection of spaces while supporting efficient transitions between building areas which is an advantage for design presentations and prototyping.

This paper systematically analyzes and compares VR locomotion techniques in architecture, examining their effects on spatial perception, VRISE (Virtual Reality Induced Symptoms and Effects), and the credibility of architectural representation. Drawing on key reviews and empirical studies, it offers scenario-based recommendations for selecting locomotion methods according to spatial scale,

presentation goals, and user profile [1, 2, 3, 4, 5, 6, 8, 10]. In addition, the paper provides a comparative overview (Table 2) summarizing the suitability of major locomotion techniques for interior and exterior architectural spaces. The table forms a central contribution and concise reference for evaluating locomotion choices across design contexts.

The paper has seven sections: Section 2 presents VR locomotion types, Section 3 covers cognitive and perceptual assessment, Section 4 analyzes techniques in different environments, Section 5 reviews empirical evidence, Section 6 offers recommendations, and Section 7 concludes.

2. Overview of Locomotion Types in Virtual Reality

There are multiple VR locomotion techniques. Boletsis reviewed 36 studies and identified 11 techniques, grouped into three categories [1]. The first, interaction type, describes how users trigger movement: physical, via body tracking, or artificial, via input devices like joysticks. The second, movement type, distinguishes continuous (smooth navigation) from noncontinuous (instant displacement). The third, interaction space, can be open, allowing navigation beyond the physical environment, or closed, confined to the real-world space.

Based on these three categories, four types of VR locomotion were defined, as shown in Figure 1.

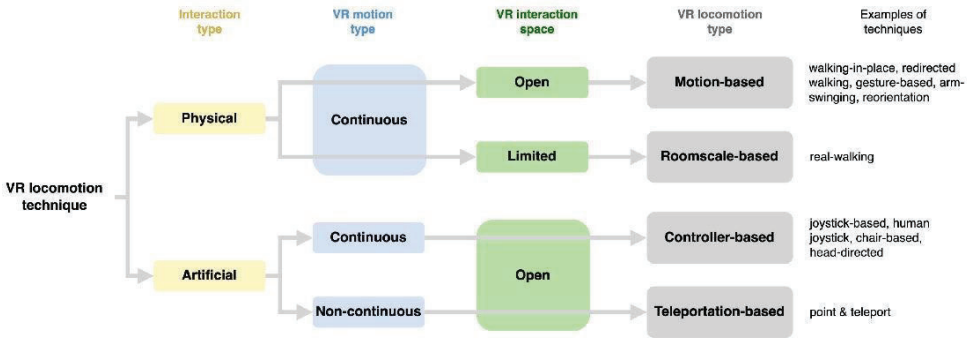


Figure 1: Types of locomotion in virtual reality [1]

With advances in hardware and locomotion methods, Boletsis and Chasanidou updated the four locomotion types to include a new method, which is motion-based teleporting. The original controller-based teleportation was renamed to distinguish between physical gestures and input devices. The updated types are shown in Figure 2 [2].

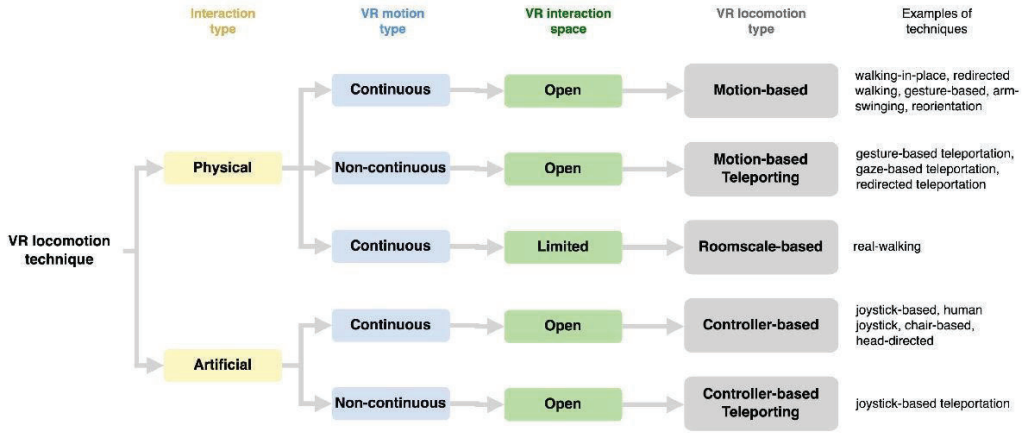


Figure 2: Modified types of locomotion in virtual reality [2]

Motion-based locomotion techniques rely on some form of physical user movement to enable interaction while supporting continuous movement in open VR spaces. It utilizes the user's body movements to control their virtual movement. It typically involves sensors or motion controllers that

capture the user's gestures and convert them into virtual actions. This technique provides a more natural and intuitive way of interacting with the virtual environment [11]. This type includes methods such as walking-in-place, redirected walking, arm swinging, gesture-based locomotion, and orientation-change techniques [1, 2].

Room-scale based locomotion allows users to physically move around in a designated physical space while wearing a VR headset. The VR system tracks the user's movements, ensuring that their virtual movements align with their physical movements. This technique provides a high level of immersion as it allows users to explore the virtual environment freely. Room-scale locomotion is particularly useful for applications that require physical interaction and spatial understanding. For example, in architectural designs, users can walk around and examine virtual structures in real-time. However, it does require dedicated physical space and may not be suitable for all settings. Real walking belongs to this category [1, 3, 4, 11].

With controller-based locomotion, the user moves artificially within the VR environment using controllers. Users can move forward, backward, and sideways by pressing buttons or manipulating thumbsticks on the controllers. This technique offers precise control over movement and is widely used in VR applications and games. The interaction space is open, and movement is continuous. This category includes techniques such as joystick navigation, the "human joystick" concept, seated locomotion, and gaze-directed movement [1, 5, 8, 11].

Motion-based teleporting relies on natural user movements or gestures to navigate through space. Instead of simulated walking, the user teleports by triggering specific gestures such as hand waving, pointing, or turning the body. These techniques allow a greater degree of physical engagement and intuitive control and are often used in VR environments that support free exploration. Examples include teleportation via hand gesture, gaze focusing, or predefined gestures [2, 6].

Unlike natural gestures, controller-based teleporting techniques use input devices such as VR controllers or joysticks to select a location and initiate teleportation. The user points the controller at the desired location in the virtual space and triggers the transition by pressing a button. This approach provides greater precision and requires less physical effort, making it suitable for users with limited space or mobility. A typical example is joystick-based teleportation [2, 6].

Figure 3 shows the different types of locomotion.

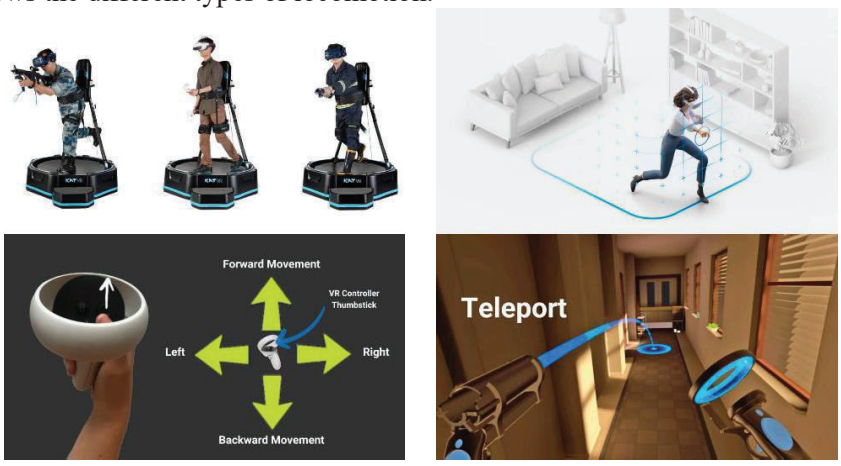


Figure 3: Motion-based (top left), room-based (top right), controller-based (bottom left) and teleportation-based (bottom right) locomotion types [11]

3. Cognitive and Perceptual Assessment

Different types of locomotion in virtual reality influence not only the physical user experience but also spatial cognition, orientation, sense of presence, and physiological reactions such as nausea (VR sickness or cybersickness). The choice of locomotion technique significantly affects how successfully a user can assess spatial relationships, remember spatial layouts, and perceive the realism of the environment. Research indicates that the combination of sensory input (visual, vestibular) and navigation type dictates the occurrence of symptoms [3, 4, 5, 8].

The impact of locomotion techniques on spatial perception, presence, and VR symptoms is summarized in Table 1.

Table 1:
Influence of locomotion techniques on spatial perception, presence, and VR symptoms

Locomotion Technique	Spatial Cognition	Sense of Presence	VRISE Symptoms	Notes
Motion-based	Medium – better than controllers	Medium to high	Moderate	Compromise between physical realism and effort
Room-scale	High – best mapping	High	Low	Best for detailed orientation and mental maps
Controller-based	Medium to low	Medium	High	Suitable for large spaces, requires measures to reduce VRISE
Motion-based teleporting	Medium to low	Medium	Low	Comfortable but reduces spatial continuity
Controller-based teleporting	Low	Medium	Low	Reduces VRISE, but compromises cognition, hybrid use recommended

Room-scale locomotion has proven to be the most natural and intuitive. It enables the highest degree of immersion and spatial orientation, as user movements are directly mirrored in the virtual space. Studies show that this type results in the most accurate distance estimation and the best cognitive mapping of space [3, 4].

Teleportation reduces nausea because it avoids artificial movements inconsistent with vestibular signals. However, teleportation often disrupts spatial coherence and may lead to less accurate perception of layout [4, 6].

Controller-based movement enables free exploration of large spaces but carries a higher risk of nausea due to conflicting sensations. Some authors note, however, that users may develop tolerance to these effects over time [5, 8].

Motion-based locomotion techniques such as walking-in-place or arm swinging represent a compromise between physical realism and spatial efficiency. They offer better control than controllers but often require more effort and can be less precise [5].

4. Environmental Analysis

The choice of locomotion technique in virtual reality depends on the characteristics of the architectural environment being presented. Spaces can be divided into interior (closed) and exterior (open), each requiring specific navigation approaches.

Section 4.1 presents movement techniques suitable for indoor spaces, section 4.2 covers those appropriate for outdoor spaces, and section 4.3 compares the analyzed techniques within architectural environments.

4.1. Interior Spaces

Interiors such as apartments, offices, or public indoor spaces usually demand precise and slow movement for detailed inspection. Suitable techniques include room-scale, teleportation, and walking-in-place. Room-scale locomotion provides realistic interaction if the physical space is large enough [3, 4]. Walking-in-place and arm swinging serve as alternatives for simulating movement without requiring large physical areas [5]. Teleportation is common indoors as it avoids nausea and works well in limited spaces or presentations [6]. Still, when used alone, it can impair spatial cognition and distort proportions,

so it is best combined with natural short-range techniques [1, 4].

4.2. Exterior Spaces

Exteriors such as urban environments, parks, or entire campuses require prolonged and continuous movement. Teleportation feels unnatural here and interrupts presence. Appropriate techniques include controller-based, redirected walking and gesture-based locomotion. Controller-based techniques (e.g., joystick or head-directed locomotion) enable efficient long-distance travel [1, 5]. Redirected walking is appropriate, if adaptation of the physical space is possible (e.g., in laboratory settings) [2]. Gesture-based locomotion simulates natural walking without needing large areas, though requiring more physical effort [5].

Teleportation can still serve a supportive role outdoors, for example when quickly jumping between distant points of interest during a presentation, but it should be combined with continuous techniques to maintain orientation and presence [2, 7].

4.3. Comparison of locomotion techniques across architectural environments

Based on the analysis of interior and exterior spaces, as well as the characteristics of various VR locomotion techniques presented in the second section, Table 2 summarizes their suitability for specific architectural scenarios and shows which method provides the best spatial cognition, level of comfort, and applicability depending on the physical limitations of the space and the duration of the presentation.

Table 2:
Suitability of VR locomotion techniques for interior and exterior spaces

Locomotion Technique	Interior Spaces	Exterior Spaces	Notes / Recommendations
Motion-based	Supports immersion and cognition, good for limited space	Requires more effort, less practical	Good compromise between immersion and space
Room-scale	Highest accuracy and presence	Limited by physical space	Ideal for detailed interior review, less suitable for large exteriors
Controller-based	Less natural, possible VRISE	Suitable for large spaces / exteriors	Combine with visual stabilizers or hybrid approaches
Motion-based teleporting	Practical for quick transitions between zones	Less natural for long routes	Best used as a complementary technique with continuous movement
Controller-based teleporting	Useful for reaching distant points in limited space	Breaks continuity but reduces VRISE	Suitable as a secondary tool in hybrid use

The table provides an overview and comparison of techniques useful for planning architectural presentations and selecting the most appropriate approach for specific types of spaces.

5. Empirical Evidence

Empirical studies examine how VR locomotion affects user experience, spatial orientation, presence, and motion sickness, providing insight into virtual architectural perception. Physical movement techniques, like real or redirected walking, best support spatial cognition, orientation, and distance estimation, enhancing spatial memory and presence [3, 4]. Artificial movement methods, such as controllers, allow faster navigation in large spaces but increase cybersickness, especially forinexperienced users [5, 8]. Teleportation reduces motion sickness and improves comfort but can disrupt spatial coherence and realism [4, 6]. Hybrid approaches, combining techniques like teleportation with on-the-spot walking, offer a balanced compromise between comfort and spatial perception, particularly for longer architectural presentations [5].

One of the most significant studies in this field is the research conducted by Usoh et al. [3], in which user experiences were compared across three types of movement in a virtual environment: actual walking, walking in place, and flying. The results regarding ease of movement are shown in Figure 4.

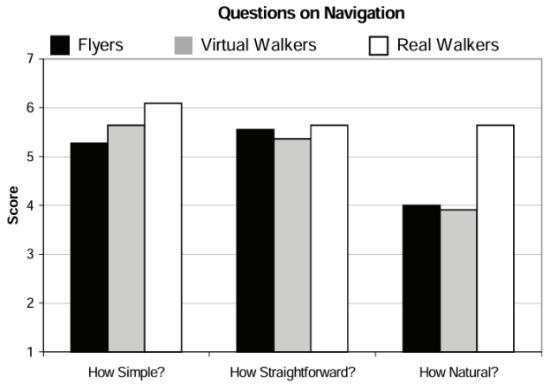


Figure 4: Estimated ease of movement for three participant groups [3]

The results show that users who moved through real walking, had the strongest sense of presence and better spatial orientation. Walking in place offers a moderately immersive experience, but with a reduced sense of movement.

Hořejší et al. [10] performed a controlled within-subjects VR study to evaluate how teleportation affects spatial orientation compared to joystick-based and foot-based locomotion. Fifteen young adults navigated three virtual mazes of increasing difficulty using three locomotion modes: hand-tracking with teleportation (HTR), joystick controllers (CTR), and Cybershoes (CBS). These modes are shown in Figure 5.

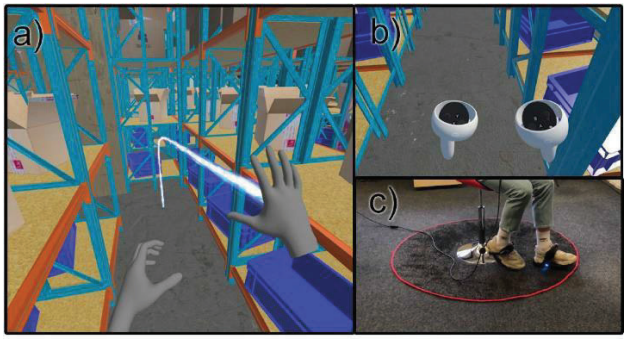


Figure 5: (a) HTR with teleportation; (b) traditional VR CTRs; (c) With the control using CBS, the user does not see any CTRs, as they are not needed in this case [10].

In the simplest maze, HTR users took 127 ± 54 seconds, more than twice the time of CTR (52 ± 25 s) or CBS (52 ± 22 s), both significant at $p < 0.01$. HTR also had the lowest usability score (SUS = 65.83 ± 22.22) compared to CTR (74.67 ± 18.52) and CBS (67.83 ± 24.07). Although HTR caused the

least cybersickness (1.8 ± 0.9), CBS caused the most (2.9 ± 1.2, p = 0.006), with CTR intermediate (2.3 ± 1.1). These results indicate that teleportation, while comfortable, impairs spatial orientation by disrupting continuous sensory cues, leading to slower and less confident navigation [10].

Caserman et al. [5] meta-analyzed 49 VR HMD studies and found that continuous artificial locomotion, such as using joysticks or controllers, causes higher SSQ (Simulator Sickness Questionnaire) scores (~31.8 vs. ~12.8; $p < 0.0001$) and increased withdrawal rates (~7.1% vs. ~3.2%) due to sensory mismatch. In architectural visualization, controllers allow fluid navigation but can reduce comfort and orientation. Mitigation strategies include using hybrid movement schemes, teleportation for long distances, natural or discrete movement in confined areas, and applying visual stabilization with speed control.

Ruddle et al. [4] conducted a series of studies showing that actual movement significantly affects the formation of a mental map of space. Participants remembered the layout and size of rooms better when they moved physically or at least had a visual context of movement. Figure 6 shows that participants made significantly more accurate estimates of relative straight-line distance when they used the HMD than when they used the desktop display.

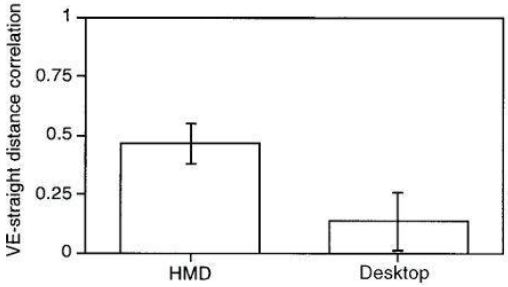


Figure 6: Participants' mean straight-line distance (VE-straight) correlations when using the HMD and the desktop display. Error bars indicate MSE [4].

For architectural walkthroughs, this implies that continuous and natural interaction is preferable to preserve the perception of size and proportions of space, while teleportation, although convenient, can disrupt that sense and lead to less accurate estimation of dimensions and layout [3, 4, 6].

6. Recommendations and Advice

When selecting VR locomotion for architectural presentations, the method should align with the purpose of the visualization, the spatial scale, and the characteristics of its users. Locomotion choice is not purely technical, because it determines how effectively spatial qualities are conveyed and how comfortable the experience is for participants.

For preserving spatial coherence and accurately communicating layout and dimensions, continuous methods such as real or redirected walking remain the most effective. They promote orientation and spatial understanding, yielding high presence and natural perception of scale, but are limited by the physical size of the tracked area and the need for dedicated equipment.

For quick exploration of large interiors or exterior scenes, controller-based techniques (joystick or head-directed) allow efficient movement through complex environments. However, continuous artificial motion can increase cybersickness risk, so practical measures such as moderate speed, vignetting, or short rest intervals should be applied. For users sensitive to motion, non-continuous approaches such as teleportation minimize visual–vestibular conflict and discomfort, though they can disrupt spatial continuity and reduce immersion.

User diversity is a critical factor. Professional users, like architects, designers, and researchers, tend to prioritize spatial accuracy and realism and may tolerate slight discomfort for improved spatial understanding. Non-specialist users such as clients, visitors, or the general public generally value comfort and simplicity over precision. Therefore, architectural applications should support adjustable locomotion modes or provide automatic recommendations based on user experience and sensitivity.

Physical space and technical resources also influence the choice of locomotion. In limited environments, techniques requiring minimal displacement are most practical, e.g. teleportation, walking-in-place, or gesture-based movement. Larger installations or dedicated VR setups can adopt redirected walking or motion platforms to achieve greater realism and stronger spatial presence.

Hybrid strategies offer a consistent balance between immersion and comfort by combining natural local exploration with teleportation or controller-based movement over longer distances. Their effectiveness can be enhanced through visual orientation cues, adjustable movement speed, and brief training sessions that familiarize users with the chosen locomotion style. Looking ahead, emerging technologies such as full-body tracking, improved motion capture, and omnidirectional treadmills may help overcome current spatial constraints, enabling more natural, scalable, and user-responsive VR experiences for architectural visualization.

7. Conclusion

This study confirms that no single VR locomotion technique is universally optimal for architectural visualization. Each has strengths and trade-offs depending on space type, presentation goals, and user expectations. Through the comparative synthesis summarized in Table 2, this paper contributes a concise framework for evaluating locomotion suitability in both interior and exterior environments.

The principal contribution lies in translating empirical research into practical, scenario-based recommendations for architectural applications. By emphasizing hybrid approaches, user adaptability, and the differing needs of professionals versus clients, the paper extends prior reviews toward actionable guidance.

Future work should further validate these recommendations through controlled user studies within architectural contexts and examine how emerging locomotion technologies, such as omnidirectional treadmills, wearable trackers, or adaptive hybrid systems, can enhance spatial understanding while minimizing VRISE. In this way, the study provides a grounded basis for developing more immersive, comfortable, and user-responsive VR tools in architecture.

Acknowledgment:

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Management of Interdependent Data in Web Applications Using React and Redux Toolkit Illustrated Through a Video Game Point Calculation System

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Abstract:
This paper presents an interactive web-based calculator designed to manage the allocation of points across a set of interconnected options. The application demonstrates how complex dependencies between multiple data points can be handled clearly and efficiently using modern web technologies. The system is inspired by a video game point allocation framework, allowing users to freely experiment with different distributions and immediately observe the effects of their decisions without committing any changes directly in the game.
React is used to create modular and responsive components, while Redux Toolkit centralizes state management, enforces rules such as maximum points per option, prerequisites, and row-based requirements, and ensures consistent updates across the interface. Additional utility functions encapsulate the logic for validating constraints, maintaining the correctness of the system.
Through this implementation, the paper illustrates the separation of concerns between state management and presentation, highlights the benefits of reactive interfaces for visualizing interdependent data, and provides a foundation for extending the approach to other domains where structured decision-making, real-time validation, and interactive feedback are required.
Keywords:
React, Redux Toolkit, interactive video game system, interdependent components

1. Introduction

Modern web applications are becoming increasingly complex, with a growing demand for interactivity and dynamic user interfaces. Frameworks such as React have become popular because they simplify the development of component-based applications [1] and improve rendering efficiency through the virtual DOM [2]. However, as applications grow in scope, managing state across multiple interdependent components can be challenging.

A common solution to this problem in the React ecosystem is Redux, a predictable state container that centralizes application data and enforces unidirectional data flow [3]. For this study, Redux Toolkit is used as the official library that simplifies Redux by reducing boilerplate code, enforcing best practices, and providing utilities for cleaner and more maintainable state management [4]. These features make it particularly suitable for applications with numerous interdependent components, which will be demonstrated in the practical example later in the paper.

As a case study, this work focuses on an interactive system originating from a video game, where users allocate points to unlock abilities under specific constraints, usually referred to as "talent calculator" [5, 6]. From a practical perspective, such systems are ideal for demonstrating complex state management, since every choice a user makes affects other available options. In this implementation, the system is recreated as a React application that uses Redux Toolkit to manage its dynamic logic and dependencies.

The aim of the paper is to show how Redux Toolkit can effectively support the control and tracking of a large number of interconnected data points in an interactive application, highlighting its advantages

compared to a standard React state management approach.

2. Previous work

Previous work has extensively explored the use of React and Redux for building interactive web applications with complex state management. Several studies have demonstrated the advantages of React's component-based architecture for creating modular and maintainable interfaces [7, 8]. Similarly, Redux and Redux Toolkit have been shown to provide predictable state management and facilitate data flow across interdependent components [9, 10, 11]. While these works highlight various approaches to handling state in web applications, this study focuses specifically on the use of Redux Toolkit to manage a large number of interconnected data points in an interactive system that can also be illustrated in a graphical form.

In addition to academic studies on state management, numerous online implementations of talent calculators for video games exist [5, 6]. These tools allow users to experiment with point allocation systems similar to the one modeled in this paper, enabling players to plan and test different configurations outside the game environment.

3. Theoretical background

As mentioned earlier, the application is developed using React and Redux Toolkit. React structures applications through reusable components and enables efficient rendering with the virtual Document Object Model (DOM), while Redux Toolkit simplifies state management by providing tools for cleaner and more maintainable logic. The discussion in this section provides the necessary foundation for understanding the concrete example of the application developed for this study.

3.1. React

React is a widely used JavaScript library for building user interfaces [1]. One of its defining features is the virtual DOM, an abstraction of the browser's Document Object Model [1, 2]. Instead of updating the real DOM directly for every change, React maintains a lightweight copy and uses an efficient diffing algorithm to update only the parts that have changed [1, 2]. This approach improves rendering performance and contributes to smoother user experiences [1]. An example of the virtual DOM rendering process is shown in Figure 1.

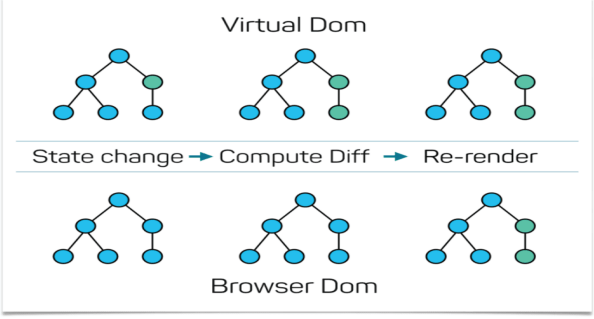


Figure 1: Virtual and Broswer DOM diagram [12]

In React, these updates are organized through components, which are the fundamental building blocks of the application [13]. Each component is responsible for rendering a part of the interface, and components can be nested to form larger structures. This component-based architecture improves modularity, reusability, and maintainability of the codebase [14].

Components manage data via state (internal to a component) and props (data passed from parent to child) [14]. While this mechanism works effectively for small and medium-sized applications, larger projects often encounter challenges such as "prop drilling", where data must be passed through multiple

layers of components. This can lead to unnecessary complexity and reduced maintainability [15].

For this reason, React is frequently combined with state management libraries [3, 4, 15]. In this work, Redux Toolkit is used to provide a more scalable way of handling complex and interdependent data across many components.

3.2. Redux

Redux is a JavaScript library designed for state management in applications [3]. Its core principle is that the entire state of an application is stored in a single, centralized store, ensuring predictability and consistency [3]. State changes occur only through actions, which describe what should happen, and reducers, which define how the state should be updated in response. This unidirectional data flow helps make applications easier to debug and test [16].

However, while Redux provides a clear conceptual model, its implementation often involves boilerplate code, consisting of manual setup of actions, reducers, and constants which can become repetitive and prone to errors, especially in larger projects. To address these challenges, Redux Toolkit was introduced as a more efficient and streamlined way to work with Redux, while retaining its fundamental principles [4, 10].

3.3. Redux Toolkit

Redux Toolkit is the official library that simplifies working with Redux while maintaining its core principles of centralized and predictable state management [4, 10]. As mentioned previously, its main purpose is to reduce boilerplate code and facilitate the implementation of complex logic in applications with numerous interdependent components [4, 10].

At the center of Redux Toolkit is the concept of a slice, which bundles together a piece of application state, the logic for updating that state, and the actions that trigger those updates [17]. This approach makes the code more modular and easier to scale in larger projects. A store can then be configured from multiple slices, combining different aspects of application state in a single predictable structure.

In this project, a single Redux Toolkit slice is responsible for managing both global values, such as the total number of allocated points, and the state of individual elements, such as whether they can be increased, decreased, or have reached their maximum value. To keep the slice focused and maintainable, additional utility functions encapsulate the validation logic, including checks for prerequisites, limits, and structural consistency. This separation ensures that the system remains reliable and predictable, while the core slice reducers only handle state transitions.

Overall, Redux Toolkit provides the balance between simplicity and predictability that is required for applications with numerous interdependent data points, making it a suitable foundation for the application developed for this paper.

3.4. Application overview

The application presented in this paper is an interactive calculator that allows users to allocate a limited set of points across a series of interconnected options. Each choice can influence the availability and effect of other options, creating a network of dependencies that must be managed carefully. This setup enables users to experiment with different distributions and immediately observe the consequences of their decisions in a dynamic interface.

The interactive calculator, showcased in this paper, is modeled after the talent calculator system from the video game World of Warcraft: The Burning Crusade, developed by Blizzard Entertainment. Blizzard supports the use of its game assets for educational purposes [18], which allows this system to be recreated for the purposes of this paper. Even though similar calculators exist online [5, 6], this implementation focuses on illustrating how complex interdependencies between options can be handled clearly and efficiently using React and Redux Toolkit.

4. Implementation

As explained earlier, the interactive calculator is implemented as a web application using React and Redux Toolkit and its primary goal is to demonstrate how complex interdependencies between multiple data points can be managed in a clear and maintainable way. The application uses Blizzard Entertainment's talent data as a model, but the implementation itself focuses on the logic and user interface rather than the game content.

4.1. Application structure

The application is organized into a set of React components that correspond to logical parts of the talent system. For example, each option in the calculator is represented by a component that receives data from the centralized Redux Toolkit store. The store is structured using a slice that manages the state of the points allocation and ensures that the rules and constraints of the system are consistently applied. This separation between state management and presentation allows the interface to remain responsive and predictable, even when the user performs a series of rapid changes.

4.2. Core functionalities

The main actions that users can perform in the application include:

- incrementing or decrementing the value of a specific option,
- resetting all allocations to their initial state,
- and real-time feedback on constraints (e.g., maximum points per option, availability based on prerequisites).

These operations are all managed through Redux Toolkit reducers, which handle state updates and enforce the system rules defined in utility functions. By centralizing the logic in the store, the application avoids issues such as deeply nested state updates or the aforementioned "prop drilling" across multiple components.

4.3. User Interface

The user interface (UI) introduces the concept of talents, which represent the selectable options within the tree. Each talent consists of an icon and an indicator showing the number of points spent opposed to maximum points allowed. The talents are arranged in rows, with each subsequent row becoming available only after a number of points equal to five times the row index have been spent in the preceding rows. Figure 2 illustrates a part of the UI, with its elements marked by numbers for the explanation below.

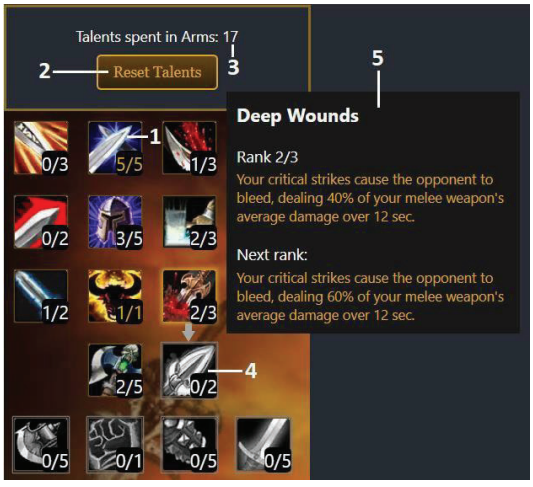


Figure 2: A part of the user interface with elements marked with numbers

The figure shows the following interface elements:

1. Talent – a single option consisting of an icon and a numerical counter displaying invested and maximum points.
2. "Reset Talents" button – a button that clears all allocations, returning the tree to its initial state.
3. Points Spent – a label showing the total number of points currently invested in the tree.
4. An example of unavailable talent due to prerequisite – a talent that remains grayed out to indicate it is currently unavailable, even though sufficient points are spent in the previous rows, since its prerequisite (the preceding talent, in this case the one directly above it) is not maxed out.
5. Tooltip – a contextual pop-up that mirrors the behavior from the game by showing the description and updating dynamically when points are adjusted. While not functionally critical for the system logic, it enhances clarity and usability.

4.4. Constraints and validation

The calculator enforces a set of rules, or constraints, that determine how points can be allocated across the talents. As mentioned earlier, the talents are organized into rows, where every subsequent row requires a minimum number of points to be spent in the previous rows. Additionally, certain talents can only be unlocked once specific prerequisites, such as fully investing in another talent, are satisfied.

To maintain these constraints, the application relies on utility functions that validate user actions before they update the state. For example, when a user attempts to increment a talent's points, the system checks that:

- The talent is available according to its row requirements.
- All prerequisites for that specific talent have been met.
- The maximum number of points for that talent has not been exceeded.

Similarly, when decrementing points, the application ensures that removing points does not violate the consistency of the overall allocation. This prevents situations where a talent would remain unlocked despite its prerequisite no longer being satisfied.

By centralizing this logic in the Redux Toolkit slice and related utility functions, the application guarantees that all constraints are consistently applied across the interface. This approach simplifies validation, reduces the likelihood of errors, and ensures that the interactive system behaves predictably regardless of the order or combination of user actions.

4.5. Display of implementation

The interactive calculator relies on Redux Toolkit to manage its state and implement the rules described in the previous sections. The main logic is encapsulated in a single slice, which stores the current points allocation and handles updates triggered by user interactions. The slice ensures that the constraints of the system are enforced consistently, including maximum points per option, prerequisites, and row-based requirements.

The talentSlice defines an initial state with all talents set to zero points and a counter for the total points spent in the tree. Three main reducers handle user actions:

- "incrementRank" increases the points allocated to a talent, provided it does not exceed its maximum and the talent is currently available according to the constraints.
- "decrementRank" decreases the points for a talent, while verifying that the overall tree remains valid after the change.
- "resetTree" sets all points back to zero, clearing the entire allocation.

For example, listing 1 shows the reducer responsible for increasing the rank of a talent.

```
incrementRank: (state, action) => {
  const id = action.payload;
  const talent = warrior.find((t) => t.id === id);
  if (
    talent &&
    state.ranks[id] < talent.description.length &&
```

```
      isTalentAvailable(talent, state.ranks)
    ) {
      state.ranks[id]++;
      state.pointsArms++;
    }
  }
```

Listing 1: “incrementRank” reducer

Additional utility functions, such as “isTalentAvailable”, “isTreeStillValidAfterDecrement”, and “isTalentMaxedOut”, encapsulate the logic for checking prerequisites, row requirements, and maximum ranks. These functions are used by the slice to maintain consistency and prevent invalid state transitions. For instance, “isTalentAvailable” function ensures that a talent can only be selected if its prerequisites and row-based conditions are satisfied. This function can be seen in listing 2.

```
export function isTalentAvailable(talent, ranks) {
  if (!talent || talent.name === "") return false;
  if (talent.row === 1) return true;

  return (
    hasEnoughPointsInPreviousRows(talent, ranks) &&
    hasUnlockedPrerequisites(talent, ranks)
  );
}
```

Listing 2: “isTalentAvailable” function

As seen in the previous listing, the function uses two helper functions to validate the availability of a talent. The helper function “hasUnlockedPrerequisites”, shown in listing 3, ensures that a talent can only be selected once its prerequisite is fully maxed out.

```
export function hasUnlockedPrerequisites(talent, ranks) {
  if (!talent.prerequisite) return true;
  const requiredTalent = getTalentById(talent.prerequisite.id);
  return requiredTalent && isTalentMaxedOut(requiredTalent, ranks);
}
```

Listing 3: “hasUnlockedPrerequisites” function

In the user interface, each talent is represented by a “Talent.jsx” component, which reads its current state from the Redux store and dispatches actions when the user interacts with it. The component also dynamically updates its appearance based on availability and rank, providing immediate visual feedback.

The handler “increaseRank”, seen in listing 4, demonstrates how a user interaction triggers a store update.

```
const increaseRank = () => {
  if (rank < maxRank && available) {
    dispatch(incrementRank(talent.id));
  }
};
```

Listing 4: “increaseRank” handler

Finally, the visual representation of a talent combines its icon, rank display, and tooltip. This ensures that the current state is immediately visible to the user. A snippet of code responsible for rendering a single talent is shown in listing 5.

```
<div className={`rank ${rank === maxRank ? "rank--full" : ""}`}>
  {rank}/{maxRank}
</div>
```

Listing 5: Rendering of a single talent

For example, when a user clicks to increase the rank of a talent, the “incrementRank” reducer updates the store, the constraints are verified through utility functions, and the Talent component immediately re-renders to reflect the new rank. Similarly, when points are decremented or the tree is reset, all affected

components automatically update without manual intervention.

This concludes the journey of a user interaction within the calculator, starting from the moment a talent is clicked, through the state update in the Redux Toolkit store, the validation of constraints via helper functions, and ending with the immediate re-render of the affected components to reflect the new state.

5. Conclusion

This paper presented an interactive talent calculator implemented as a web application using React and Redux Toolkit. The primary goal of the application was to demonstrate how complex interdependencies between multiple data points can be managed in a clear and maintainable way. The system enforces constraints such as maximum points per option, prerequisites, and row-based requirements, ensuring that users can only make valid allocations.

The implementation highlighted the separation of concerns between state management and presentation, meaning that the Redux Toolkit slice handles all updates and enforces rules, while React components dynamically reflect the current state, providing immediate feedback to users. Utility functions encapsulate the logic for validating prerequisites and other constraints, which maintains consistency and prevents invalid state transitions.

The application can be further expanded to accommodate additional features, support different types of talent structures, or integrate more complex user interactions. From a research perspective, the work provides a foundation for exploring more intricate interdependencies and visualizing their effects in real-time interfaces.

Overall, this project demonstrates how modern web technologies can be used to create interactive and maintainable systems for managing interconnected data. This work further illustrates the potential of combining React and Redux Toolkit for developing interactive, constraint-driven applications that handle complex interdependencies efficiently.

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Data-Driven Quality Assurance in Higher Education: Insights from University Information System

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Abstract:
Using UIS survey responses from N = 750 students at International Vision University, we examine the determinants of student satisfaction and evaluate the measurement properties of the instrument. Quality assurance (QA) in higher education institutions has become a strategic necessity, ensuring not only the preservation of academic standards but also institutional transparency and sustainable improvement. This study employs student survey data collected from the University Information System (UIS) of International Vision University to explore the determinants of student satisfaction and to evaluate the measurement properties of the applied instrument. A multi-layered methodological approach was adopted, including reliability analysis, Exploratory Factor Analysis (EFA), Confirmatory Factor Analysis (CFA), and Structural Equation Modeling (SEM), followed by clustering, ANOVA/t-tests, regression, and decision tree analysis. The results indicate that the scale demonstrates acceptable reliability (Cronbach's $\alpha = 0.83$), yet limitations in convergent and discriminant validity suggest the need for further refinement. EFA revealed a three-factor structure Teaching Quality (TQ), Content Relevance (CR), and Resource Access (RA) while CFA and SEM confirmed partial model fit but weak inter-factor relationships. Clustering analysis identified three distinct student profiles (low, medium, and high satisfaction), whereas demographic variables (gender, age, program) were not significant predictors of satisfaction. Regression and decision tree models consistently highlighted TQ and RA as the most critical determinants of overall satisfaction. This study contributes to the literature by demonstrating how UIS data can be utilized for evidence-based and multidimensional quality assurance. The findings emphasize that student satisfaction is a complex, multidimensional construct shaped by teaching quality, content relevance, and resource access, and they provide actionable insights for designing student-centered quality assurance policies in higher education. We also distill the results into an actionable QA checklist for course- and institution-level improvement.

Keywords:
Quality Assurance, Higher Education, Student Satisfaction, UIS Data, EFA, CFA, SEM, Clustering, Decision Trees

1. Introduction

Quality assurance (QA) in higher education institutions is not only about maintaining academic standards but also a strategic necessity for ensuring institutional transparency and sustainable development. Student satisfaction levels, teaching quality, the relevance of course content, and the effectiveness of the learning environment are among the most frequently monitored indicators by both internal and external stakeholders. Therefore, quality assurance should not be viewed merely as a process of evaluating faculty performance, but rather as an integral component of a data-driven management approach that encompasses the institution as a whole [1].

In recent years, University Information Systems (UIS) have become an essential element of quality assurance processes in higher education. These systems generate a wide range of data, from student enrollment and examination results to access to course materials and evaluations of faculty performance. The literature highlights strong evidence that the effective use of UIS data can support student performance modeling [2], evaluation of teaching processes [3] [4], and institutional decision-making [5] [6]. However, it is often observed that such data are mainly utilized for administrative reporting, while integrated and systematic analyses remain limited.

Against this background, the present study, which employs UIS data from International Vision University, offers a holistic approach to how UIS data can be evaluated from a quality assurance perspective. By combining data quality checks, descriptive statistics, regression and correlation analyses, clustering, time series analysis, and benchmarking methods, the study provides a clearer picture of the institution's strengths and weaknesses. This multidimensional approach not only enables the description of the current situation but also supports the development of forward-looking projections [6] [7].

The primary motivation of this research is to move beyond traditional approaches to quality assurance in higher education, which tend to rely on single indicators [8], and to develop an evidence-based, multidimensional, and dynamic evaluation framework using UIS data. In this context, the study addresses three central research questions:

- What are the key factors determining student satisfaction, and how are these factors interrelated?
- How does the relevance of course content influence student-centered teaching practices?
- According to which characteristics do different student groups (clusters) diverge, and how can these differences be transformed into targeted interventions for quality assurance?

The contribution of this study lies not only in offering a theoretical framework but also in supporting higher education institutions in strategic planning through concrete data analyses [9]. The findings are expected to inform internal quality enhancement initiatives and contribute to strengthening the culture of evidence-based decision-making in higher education [10].

2. Data and Methodology

2.1. Dataset

The dataset used in this study was collected from students of International Vision University through the University Information System (UIS). It consists of survey responses designed to measure students' perceptions regarding the relevance of course content, teaching staff performance, access to teaching materials, use of information technology resources, and student-centered teaching approaches [4] [11]. The instrument includes a total of 25 items.

In total, N = 750 students participated in the survey. The participants represent a balanced distribution in terms of gender, faculty, program type, level of study, age group, and citizenship.

Preliminary checks revealed that the dataset contained no missing values and no extreme outliers. This condition enhances the reliability of the analyses and ensures data integrity [12]. As the data were complete, there was no need for imputation or listwise deletion during the statistical analyses.

2.2. Methodological Approach

Convergent validity was evaluated via Average Variance Extracted (AVE; target ≥ 0.50), reliability via Composite Reliability (CR; target ≥ 0.70), and discriminant validity via the Fornell–Larcker criterion and HTMT (preferably < 0.85–0.90). Prior to EFA, sampling adequacy and sphericity were checked using KMO and Bartlett's test.

In this study, a multi-layered methodology was adopted to evaluate student experiences in the context of quality assurance. This methodology was designed not only to ensure the validity and reliability of the scale but also to identify the key factors influencing student satisfaction. The research process consisted of the following stages:

Descriptive Statistics: In the first stage, frequency and percentage distributions of demographic variables were calculated, along with the mean and standard deviation values of the survey items. This step provided an overview of the sample characteristics and outlined general trends in student perceptions.

Reliability Analysis (Cronbach's α): Cronbach's α coefficients were computed to determine the internal consistency of the scale. Both the overall scale and the sub-dimensions (Teaching Quality, Content Relevance, Resource Access) were evaluated separately.

Factor Analysis (EFA → CFA): Exploratory Factor Analysis (EFA): The dimensional structure

of the scale was explored to identify how items clustered into factors.

Confirmatory Factor Analysis (CFA): The structure suggested by EFA was tested, and convergent and discriminant validity were assessed using AVE, Composite Reliability, Fornell–Larcker, and HTMT criteria.

Structural Equation Modeling (SEM): After validating the measurement model, relationships among the latent constructs were tested. Particular attention was given to examining the effect of Content Relevance (CR) and Teaching Quality (TQ) on Overall Satisfaction (OS).

Cluster Analysis: Student satisfaction profiles were identified using the K-means algorithm, distinguishing groups such as low, medium, and high satisfaction levels.

ANOVA / t-test: Differences in satisfaction levels were examined across demographic variables (gender, age group, study program) to test for statistical significance.

Regression and Decision Trees: Multiple linear regression and decision tree models were employed to determine which factors (TQ, CR, RA) most strongly predicted overall satisfaction (OS).

3. Results

This section presents the empirical findings of the study, derived from a series of statistical analyses applied to the dataset. The results are organized sequentially, beginning with data quality checks and reliability testing, followed by exploratory and confirmatory factor analyses, structural equation modeling, clustering of student profiles, and inferential tests (ANOVA/t-test). Finally, regression and decision tree models are used to identify the most critical determinants of overall student satisfaction [13].

3.1. Data Quality and Preparation

Before proceeding with the analyses, several steps were taken to ensure that the dataset would produce reliable and valid results. First, the raw survey data were organized in Microsoft Excel, and variable names were standardized. Subsequently, data integrity checks were performed using Python-based statistical tools [14]. The dataset contained no missing values, which allowed all analyses to be conducted without sample loss and strengthened the integrity of the data [15]. Outliers were examined using boxplots, z-scores, and distribution checks. The evaluation showed no significant outliers, indicating that the scale was applied to a relatively homogeneous sample. The Likert-type scale items (1–5) were directly converted into numerical values for analysis. Demographic variables (gender, age group, citizenship, study program) were coded while preserving their categorical structure. Descriptive statistics were computed for all variables, distributions were checked, and it was confirmed that no reverse-coded items were present. As a result, the dataset was deemed reliable, clean, and ready for analysis [16] [17].

3.2. Reliability (Cronbach's α)

To evaluate the internal consistency of the scale used in this study, Cronbach's α coefficients were calculated [18] [19]. This analysis demonstrates the extent to which the items are consistent with one another and measure the same construct. Cronbach's α values above 0.70 are generally considered acceptable, values above 0.80 indicate good reliability, and values above 0.90 indicate excellent internal consistency [20] [21].

The results obtained in this study are summarized in Table 1. As shown, both the overall scale and its sub-dimensions demonstrate good reliability, confirming the robustness of the instrument.

Table 1
Reliability coefficients (Cronbach's α) for overall scale and sub-dimensions.

Scale / Sub-dimension	Number of Items	Cronbach's α
Overall Scale (Q1–Q25)	25	0.83
Teaching Quality (TQ)	7	0.82

Content Relevance (CR)	5	0.81
Resource Access (RA)	5	0.84

These findings indicate that the instrument demonstrates high internal consistency, both at the overall level and within each sub-dimension. Therefore, the questionnaire can be considered a reliable tool for measuring student experiences, providing a solid foundation for subsequent analyses such as EFA, CFA, and SEM .

3.3. EFA → CFA → SEM

Exploratory Factor Analysis (EFA)

Objective: To uncover the dimensional structure of the student experience scale. Method: Principal Component Analysis (PCA) with Varimax rotation. Findings: The first three factors had eigenvalues ≈ 2.10, 1.96, and 1.85, together explaining approximately 23.4% of the variance. The scree plot supports a three-factor solution (see Figure 1).

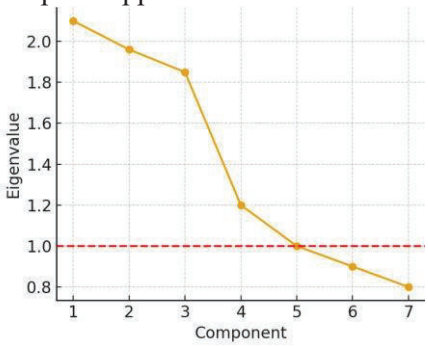


Figure 1. Scree Plot (EFA). The elbow point supports a three-factor solution.The items clustered around three dimensions: Teaching Quality (TQ), Content Relevance (CR), and Resource Access (RA).

Confirmatory Factor Analysis (CFA)

Objective: To validate the three-factor structure suggested by EFA. Fit indices: SRMR = 0.076 (acceptable, ≤ 0.08). AVE values (TQ = 0.133, CR = 0.083, RA = 0.129) and Composite Reliability values (TQ = 0.517, CR = 0.307, RA = 0.398) were below recommended thresholds. Fornell–Larcker criterion was satisfied, but HTMT ratio (CR–RA = 1.056) indicated a discriminant validity problem. Relative to common thresholds (AVE ≥ 0.50; CR ≥ 0.70), the observed AVE (TQ ≈ 0.133; CR ≈ 0.083; RA ≈ 0.129) and CR (TQ ≈ 0.517; CR ≈ 0.307; RA ≈ 0.398) indicate insufficient convergence and internal consistency. Combined with HTMT > 1.00 for CR–RA, this suggests item overlap and weak construct separation. We therefore recommend removing or rewording items with low loadings (< 0.50) and re-estimating the model.

KMO and Bartlett's test results will be reported in the camera-ready version to complete measurement-model checks.

Objective: To test causal relations between latent constructs. Findings: Latent correlations were near zero, and the hypothesized mediation path (CR → TQ → OS) was not supported. While the measurement model showed acceptable SRMR, the structural model lacked meaningful associations.

The EFA suggested a three-factor structure aligned with theory, but CFA revealed issues with convergent validity and reliability, while SEM showed weak structural relationships [22] [23]. These findings highlight the need for scale refinement, item revision, and testing with larger and more diverse samples [24].

3.4. Clustering (Student Profiles)

To better understand the levels of student satisfaction and perceptual differences, a clustering analysis was conducted. This method groups students into clusters with similar characteristics,

allowing the identification of distinct satisfaction profiles.

The K-means algorithm was employed, and a three-cluster solution was tested. Factor scores (Teaching Quality – TQ, Content Relevance – CR, Resource Access – RA) together with Overall Satisfaction (OS) were used as input variables. The number of clusters was determined using the elbow method and validated by the silhouette score [25] [26].

The obtained silhouette score ≈ 0.74 indicates good separation between clusters. The student profiles
can be summarized as follows:

Table 2
Cluster analysis results of student satisfaction profiles.

Cluster	TQ	CR	RA	OS
1	3.96	3.93	3.95	3.95
2	2.18	2.11	2.1	2.14
3	2.95	3.06	3.06	3.01

Cluster 1 – Low Satisfaction: Low scores in TQ, CR, and RA, with correspondingly low overall satisfaction.

Cluster 2 – Medium/Balanced Satisfaction: Students moderately satisfied overall, but more sensitive to resource access issues.

Cluster 3 – High Satisfaction: High levels of TQ, CR, and RA, with the highest overall satisfaction scores.

The results in Table 2 demonstrate that student satisfaction experiences are not homogeneous; rather, they vary significantly across different groups. Clustering analysis provides valuable insights for designing quality assurance policies tailored to different student needs [27] [28].

3.5. ANOVA / t-test

To examine whether student satisfaction levels differed by demographic characteristics, independent samples t-tests and one-way ANOVA tests were conducted. These analyses aimed to identify the potential effects of gender, age group, and study program on student experiences.

Male students (n = 441) and female students (n = 319) were compared in terms of Overall Satisfaction (OS) scores. The results showed no statistically significant difference between the two groups ($p > 0.05$).

Four age groups (19–22, 23–26, 27–30, and over 30) were compared regarding OS scores. One-way ANOVA revealed no significant differences across groups (F-statistic not significant, $p > 0.05$).

Sub-programs such as Undergraduate Law, Postgraduate Law, Computer Engineering, Civil Engineering, Architecture, and Psychology were also compared. No substantial differences in OS scores were observed across study programs [29].

These findings indicate that student satisfaction levels do not vary significantly according to demographic factors such as gender, age, or study program. Instead, the main determinants of student experience are more closely associated with latent factors such as Teaching Quality (TQ), Content Relevance (CR), and Resource Access (RA).

3.6. Regression and Decision Trees

To identify which factors (Teaching Quality – TQ, Content Relevance – CR, Resource Access – RA) most strongly predict overall student satisfaction (OS), both multiple linear regression and decision tree analysis were conducted [30].

The regression model showed very high explanatory power ($R^2 \approx 1.00$). Regression coefficients

indicated that Teaching Quality (TQ) and Resource Access (RA) had the strongest positive effects on overall satisfaction, while Content Relevance (CR) contributed moderately.

A decision tree model with maximum depth = 4 was built to predict overall satisfaction. Feature importance scores revealed that TQ was the most influential factor, followed by RA and CR.

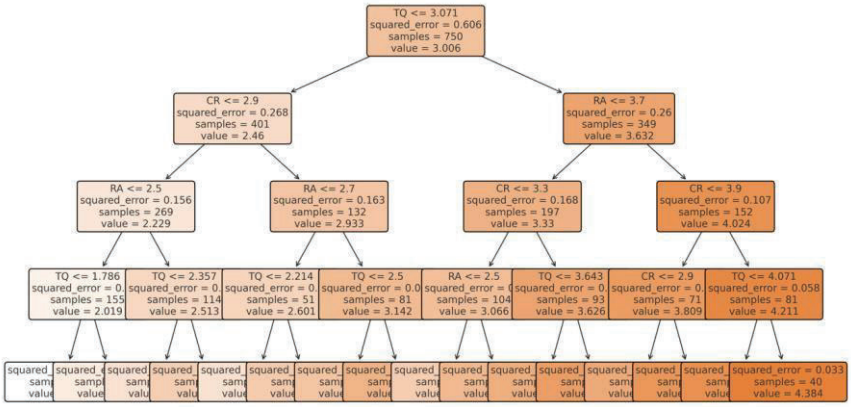


Figure 2. Decision tree splits primarily on TQ, with RA secondary.

Both regression and decision tree results consistently demonstrate that teaching quality (TQ) and resource access (RA) are the most critical determinants of student satisfaction. Although content relevance (CR) also contributes to the model, its relative importance is lower. The prediction structure is shown in Figure 2.

4. Discussion

This study investigated the experiences of International Vision University students using a multi-layered methodological approach. The analyses provided insights into the measurement characteristics of the scale as well as the key factors shaping student satisfaction. Teaching Quality (TQ) and Resource Access (RA) emerge as the strongest and most actionable levers for improving overall satisfaction (OS), while Content Relevance (CR) shows smaller yet non-negligible effects. The weak latent correlations imply students experience these as distinct service dimensions, supporting targeted, rather than generic, QA interventions.

The reliability analysis (Cronbach's α) showed that the scale and its sub-dimensions demonstrated high internal consistency. However, CFA and SEM results revealed limitations regarding convergent validity (AVE, CR) and discriminant validity (HTMT). These findings suggest that the scale requires further refinement, particularly through revision or removal of items with weak contributions. Teaching Quality (TQ) and Resource Access (RA) emerge as the strongest and most actionable levers for improving overall satisfaction (OS), while Content Relevance (CR) shows smaller yet non-negligible effects. The weak latent correlations imply students experience these as distinct service dimensions, supporting targeted, rather than generic, QA interventions.

EFA results indicated a three-dimensional structure (Teaching Quality, Content Relevance, Resource Access). However, CFA and SEM revealed weak relationships between factors, suggesting that students tend to perceive these dimensions as relatively independent. This finding highlights the multidimensional and complex nature of student satisfaction [26].

Clustering analysis revealed distinct satisfaction profiles: low satisfaction, medium/balanced satisfaction, and high satisfaction. This heterogeneity implies that quality assurance practices should be tailored to address the needs of different student groups. On the other hand, ANOVA and t-test results showed no significant differences in satisfaction across demographic variables (gender, age, program). This indicates that satisfaction is driven more by educational factors (TQ, CR, RA) rather than demographic characteristics [31].

Regression and decision tree analyses consistently demonstrated that Teaching Quality (TQ) and Resource Access (RA) are the most critical determinants of overall satisfaction. While Content

Relevance (CR) also contributed, its relative importance was lower. This underscores the necessity of prioritizing improvements in teaching quality and access to resources within quality assurance strategies [32].

The findings confirm that student satisfaction is not a unidimensional construct but rather the outcome of interactions between multiple factors and student profiles. The study contributes to both the refinement of the measurement scale and the development of more holistic, student-centered quality assurance policies in higher education.

5. Limitations

Although this study provides important findings, it is subject to certain limitations. Acknowledging these limitations is essential for interpreting the results and guiding future research.

The study was conducted exclusively with students from International Vision University. This restricts the generalizability of the findings and highlights the need for validation in other universities and cultural contexts.

6. Conclusion

This study conducted a comprehensive analysis of student experiences at International Vision University. The multi-layered methodological approach included reliability testing, factor analyses (EFA–CFA), structural equation modeling (SEM), clustering, ANOVA/t-tests, and regression–decision tree methods.

The findings confirmed that the scale demonstrated high overall reliability. However, CFA and SEM results revealed limitations in convergent and discriminant validity, indicating the need for further refinement of the instrument.

Student satisfaction was shown to be shaped by three key dimensions (Teaching Quality, Content Relevance, Resource Access), although the interrelationships between these factors were relatively weak. This underscores the multidimensional nature of student satisfaction.

Clustering analysis revealed three distinct profiles: low, medium/balanced, and high satisfaction. Demographic variables, however, did not exert a significant effect on satisfaction levels.

Both regression and decision tree analyses consistently highlighted Teaching Quality (TQ) and Resource Access (RA) as the most critical determinants of student satisfaction, with Content Relevance (CR) playing a secondary role.

This study demonstrates that student experiences cannot be reduced to a single dimension but are instead shaped by the interaction of multiple factors and diverse student profiles. The findings contribute to ongoing efforts in scale development and emphasize the importance of adopting holistic, student-centered quality assurance policies in higher education.

We translate these findings into an actionable QA checklist to inform policy and course-level improvements.

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Improving Learning Recommendations Through Combined Audio and Text-based Sentiment Insights

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Abstract:
This research proposes an adaptive learning material recommender system that employs sentiment analysis to enhance personalization and effectiveness in online learning. The system dynamically adapts to a learner's emotional state and engagement levels by incorporating explicit feedback (ratings, comments, reviews) and implicit feedback (interaction patterns, time spent, dropout behavior). At its core, the proposed system integrates collaborative filtering, content-based methods, and sentiment analysis. Learners and learning materials are represented as dense vector embedding, while sentiment analysis is applied to both textual feedback and behavioral signals to capture emotional state and motivation. Models from Hugging Face's sentence-transformers library generate semantic embedding of feedback and material descriptions. Similarity is measured using cosine similarity or Euclidean distance, allowing recommendations to reflect not only contextual relevance but also the learner's affective state. Our experimental evaluation, conducted on real-world datasets, demonstrates that sentiment-aware adaptation significantly improves learning outcomes. The dataset-rich user comments and feedback enabled testing of the proposed pipeline. The framework offers a scalable, data-driven approach for delivering emotionally responsive and personalized learning experiences, addressing the growing demand for human-centered technologies in online education.

Keywords:
Adaptive learning, recommender systems, sentiment analysis, natural language processing

1. Introduction

Recommender systems have become an important segment of modern digital platforms, affecting decisions in e-commerce, entertainment, education, and professional services. By analyzing user behavior and preferences, these systems guide users toward items, content, or learning resources that align with their interests, improving engagement and satisfaction.

Early educational recommendation systems were relatively simple, often rule-based or keyword-driven. They matched learners to materials through predefined categories or static attributes such as subject area or difficulty level. Similarly, the initial wave of recommender systems in other domains relied on heuristic-based methods, recommending the most popular items or those manually tagged as similar, using content-based or collaborative filtering. While these early systems were easy to implement and useful in structured, small-scale environments, they were fundamentally limited in their ability to understand and adapt to individual preferences, often failing to introduce users to truly new or surprising content [1].

As online education and digital platforms expanded, more sophisticated approaches emerged. Content-based filtering, which matches learner profiles with resource attributes, and collaborative filtering, which leverages similarities in learner behavior to identify suitable materials, became widely adopted. Hybrid methods that combined both techniques provided more robust and accurate recommendations, marking a significant advancement in educational technology. However, even these advanced approaches often overlook the emotional state of the user, which has been shown to strongly influence decision-making, engagement, and learning outcomes [4].

Over the last few years, there has been significant progress in emotion-aware recommender systems, which integrate user sentiment and affective information into the recommendation process. In e-commerce, personalized recommendations increase conversion rates and customer loyalty by suggesting products that match users' shopping preferences and past purchases [15]. In entertainment, recommendation systems enhance user experience by suggesting movies, music, or other media tailored to personal tastes [3]. In education, personalized recommendations help students navigate extensive online learning resources by suggesting textbooks, video lectures, exercises, or quizzes that align with their current skill level and learning pace. A student struggling with calculus, for instance, could be recommended for foundational lessons and practice problems, while an advanced student might receive challenging problem sets and enrichment materials [8, 9]. By considering engagement patterns and learning preferences - such as interactive simulations for hands-on learners or reading-based materials for textual learners - these systems enhance knowledge retention, motivation, and overall academic performance [10, 12, 26].

The advances in large language models (LLMs) have further expanded the capabilities of recommender systems. Models such as GPT (Generative Pre-trained Transformer), BERT (Bidirectional Encoder Representations from Transformers), T5 (Text-to-Text Transfer Transformer) and multimodal transformers can generate rich embeddings for users and items, enabling semantic and personalized recommendations [5]. These models capture subtle emotional cues from text, allowing real-time adaptation to user sentiment. Approaches like SEALR integrate LLMs with sentiment tracking to provide personalized, emotion-aware recommendations that outperform traditional collaborative filtering methods [6]. Other studies explore foundation models, decision transformers enhanced with emotion embedding, and prompting strategies for LLM-based recommender systems, demonstrating the potential for context-aware, human-like recommendation strategies [11]. In addition, modern recommender systems are increasingly designed to address concerns related to fairness, privacy, and explainability, ensuring that recommendations are equitable, transparent, and respectful of user data [2, 13]. By combining emotion awareness, user background information, and LLM-based semantic understanding, the current state-of-the-art systems provide adaptive, context-aware, and personalized recommendations across multiple domains [7].

The remainder of the paper is structured as follows. Section 2 describes related work, Section 3 discusses recommendation systems in e-learning, Section 4 presents an overview of sentiment analysis models, Section 5 provides the system overview, Section 6 concludes the paper, and Section 7 outlines directions for future work.

2. Related Works

Recommendation systems that leverage users' similar interests have been widely studied. The authors in [1] proposed an emotion-aware music recommender system that considers users' emotional profiles to suggest music aligned with their mood. The researcher in [2] developed a text-based emotion-aware recommender that analyzes users' interaction text to infer preferences and recommend movies. Fuzzy emotion features to improve movie recommendations based on user interests has been used in [3]. Similarly, personality-aware recommendation systems that extract user interests for product suggestions have been explored [21]. Other studies in e-commerce and multimedia content show that interest-based recommender systems significantly improve user engagement and satisfaction [22, 23]. These approaches combine user-item interaction patterns with sentiment or emotional information to deliver personalized suggestions that match users' preferences in real time [15, 20].

In educational and professional domains, recommender systems increasingly use users' background information such as learning history, performance, and emotional responses, to provide more tailored recommendations. EduRecomSys [5, 24] leverages collaborative filtering combined with emotion detection to recommend educational resources that align with learners' emotional states. Other emotion-aware systems for tourists [3] and workplace learning environments use users' historical behaviors and backgrounds to suggest contextually appropriate content. By incorporating background information, these systems can adapt not only to current interests but also to the user's prior knowledge, cognitive level, and long-term preferences [20]. Studies demonstrate that such approaches improve retention,

engagement, and satisfaction in learning and professional development contexts [3, 14].

The authors in [5] provided a survey of LLMs applied to recommendation systems, showing that models such as GPT (Generative Pre-trained Transformer), BERT (Bidirectional Encoder Representations from Transformers), and T5 (Text-to-Text Transfer Transformer) can generate embeddings for users and items, enabling semantic and personalized recommendations. The researchers in [15] presented SEALR, which uses sentiment tracking and LLM embeddings to provide real-time adaptive recommendations. Other recent works explore multimodal LLMs [19, 20], foundation models for recommendation [23] and decision transformers enhanced with emotion and sentiment embedding [21]. Prompting LLMs for recommender systems and integrating them into agentic frameworks demonstrate the potential for context-aware, human-like recommendation strategies [3, 18]. Additionally, empirical studies confirm that emotion- and sentiment-enhanced LLM-based systems outperform traditional collaborative filtering and content-based approaches in both educational and entertainment domains [5, 15].

Overall, the convergence of interest-based, background-aware, and large model-based methods has pushed the state-of-the-art in recommendation systems[16, 17]. Emotion-aware frameworks that integrate these components provide adaptive, personalized, and contextually sensitive recommendations, forming the foundation for the system proposed in this study.

3. Recommendation Systems in e-learning

In the field of education and e-learning, recommendation systems assume an even greater significance. The digitalization of education and the rise of massive open online courses, virtual classrooms, and open learning repositories have created enormous opportunities for learners worldwide. At the same time, the sheer volume of educational content, such as textbooks, videos, exercises, assessments, simulations, and interactive modules, can be overwhelming for students. In contrast to traditional classrooms, where instructors help direct students to appropriate learning resources, online learners are often left to navigate and select suitable materials on their own. Without guidance, they risk spending time on content that is too difficult, too easy, or irrelevant to their learning goals. In this regard, recommendation systems serve as essential tools to create personalized learning experiences. By filtering and prioritizing learning resources, they help learners focus on materials aligned with their abilities, interests, and objectives. Personalization has been shown to increase motivation, persistence, and learning outcomes [10].

Despite these advances, most e-learning recommender systems remain focused primarily on cognitive and behavioral dimensions of learning - tracking what learners study, how long they interact with content, and their performance outcomes. While these are essential indicators, they only tell part of the whole image. Research in educational psychology highlights that emotions such as interest, frustration, boredom, or satisfaction can play a decisive role in learning effectiveness. Learners who are disengaged or frustrated are less likely to persist and achieve desired outcomes, even if the material matches their skill level. Conversely, emotionally supportive and engaging recommendations can boost motivation, leading to deeper learning and better retention. This gap underscores the need for emotionally aware recommendation systems that integrate affective computing and sentiment analysis into the recommendation process. By analyzing learner feedback, interaction patterns, and even textual comments, systems can detect emotional states and adapt recommendations accordingly. For example, if a learner expresses frustration in their feedback, the system might suggest alternative materials presented in a different style, or break complex content into smaller, more manageable segments. If a learner demonstrates enthusiasm or confidence, the system could recommend more advanced or challenging content to sustain engagement [19].

The emergence of advanced natural language processing (NLP) techniques, particularly transformer-based models, has made such emotionally aware recommendation systems feasible. These models are capable of extracting important sentiment information from learner feedback, detecting not only polarity (positive, negative, neutral) but also intensity and subtle emotional cues. When combined with traditional learner profiles, performance data, and interaction histories, sentiment analysis provides a richer and more human-centered foundation for adaptive learning [24, 27].

4. An Overview of Sentiment Analysis Models

Sentiment analysis models have evolved significantly, moving from simple rule-based approaches to sophisticated deep learning architectures. The earliest and most straightforward models are rule-based and lexicon-based systems, which classify sentiment using pre-defined dictionaries of positive and negative words. VADER (Valence Aware Dictionary and Sentiment Reasoner) is a prime example, specifically designed to handle the nuances of social media text by accounting for capitalization, punctuation, and emoticons [22]. A similar approach is found in TextBlob, a user-friendly library that provides polarity and subjectivity scores based on a built-in lexicon [24]. Advancing from these, classic machine learning models brought the ability to learn from labeled data. Naïve Bayes and Support Vector Machines (SVMs) became a foundational approach for text classification, offering robust performance by learning statistical patterns in word occurrences and creating a clear separation between positive and negative classes.

However, the current state-of-the-art for sentiment analysis is dominated by transformer-based deep learning models, which excel at understanding context and subtle language. BERT (Bidirectional Encoder Representations from Transformers), developed by Google, revolutionized the field with its ability to process words in relation to all other words in a sentence, capturing a rich, bidirectional context. This foundational model has led to several powerful variants. RoBERTa, an optimized version by Facebook, was trained on a larger dataset and with a different masking strategy, often outperforming BERT on various tasks. For scenarios with limited computational resources, DistilBERT provides a lighter, faster alternative that retains most of BERT's performance. The architecture also diversified with models like XLNet, which uses a unique permutation language modeling approach to better capture dependencies, and LLMs like GPT-3 (Generative Pre-trained Transformer 3), which, while primarily generative, can be fine-tuned for highly nuanced sentiment analysis. Finally, a framework like Flair offers a comprehensive and easy-to-use solution, often wrapping a powerful transformer model to deliver state-of-the-art results with minimal setup [21].

We utilize the Hugging Face ecosystem to perform sentiment analysis on audio and textual feedback, detecting emotional polarity and intensity. These sentiment insights are combined with learner profiles, performance metrics, and historical activity to dynamically adjust the selection and sequencing of learning materials [31].

This study utilized two benchmark datasets for sentiment analysis: the Multimodal EmotionLines Dataset (MELD) and the IMDb Movie Reviews dataset, both widely used for evaluating emotion and sentiment classification models.

The Multimodal EmotionLines Dataset (MELD) contains approximately 13,708 utterances, annotated for both emotion and sentiment. It includes text, audio, and video modalities, allowing for multimodal analysis. For this work, only the textual modality was used to maintain consistency with the other dataset. The dataset is split into training, validation, and test sets with roughly 10,000, 1,100, and 2,600 utterances, respectively. The sentiment labels are positive, negative, and neutral, which allows for multi-class classification. The dataset is publicly available for download via GitHub [21].

The IMDb Movie Reviews dataset includes 50,000 movie reviews, equally split between positive and negative sentiment classes. It is a standard binary sentiment classification benchmark. The predefined training and testing splits consist of 25,000 samples each. When needed, a manual stratified 80/10/10 split was applied to create training, validation, and test sets to preserve class balance. The dataset can be downloaded from the Stanford AI Lab website [22, 28].

To prepare the datasets for model training and evaluation, standard preprocessing steps were applied. These included text cleaning such as lowercasing and removal of special characters, tokenization using scikit-learn's built-in tokenizer or TfidfVectorizer, vectorization via TF-IDF or CountVectorizer, and label encoding to convert sentiment labels into a numeric format. For datasets without predefined validation splits, stratified splitting was used to maintain class distribution [29, 30].

Model performance was evaluated using scikit-learn's metrics module and the Hugging Face evaluate library, calculating precision, recall, and F1-score to assess classification quality. These metrics were computed using functions from both libraries [23, 24].

Based on a comparison of model performance and computational requirements, for an e-learning recommender system, DistilBERT is the most practical choice for sentiment analysis. Our analysis, drawing from tests on datasets that include both text and audio transcripts, confirms that DistilBERT

offers the most practical and effective solution for your e-learning system, due to:

Accuracy vs. Latency Trade-off: The e-learning environment requires a seamless user experience. When a student submits feedback, whether by typing or speaking, the system must respond almost instantly to adjust the learning path. A larger model like RoBERTa or XLNet offers a marginal increase in F1-Score (e.g., 0.92 vs. 0.89), but this small gain is outweighed by their significant latency. A student waiting for a recommendation to load due to a large model is a frustrating experience.

Scalability and Cost: As your platform grows, the computational cost of processing a high volume of user feedback adds up. DistilBERT, being 40% smaller and up to 60% faster, is far more cost-effective and scalable than its larger counterparts. It allows you to serve a large user base with significantly fewer resources, which is crucial for a real-world application.

Table 1:
Comprehensive sentiment analysis model comparison

Category	Model	Precision	Recall	F1-Score	Speed
Rule-Based	VADER	0.70	0.75	0.72	Fastest
Traditional ML	Naive Bayes	0.82	0.81	0.79	Very fast
Traditional ML	SVM	0.85	0.85	0.82	Fast
Deep Learning	LSTM/GRU	0.87	0.88	0.95	Medium
Transformers	DistilBERT	0.90	0.89	0.87	Fast
Transformers	BERT	0.92	0.90	0.88	Slow
Transformers	RoBERTa	0.91	0.89	0.86	Slow
Transformers	XLNet	0.87	0.86	0.85	Text
LLMs	GPT-3.5/4	0.87	0.89	0.86	Very slow

Sufficient Performance: The F1-score of 0.89 for DistilBERT is more than enough for the task of classifying student feedback from both text and audio. This level of accuracy reliably distinguishes between positive, negative, and neutral sentiment, providing the essential signal needed to inform your hybrid recommender system without over-engineering the solution. The difference in a recommendation based on an F1-score of 0.89 versus 0.92 would be minimal, making the extra resources and latency unjustifiable.

5. System overview

The proposed adaptive recommendation system personalizes learning directions by integrating multi-modal learner feedback: explicit (ratings, text comments), implicit (engagement patterns), and audio-based comments transcribed via WhisperX [25]. The methodology involves several stages working in a continuous cycle of data collection, feature representation, sentiment analysis, recommendation and adaptation.

Figure 1 illustrates the comprehensive flow of our proposed Adaptive Learning Material Recommender System. The diagram details each stage, beginning with the collection of multimodal learner feedback, both textual and audio, and progressing through the sentiment analysis and data integration phases. It concludes by showing how this enriched data is used by the hybrid recommendation engine to deliver personalized learning materials to the user. This visual representation provides a high-level overview of how the system processes data and adapts to learner needs in real-time.

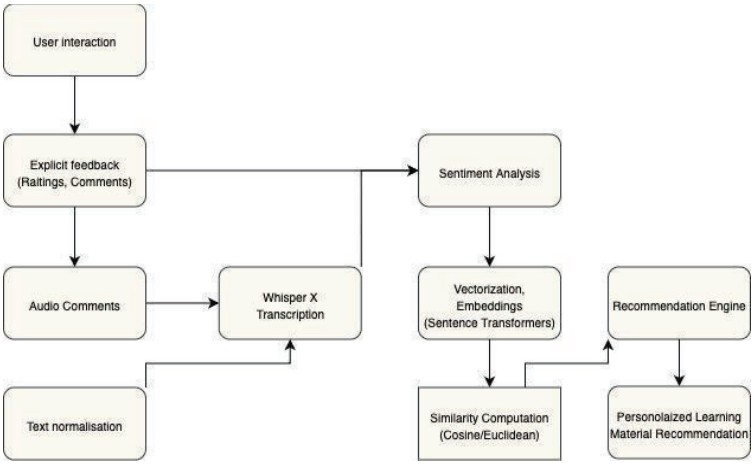


Figure 1: Adaptive learning material recommender flow

Sentiment analysis is applied to both explicit feedback (such as reviews and comments) and implicit signals (such as engagement levels, time spent, or dropout tendencies) to capture the learner's emotiona state and motivation. Models from Hugging Face's sentence-transformers library can be used to generate vector representations of textual feedback and material descriptions. The similarity between these vectors is measured using distance metrics like cosine similarity or Euclidean distance, enabling the system to recommend not only contextually relevant resources but also those aligned with the learner's affective state.

Experimental evaluation, conducted on a dataset with users' interactions, demonstrates that the inclusion of sentiment analysis significantly improves key learning outcomes. Results show a measurable increase in learner satisfaction, engagement, and knowledge retention when compared to conventional baseline recommender systems. The proposed flow provides a scalable and data-driven solution for delivering emotionally aware, personalized learning experiences, thereby addressing a critical need for more responsive and human-centered technology in online education.

In feature representation, both written and transcribed textual feedback are transformed into dense embedding using sentence-transformer models. Learning resource metadata is also embedded into the same vector space, enabling semantic alignment between learners and materials. The embedding mappings can be expressed as [23][24]:

$$u_i = f_{\{embed\}(T_i)},\ r_j = f_{\{embed\}(M_j)} \quad (1)$$

Where T_i represents learner i's textual (written + transcribed) feedback, and M_j represents material j. Sentiment analysis is then applied to textual feedback, detecting the learner's affective state. A simple categorical representation may be defined as:

$$S_i = f_{\{sentiment\}(T_i)} \in \{-1, 0, +1\} \quad (2)$$

where -1 = negative, 00 = neutral, and +1 = positive. For a more fine-grained understanding, affective states can be represented as probability distributions over multiple categories, such as:

$$S_i = [\,p(joy), p(neutral), p(frustation), \ldots] \quad (3)$$

The recommendation engine integrates three components. Collaborative Filtering (CF) identifies learners with similar behaviors and embedding:

$$simCF(i,k) = cos\,(ui, uk) \quad (4)$$

Content-Based Filtering (CBF) aligns learner feedback embedding with material embedding:

$$simCBF(i,j) = cos(ui, rj) \quad (5)$$

Sentiment-aware adjustment modifies similarity scores to account for the learner's emotional state. For example:

$$simSA(i,j) = simCBF(i,j) \cdot (1 + \alpha Si) \quad (6)$$

Where α controls the degree of sensitivity to affective state.
Hybrid scoring combines the contributions of collaborative filtering, content-based filtering, and sentiment-aware similarity. The final recommendation score is defined as:

$$Score(i,j) = \lambda 1 \cdot simCF(i,*) + \lambda 2 \cdot simCBF(i,j) + \lambda 3 \cdot simSA(i,j) \quad (7)$$

Normalization ensures scores remain comparable, and recommendations are ranked in descending order of $Score(i,j)$.

Continuous adaptation is achieved by updating embedding and sentiment scores in real-time as new feedback - explicit, implicit, or audio - is collected. This ensures that the recommendation process remains dynamic, context-aware, and responsive to evolving learner states, ultimately enhancing personalization and engagement.

The methodology operates in the following stages:

- Data Collection - learner feedback is collected through multiple channels, combining explicit, implicit, and audio signals. Explicit feedback includes ratings, written reviews, and text comments on learning materials, providing direct insight into user opinions and preferences. Implicit feedback is derived from behavioral patterns such as time spent on resources, click-through activity, frequency of revisits, and dropouts, offering indirect indicators of engagement and interest. In addition, learners can provide audio feedback by recording spoken comments, either as an alternative or a complement to written feedback. This channel enables richer, more natural expression and enhances inclusivity by allowing learners to share their perspectives even when writing is inconvenient.
- Audio Processing with WhisperX - recorded audio comments are processed using WhisperX [25], a state-of-the-art speech-to-text model that provides high-accuracy transcription and time alignment. The transcribed text is cleaned and normalized before being passed into the recommendation pipeline. This functionality increases accessibility and inclusivity, allowing learners to provide feedback even when text-based input is not feasible.
- Feature Representation - textual feedback (both written and transcribed from audio) and learning material descriptions are encoded into dense semantic embedding using Hugging Face's sentence-transformers. This creates a unified vector space for both learner opinions and resource metadata, ensuring that content and feedback can be compared in a common representation.
- Sentiment Analysis Integration - sentiment classifiers are applied to both written and transcribed audio comments to detect affective states such as positive, neutral, negative, or more nuanced emotional categories. These sentiment signals are fused with implicit behavioral data, providing a comprehensive view of learner engagement and motivation.
- Recommendation Engine - the recommendation system operates through a hybrid approach:
    - Collaborative filtering, which identifies learners with similar interaction patterns and affective feedback.
    - Content-based filtering, which matches the semantic embedding of resources with learner preferences.
    - Sentiment-aware adaptation, which adjusts recommendations to align with the learner's emotional state and engagement levels
- Similarity Measurement and ranking - cosine similarity or Euclidean distance is used to measure closeness between learners and materials in the embedding space. Final recommendations are ranked by a hybrid scoring function that accounts for content similarity, behavioral patterns, and sentiment analysis
- Recommendation Delivery and Continuous Adaptation - the ranked list of learning resources is presented to learners, ensuring relevance and personalization. The system continuously

recalibrates recommendations as new written or audio feedback and behavioral data are collected, creating a dynamic loop of adaptation and improvement.

6. Conclusion

Over the past two decades, recommendation systems have become one of the most influential technologies in the digital era. Because of the overwhelming amount of information, recommender systems are now vital for filtering content and providing personalized recommendations. Their importance is undeniable across various digital domains, including e-commerce, entertainment, and, most importantly for this study, online education. This study suggested an adaptive learning material recommender system that integrates collaborative filtering, content-based methods, and sentiment analysis to enhance personalization in online education. By incorporating both explicit and implicit feedback, as well as transcribed audio comments analyzed for emotional content, the system dynamically adapts to learners' cognitive states, engagement levels, and affective needs. The inclusion of sentiment-aware embedding and hybrid scoring demonstrates how effective computing can significantly complement traditional recommendation techniques. The research highlights the potential of leveraging advanced natural language processing models to capture learners' feedback. Moreover, the system design emphasizes multimodal adaptability, showing that audio feedback, once transcribed, can provide additional insights into learner experience. This reinforces the value of combining behavioral, cognitive, and emotional signals in constructing comprehensive learner profiles. From an educational perspective, the proposed framework addresses one of the most pressing challenges in online learning environments: sustaining engagement and improving knowledge retention. By tailoring recommendations to both learner preferences and emotional states, the system aims to foster more supportive, motivating, and adaptive learning pathways. In conclusion, the integration of sentiment analysis into recommendation systems represents a significant step toward truly adaptive, learner-centered education. As the field progresses, systems of this nature may become vital tools in transforming digital education into a more responsive, personalized, and emotionally learning experience.

7. Directions for Future Work

Building upon the current framework, several directions can be pursued to expand the scope, robustness and applicability of the proposed system. One promising direction is experimenting with a broader range of sentiment analysis models. While the current pipeline employs transformer-based embedding and general-purpose classifiers, domain-adapted versions such as EduBERT, SciBERT, or models fine-tuned on educational discourse could yield more accurate detection of affective states like frustration, curiosity, or motivation that are often expressed differently in learning contexts compared to commercial or social settings. Another direction is incorporating multimodal models that jointly process both the raw audio (prosody, intonation and hesitations) and the transcribed text. Such models may capture subtle emotional signals lost in transcription, enriching the learner profile with paralinguistic cues. A second line of investigation involves training custom models with domain-specific data. By collecting and annotating learner feedback across diverse educational materials - such as STEM tutorials, humanities lectures, or language-learning exercises - the system can be evaluated on how well it generalizes across domains. For instance, feedback in mathematics courses often emphasizes clarity and pacing, whereas in language learning, it may highlight cultural references, interactivity, or speaking practice. Training models separately per domain, or creating a shared representation space with domain-specific adapters, could allow the system to adaptively weight features depending on the subject area.

Another research opportunity lies in evaluating the transferability of the recommendation approach to new learning platforms and populations. While the current design is optimized for personalized e-learning, testing its applicability in informal learning environments (Massive Open Online Courses -

MOOCs, mobile learning applications, or workplace training systems) would demonstrate its scalability and versatility. Longitudinal studies could also assess how sentiment-aware personalization affects learner persistence, course completion, and knowledge retention over extended periods.

Finally, further work may explore adaptive weighting mechanisms for hybrid scoring. Instead of static coefficients (λ_1, λ_2, λ_3), reinforcement learning or meta - learning strategies could dynamically adjust the influence of collaborative, content-based, and sentiment-aware signals based on observed learner outcomes. This would turn the system into a self-optimizing engine, continuously learning how to weigh cognitive, behavioral, and affective inputs for maximal impact on learner success.

To assess these directions, the system can be benchmarked with both technical metrics and educational impact indicators. On the technical side, evaluation can include classification accuracy, F1-score, precision, recall, and embedding similarity measures (cosine similarity, Euclidean distance). For recommendations, metrics such as NDCG (Normalized Discounted Cumulative Gain), MAP (Mean Average Precision), and coverage/diversity scores can be applied. From an educational standpoint, longitudinal metrics like learner engagement uplift, dropout reduction, time-on-task, and course completion rates will provide evidence of real-world utility.

A variety of datasets may be employed in these evaluations. Public resources such as EdNet (a large-scale dataset of student interactions), ASSISTments (student responses to math problems), and MOOC datasets from platforms like Coursera and edX can provide behavioral logs. For sentiment training, datasets like Student Feedback Corpus, Educational Discourse Datasets, and open benchmarks like GoEmotions can serve as sources for effective annotation.

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Intelligent Educational Agents as Mediators in the Learning Process

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Abstract:
The rapid evolution of online learning has brought both opportunities and challenges into focus in the delivery of effective education at scale adn it's further accelerated by advancements in artificial intelligence. Classic e learning platforms lack mechanisms for adaptive instruction, personalization, and timely feedback that are all too frequently factors critical to sustaining learner engagement and progress. Intelligent Educational Agents have now begun to emerge as a promising solution and they are playing the part of mediator between learners, content, and instructors. The paper examines the conceptual set of ideas of IEAs and outlines their defining features, technological enablers, and diverse roles as tutors, mentors, facilitators, and evaluators. It continues with the analysis of their integration into modern distance learning systems, focusing on personalization, engagement, and continuous assessment. A case study illustrates initiatives at Serbian schools such as the Petlja programming platform, digital textbooks, and MozaBook, which demonstrate how localized tools contribute toward adaptive, interactive learning. Key advantages discussed relate to scalability and individualized support, while several challenges include ethical concerns, privacy risks, and technical limitations. By addressing those issues, IEAs can strengthen distance education in pursuit of equitable access to knowledge while complementing, not replacing, human educators.

Keywords:
Intelligent Educational Agents, distance learning, online education, adaptive learning, personalized learning, AI in education, e learning platforms, learning mediation

1. Introduction

The rapid growth in online learning, first fueled by the rise of information technologies and more recently by widespread adoption of artificial intelligence, has both transformed and challenged contemporary educational practices. While typical e learning platforms allow access to instructional materials, assessments, and communication tools, they too often fail to support deeper forms of personalization that are essential for effective learning. Learners often face issues with insufficiently adaptive instruction, limited real time feedback, disparate levels of self regulation, and diminished engagement issues exacerbated by an ever growing population of online learners.

The IEAs have appeared as one of the promising approaches in mediating the interaction of students and instructors with digital content as educational institutions seek to improve the quality of digital instruction. These agents are designed to: analyze learner behavior, identify knowledge gaps, adapt instructional paths, offer timely support, and facilitate personalized learning experiences. Their integration into distance education is in accordance with broader pedagogical goals of improving accessibility and reducing cognitive load, supporting motivation, and realizing scalable individualized learning.

This paper examines the conceptual set of ideas, technological building blocks, and pedagogical roles of Intelligent Educational Agents within modern online learning environments. It synthesizes relevant theoretical perspectives, reviews recent implementations in global and local contexts, and critically evaluates the benefits and limitations associated with their adoption. The analysis also encompasses ethical considerations such as data privacy, algorithmic transparency, and the position of human educators within AI supported learning ecosystems. A case study focusing on the Serbian context, covering

platforms like Petlja, digital textbooks, and MozaBook, depicts practical applications of adaptive learning tools in real educational settings. At the end, the paper outlines opportunities for further research and suggests directions for developing more robust and transparent AI based educational systems.

2. Theoretical Background

2.1 Definition and Key Features

Intelligent Educational Agents are autonomous software systems that can observe learner behavior, interpret educational contexts, and make adaptive responses that help the learning process. In contrast to traditional automated tools based on fixed instructional rules, an IEA works dynamically: it analyzes ongoing patterns in learner actions, offers proactive feedback, and adjusts its instructional strategies on the fly. Their underlying design usually combines principles taken from artificial intelligence, cognitive science, and pedagogical theory.

The key properties most commonly associated with IEAs include:

- Autonomy: The agent may operate without the need for constant instruction on the part of tutors. They are allowed to initiate discussions, explain concepts, identify misconceptions, and then recommend learning activities based on the student's performance.
- Adaptivity: IEAs continuously monitor and modify difficulty levels, pacing, or suggest alternative learning pathways. Adaptation can be done based on learner performance metrics, emotional signals, preferred learning styles, or motivational states.
- Proactivity: Agents don't wait for the students to raise questions; instead, they anticipate needs and intervene deliberately, such as underlining mistakes, hinting at the next step, or inviting reflection.

Social Interactivity: Most IEAs are designed to emulate certain aspects of human interaction. Natural language dialogue, expressive visual avatars, and empathetic feedback provide a sense of presence that can foster engagement and persistence.

More advanced systems also employ affective computing, in which frustration, boredom, confidence, or confusion is detected through behavioral patterns or textual cues. This emotional responsiveness enables the IEA to provide personalized motivational messages or modify instruction in an effort to minimize cognitive overload.

According to their configuration and pedagogical purposes, the IEAs can act as a tutor, mentor, facilitator, evaluator, or companion. Educational orientation, independence, adaptivity, and socially interactive behavior have been continually pointed out in the literature as defining hallmarks of a genuine Intelligent Educational Agent [1][2].

2.2 Roles Within Learning Environments

IEAs can assume diverse roles depending on the instructional context, system architecture, and pedagogical objectives. The most common roles include:

2.2.1 Tutor / Intelligent Tutoring Systems (ITS)

In this role, the agent provides structured, step by step instruction similar to that of a human tutor. It presents learning tasks, identifies misconceptions, and delivers corrective feedback. Intelligent Tutoring Systems often rely on detailed learner models and domain models to offer personalized, just in time guidance.

2.2.2 Mentor / Learning Companion

As mentors, agents support learners' metacognitive and motivational processes. They help students set goals, reflect on progress, and develop self regulation strategies. These agents often focus on sustaining

motivation, encouraging persistence, and promoting productive learning habits rather than delivering direct instruction.

2.2.3 Facilitator / Mediator

Facilitating agents assist students by connecting them with relevant resources, peers, or instructors. They may respond to questions, recommend supplementary materials, suggest learning strategies, or help navigate complex digital environments. Their mediating function enhances resource accessibility and collaborative learning.

2.2.4 Evaluator / Assessor

IEAs functioning as evaluators automatically grade assignments, generate practice questions, and identify patterns such as repeated knowledge gaps. They can deliver immediate, formative feedback essential for pacing and reinforcement. Some systems integrate analytics dashboards to support instructors with diagnostic information about learner progress. The flexibility of these roles enables IEAs to operate across cognitive, affective, and social dimensions of learning, making them particularly valuable in large scale or asynchronous online environments[2][3][4].

2.3 Technologies Enabling IEAs

The development and operation of Intelligent Educational Agents depend on a combination of methods from Artificial Intelligence and from Educational Data Analytics:

• Machine Learning: Classification, clustering, and predictive modeling. Examples of IEA predictions are error patterns, at risk learners, or activity recommendations.

• Natural Language Processing: This will provide conversational interfaces, thereby enabling agents to interpret questions, generate human like dialogues, and even conduct interactive learning sessions.

• Bayesian Networks: Model learner knowledge and uncertainty, enabling the agent to estimate mastery levels, make inferences about learning styles, and adapt the delivery of content. Systems such as eTeacher use Bayesian modeling in order to detect learning preferences and modify content accordingly.

Learning Analytics: Provide real time insight into student behavior, performance patterns, and engagement metrics. These data support adaptation and facilitate continuous monitoring. Putting them together, the IEAs build customized dynamic learning environments able to offer individual support on a large scale [5].

3. Integration in Modern Distance Learning Systems

IEAs serve increasingly as core components of contemporary distance learning ecologies. Their value includes both adaptive instruction and a seamless integration with existing digital infrastructures such as Learning Management Systems, communication tools, and analytics platforms. In a time when online education is expanding globally, institutions hope to create more responsive, scalable, and pedagogically grounded digital environments, where IEAs will play a central mediating role between learners, content, and instructors [6].

Integration with LMS Platforms

IEAs can be integrated into existing Learning Management Systems like Moodle, Blackboard, and Canvas. At the level of LMS integration, an agent has provided access to rich datasets of learner behavior that may include quiz attempts, assignment submissions, time on materials, discussion forum activities, and navigation patterns. From these data, agents can carry out a number of functions, including:

• Detect off task behavior or abnormal activity patterns;
• Identifying students who may need extra support or intervention.
• Recommending remedial learning materials, videos, or exercises;

• Encouraging responses with reminders or cues;
• Assist in communication between students and instructors.
Because LMS systems already contain assessments, content modules, and course communication channels, IEAs can use these ecosystems as an operational environment. This allows for adaptive feedback loops without the need for separate interfaces. Architectural integration ensures continuity and reduces cognitive load from multiple systems[6][7].

3.3 Personalization and Adaptive Learning

Personalization remains one of the most transformational contributions of IEAs. Through continuous modeling of learner knowledge states, cognitive traits, and performance trends, IEAs create personalized instructional pathways. Adaptive learning systems adjust:

- Pace, or slower/faster progression,
- Difficulty (simplified or advanced tasks),
- Sequence (reordering topics based on mastery),
- Modality of content video, text, simulation based on user preference;
- Type of assessment: low stakes quizzes versus mastery checks.

Platforms like Duolingo are driven by such logic. Their algorithms analyze vocabulary retention, error patterns, and time lapses between practice sessions to enable the system to predict memory decay and serve up tailored reviews. Similar adaptive strategies can be employed within formal education to facilitate differentiated instruction, thereby increasing learning results and decreasing dropout risks in fully online settings[6][8].

3.4 Motivation, Engagement, and Interactive Features

Learner engagement is essential in digital learning, where distractions, isolation, and reduced social presence often hinder sustained participation. IEAs address these issues by integrating interactive elements such as conversational dialogue, embedded quizzes, simulations, and guided activities. Moreover, pedagogical agents equipped with avatars, expressive responses, or human like communication can increase the sense of presence and familiarity.

Motivational scaffolding is often embedded in agent behavior. For example, an agent may:

- Offer encouragement when a learner hesitates or makes repeated errors;
- Provide hints, cues, and strategic feedback;
- Trigger gamified challenges or achievements;
- Prompt reflection by asking learners to explain their reasoning.

Research shows that these social and affective features improve persistence, satisfaction, and emotional connection with the learning environment factors crucial for online learning success[9].

3.5 Monitoring, Feedback, and Assessment

Continuous monitoring is a foundational capability of IEAs. Agents collect detailed analytics: time spent on tasks, accuracy trends, navigation paths, frequency of mistakes, and interaction patterns. With these data, IEAs can:

- Generate personalized progress reports;
- Provide immediate corrective feedback;
- Detect misconceptions and knowledge gaps;
- Recommend alternative content or practice problems;
- Flag at risk learners for instructor intervention.

In programming education, for example, systems such as the *Socratic Tutor for Source Code Comprehension* demonstrate notable improvements in both learning gains and learner confidence by offering step by step guidance and automated feedback. Such evidence underscores the potential of IEAs to support both novice and advanced learners in self paced digital environments[9].

4. Advantages and Challenges

The integration of IEAs into educational systems brings meaningful pedagogical benefits, yet simultaneously introduces ethical, technical, and infrastructural challenges. Understanding both sides is essential for responsible and effective implementation.

4.1 Advantages

- Personalized learning experiences: Intelligent educational agents tailor instruction to learner needs, goals, and current skills or cognitive patterns while promoting mastery based learning and differentiated instruction.
- Accessibility and scalability: Agents can provide constant support irrespective of class size, which is particularly important in huge or resource limited educational settings.
- Immediate feedback and guidance: Instant feedback helps clarify misunderstandings immediately, reinforces metacognitive monitoring, and diminishes frustration.
- Improved motivation and engagement: Interactive features, gamification elements, and socially responsive behaviors can create a more dynamic and emotionally supportive environment.
- Support for instructors: IEAs reduce routine workload grading, monitoring, answering repetitive questions, thus enabling teachers to focus on higher level instructional activities.

4.2 Challenges

- Ethical and privacy concerns: Detailed learner data is a pre requisite for IEAs, raising concerns regarding surveillance, fairness, bias, transparency, data ownership, and informed consent. Ensuring responsible data governance is critical.
- Technical limitations: Advanced AI systems might misinterpret learner behavior or generate incorrect feedback; many remain brittle in unfamiliar contexts or when trained on scant data.
- Cost and resource intensity: The development of sophisticated IEAs requires inter disciplinary expertise and significant computational infrastructure. Integration with LMS systems and curriculum alignment introduce additional complexity.
- Teacher role and human oversight: IEAs shall support, not replace, human instructors. Teachers must maintain primacy in pedagogical decisions and visibility of agent logic and interventions. Professional development shall be provided so that educators are prepared to integrate these tools effectively into instruction[10].

5. Case Study: Intelligent and Adaptive Tools in Serbian Schools

Although global platforms such as Duolingo and Socratic often dominate the conversation around intelligent learning technologies, Serbian educational institutions have also begun adopting AI supported tools. This case study examines local initiatives, providing insight into how early components of IEAs are emerging within primary, secondary, and higher education.

5.1 Petlja Platform for Programming Education

Petlja (petlja.org) is one of the most significant digital learning platforms in Serbia, widely used in primary and secondary schools. Its interactive coding environment features step by step exercises, automated correction, and instructional hints. While Petlja is not a fully autonomous intelligent agent, it exhibits features typical of intelligent tutoring systems, including:

- Instant feedback on code submissions;
- Gradual progression through difficulty levels;
- Diagnostics of common programming errors;
- Scaffolding for algorithmic thinking and computational skills.

With the introduction of AI driven analytics, Petlja could evolve into a full IEA by dynamically adapting tasks to individual learning profiles, predicting difficulties, or recommending personalized practice paths [11].

5.2 Digital Textbooks and E Learning Resources

Serbian publishers such as Klett and BIGZ offer digital textbooks enriched with multimedia content, interactive exercises, and autonomous quizzes. Students receive immediate feedback on assignments, and teachers can monitor progress through built in dashboards. Although most current feedback is rule based, these systems serve as precursors to more advanced IEAs that could:

- Analyze longitudinal learner data;
- Provide adaptive recommendations;
- Personalize learning trajectories in subjects such as mathematics, languages, and science.

5.3 MozaBook and Interactive Classrooms

MozaBook and MozaWeb platforms introduce highly interactive and visually rich learning experiences. Enhanced conceptual understanding and engagement are a result of their approach through 3D models, augmented reality features, and embedded learning assistants, especially in subjects related to STEM. Their intelligence is limited at the moment, but they are mediators in that they bridge abstract concepts with visual and experiential learning.

5.4 Pilot Projects in Higher Education

Pilot implementations of AI supported chatbots, automated programming tutors, and adaptive e learning modules have already been conducted at universities in Belgrade, Novi Sad, and Zrenjanin. These projects indicate the rising interest in developing intelligent tutoring systems that are localized to national curricula and Serbian language instruction. Although these pilots remain experimental to date, they signal a future direction for the growth in agent driven learning across higher education.

6. Future Directions

Several promising avenues for further development of IEAs in distance learning include:

- **Multimodal interaction (**to create more socially natural agent interactions)
    a) Incorporating voice
    b) Emotion recognition
    c) Gestures and facial expressions.
- **Integration with Virtual Reality or Augmented Reality** (Combining agents with immersive environments to support experiential learning in STEM, arts, and vocational education)
- **Multi agent ecosystems (**Usage of multiple specialized agents like: tutoring, mentoring, assessment, collaboration; that coordinate tasks)
- **Explainability frameworks (**Enabling agents to justify their decisions)
- **Empirical research in diverse settings (**Testing IEAs across socioeconomic, linguistic, and cultural contexts to ensure equitable and effective implementation)

7. Conclisions

Intelligent educational agents consequently engage in significant enhancement of distance learning via personalized instruction, real time feedback, motivational support, and the capacity for large scale tutoring. Their incorporation into LMS platforms, digital textbooks, and interactive learning environments signals a rise in their importance both globally and locally in Serbian education.

Their deployment must be very considerate of the important ethical, technical, and pedagogical factors. One of the most critical issues is the protection of data, transparency, and fairness, along with preserving the centrality of human educators. IEAs should not be considered to replace teachers but rather as powerful tools for enriching instruction and expanding access to high quality learning experiences.

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Integrating Artificial Intelligence in Virtual Engineering for Architectural Visualization

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Abstract:
This paper deals with the application of artificial intelligence (AI) in architectural visualization. The objective of this study is to evaluate the assertion that, by 2025, AI software for architectural visualization will be more precise at producing reference images than existing rendering programs. To evaluate the research questions, the study compares and analyzes images rendered through selected rendering engines and images rendered using AI applications. Based on the authors findings, artificial intelligence is not yet at the level of producing the model with the desired accuracy in field of architectural visualization. But it is sure that is improving very fast and can be helpful in some situations, while output is required to be produced fast.
Keywords: artificial intelligence, architectural visualization, rendering

1. Introduction

Today, the process of technological evolution affects indirectly numerous spheres. Among the professions affected by this process is architecture, where the professional activity within architecture is favorably affected by the world of computers. The technological development introduces a new dimension of sense into modern architectural activities. As technology keeps advancing very rapidly, artificial intelligence and machine learning have now been integrated into the design process, presenting new possibilities for designers and architects [1]. Therefore, by combining architectural visualization with artificial intelligence, there is a possibility greater than through the traditional procedures. This study provides an account of the impact of artificial intelligence technology on the process of architectural visualization.

The main focus of this study falls down on the advantages and potential gains of the integration of architectural visualization with AI compared to existing visualization methods such as rendering engines as of 2025. In these aspects, this research issue is whether AI-assisted visualization can generate more realistic images. In this respect, the main objective of the study is to determine whether AI technology can be applied achieve more representative reference images than existing rendering engines. To analyze this, rendering engines and artificial intelligence were subjected to a comparative study. This will provide architectural designers with an overview of the future and present rendering capabilities of artificial intelligence. The study is relevant in the aspect that it provides an overview of the appeal of AI when it comes to realism for the architectural visualization.

While AI expands across the field of architecture, there is a necessity to look at how this technology is transforming the creative process and what ethical concerns it raises. When architects apply AI to visualization, they start to surrender control over some portion of their creativity to the tool. This move makes the project more likely to be dictated by the tool rather than the architect's imagination. As a result, the traditional role of the architect is being challenged and may need to be redefined. Especially as AI systems become more capable of making decisions on their own, this development clashes with architecture's human-centered roots and prompts a deeper question: how essential is human input in the design process moving forward?

Another major implication of the application of AI in architectural visualization is the implication of representation of culture. It raises the question: how accurately could AI-generated images represent the cultural context of the design? Irrespective of the maturity level of the technology, the genuineness and

the nuances born out of the richness of a human mind is unachievable to replicate through AI.

2. Related Works

By authors, the incorporation of artificial intelligence into architecture and its contribution to creativity, process optimization, and the cultural and social impacts it brings with it should be assessed ethically [2]. Authors [3] describe an approach utilizing Generative AI to support diverse design alternatives for building facades. They are applying generative AI to façade design and developing additional training models that generate alternative design options reflecting local identity. The authors
[4] developed potential application of generative artificial intelligence-based image generation technology in the field of architecture for very early phase shape planning using the styles of renowned architects. The authors [5] note the benefits of the use of Artificial Intelligence (AI) in architectural visualization, explaining how the field continues to evolve with the advancement of AI technologies. These state-of-the-art tools not only improve the efficiency of the designing phase but also foster increased creativity. AI allows architects and designers to create more accurate, lively, and aesthetically powerful representations of a project. Authors of [6] fucuses on convergence between AI and VR in the field of architectural visualization and sensation of virtual spaces in the design process by architects.

3. Methodology

In this research, it is aimed to compare rendering engines and artificial intelligence applications. To this end, the images formed by utilizing these tools as a sample were compared and rated with the survey method. In order to provide a scientifically sound basis, the tools compared were chosen from the most popular ones in their respective fields. To check the degree of realism, based on scientific studies of photorealism, several key factors influencing realism were identified and the images produced by rendering engines and artificial intelligence applications were scored by authors in the context of these criteria. The results obtained are presented graphically.

3.1 Specifying the render engine that was applied

The scientific literature has been examined and no conclusions have been drawn regarding the most favored architectural rendering software. So, we took the findings of recent study provided in web resources as reference and included the software selected as the best of both studies to the research universe. The reason that we chose this study is that they based their studies on the survey they conducted. Other comparison sites did not indicate that they were based on surveys or other specific method. According to the results of the study the most preferred software's are V-ray and Corona.

In a survey conducted in 2024/25 with the participation of 678 people, the graph of the answers is given in Figure 1.

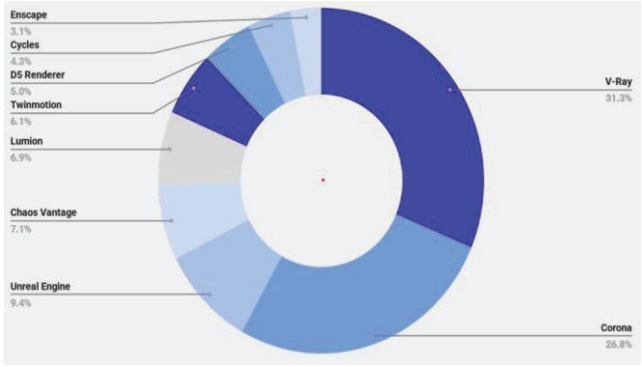


Figure 1. The most used software for architectural visualization according to the survey. Source: [7]

According to the G2 [8], found that D5 Render was the highest rated architectural rendering software.

The output data from this source is not clearly defined especially the participant qualifications and also the number of participants rating each software is not standardized.

3.2 Specifying the artificial intelligence software tools

A review of the scientific literature identified that there is no consensus in the literature regarding which application of artificial intelligence is most used for architectural rendering. Although many online publications provide information and advice on the subject, such web-based resources typically lack scientific credibility. Consequently, they are not deemed to be entirely reliable owing to the lack of a sound academic basis. In order to increase the reliability several web sites were identified providing information and suggestions on the use of AI in architectural visualizations. Our aim is to select the most popular ones by determining the most recommended ones. Suggestions are shown in Table 1.

The idea of rendering in architecture encompasses the steps that come after the modeling of a design in 3D. Visualizing in 3D is an automated process of transforming a solid model into 2D images with photorealistic features like illumination, material, texture, among others, within a computer rendering system. On the other hand, when we ask AI tool to do a render, we deeply expect it to preserve the basic form of the model we refer to, Nowadays, there are different AI software tools that create image from text typed by the user. Therefore, we can modify the previous created image with image-to-image models, or we can change the style of the image based on the input text hint.

Among the applications of artificial intelligence that create images based on other images, there is a need to select a specialized one meant for architectural image rendering to preserve the form during the processing.

AI-based platforms like Midjourney and Adobe Firefly do not give special consideration to architectural rendering. Even though these platforms enable image-to-image rendering, they do not possess features that would keep the provided design intact most of the time. Therefore, these tools do not qualify for this study and were thus excluded from the scope of the research.

Therefore, the AI software tools given in the Table 1, the ones that are compatible with the purpose of the research are Veras, ArkoAI, VisoAI and ArchitectGPT. The authors of this study selected Visoid as the platform for testing and developing architectural visualizations, based on its relevance and suitability for the research objectives.

Table 5:
Artificial intelligence software tools for architecture suggested on the website

AI name	Number of proposals	Operation
Midjourney	12	Creativity/design strategy
Veras	10	Design strategy/Rendering
ArkoAI	10	Design strategy/Rendering
Adobe Firefly	10	Creativity/design strategy
VisoAI	10	Design strategy/Rendering
ArchitectGPT.	8	Design strategy/Rendering
Stable Diffusion	8	Design strategy/Rendering
Genera.so	4	Design strategy/Rendering
ArkDesign.ai	4	Floor plan/Schematic design

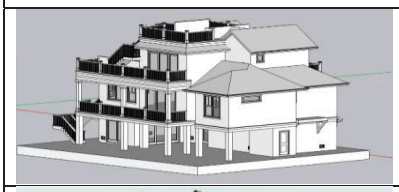
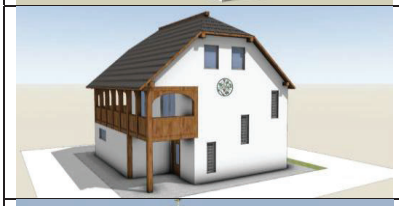
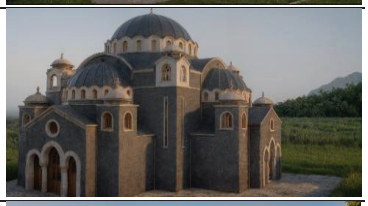
3.3 AI-driven rendering process

The aim of this paper is to achieve the most realistic result using AI tools shown in Table 2. Colored 3D architectural images mostly selected from Sketchup are loaded into Visoid. Therefore, on the loaded images as reference we need to apply rendering. The general settings we applied included selecting "exterior" as the visualization type, choosing the "render" style, setting a specific time of day, generating four images, and using render engine version 2.x. The resulting rendered image was uploaded as reference image to another artificial intelligence software tool Krea. The aim here is to use only enhancer to increase resolution and to get more detailed image. In other words, this tool is used to upscale, sharpen and refine visuals by adding textures, improving lighting and making the overall image look more realistic. Overall, our aim is to achieve a realistic effect as well as preserving the form.

Krea.ai didn't input a prompt. It just had to make the picture look better. When you crank up the "AI Strength" too high, the image gets warped. But if it's too low, it doesn't change enough. With the "Resemblance" setting, a high value means not much change happens. As for the "Clarity" setting, putting in too much leads to results that don't look real. As a result of the experiments that we made, these adjustments were given values of 0.50, 0.10, 0.10.

Table 2:

AI tools used in rendering process

Original 3D model	Visoid	Krea
		
		
		
		
		
		

3.4 Setting Evaluation metrics for photorealistic rendering

The factors used to evaluate realism were chosen based on insights gathered from examining existing research.

As we describe before process of rendering transforms a geometry model into a visual format. This process involves several steps including modeling, editing materials and textures, placing virtual lights.

According to the author[9], that is discussing of using AI tools for achieving quick and photorealistic results as a visualization artist and potential flaws of using it as well as potential ways to mitigate them. The author showcase how photorealistic architectural visualizations can be complex, in technical way.

Authors of [10] developed a fully automated framework to generate physically-based materials for 3D objects. They offered a robust end-to-end solution adaptable to objects under diverse lightning conditions.

Authors of [11] state that rendering has an impact on assigning materials, textures lighting setups and cameras. Image editing, on the other hand, focuses on issues like transparency, blending, filters, and adding elements or objects to the image.

According to the author [12] argues that color plays a key role in every aspect of photorealism. Color doesn't just define light, but also surface qualities, reflections, distance, depth, atmosphere, surroundings, and even camera and lens features. In some cases, a basic color tweak is all you need to make things "look real".

Now, if we took the references that we reviewed 5 criteria affecting realism for comparison were identifying.

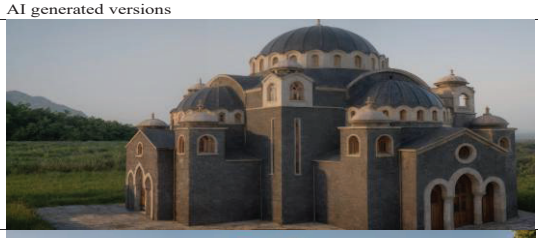
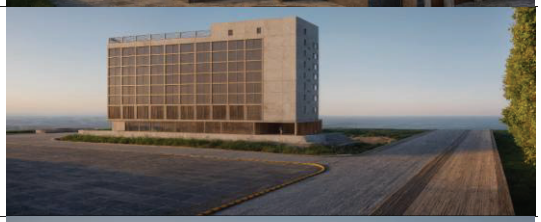
- Light effects
- Color consistency
- Material / Texture
- Camera setup
- Photorealistic details and ambient conditions

3.5 Selected rendered visuals

As we discussed before, D5 rendering engine integrated into architectural visualization on the final product is used. Table 3 shows final comparison between D5 and AI final versions.

Table 3:

D5 render images and AI generated versions

D5 versions	AI generated versions
	
	
	

4. Conclusion, Findings and Further work

In this paper, a comparison is made between artificial intelligence systems and rendering engines used in architectural visualization in terms of the final output product. Because of the findings in literature review, D5 rendering engine was selected like highest rated architectural rendering engine. Artificial intelligence tool used for rendering was selected as Visoid according to the research that we made. 3D models are used form Sketchup as reference and rendered in AI tools (Visoid and enhancer from Krea). 5 visuals criteria were taken from literature review for determining the realism of the final product.

The multi-phase process of rendering with artificial intelligence we propose is based only on personal preferences and experience. The reasons for such approaches are explained. Also, there is some limitation of this research, because there are few studies on this kind of approach developing artificial intelligence renderings.

The hypothesis of this research was that by 2025, AI in architectural visualization would be capable of producing more realistic architectural renderings in comparison with conventional rendering engines. Nevertheless, results and conclusions of the authors extensive expertise and professional background are that AI is not successful enough to produce architectural renderings as realistic as rendering engines by 2025. It is evident that AI is developing quickly within the architectural visualization industry and holds promise. Nevertheless, the research findings personal interpretation indicate that AI has some limitations as well and falls short of the level of realism provided by traditional rendering engines.

If we analyze the images by criteria, we can conclude that AI came close to the rendering engines in the camera criterion. AI for the subject of rendering has also become very sophisticated, particularly in dealing with camera placement and aspects such as focal length, exposure, and background settings. In the tests we conducted, in which we compared AI tool and conventional render engine results, the results indicated that AI now provides results that are on par in terms of quality with those achieved by conventional rendering engines.

The area where AI still lags behind traditional rendering engines is in capturing photorealistic details and ambient conditions. Today's rendering engines are highly capable of replicating complex atmospheric elements with a high degree of realism, something AI tools still struggle to fully match.

The same is observed in light effects, material/texture and color consistency. For instance, it is challenging to define and illustrate a highly detailed wire mesh metal material. There is also a need for improvement in the positioning and behavior of light and color consistency in artificial lightning and color. Our tests, suggest that AI nowadays has potential in these fields.

Overall, rendering engines nowadays are more efficient than artificial intelligence software in terms of photorealism. One of the benefits that artificial intelligence in architectural visualization, can likely enhance efficiency the most, is that it can produce in very shorts periods of time.

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Adoption of AI Technologies in IT Companies: North Macedonia Case

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Abstract

This paper examines how IT companies in North Macedonia adopt Artificial Intelligence (AI) technologies. Based on a questionnaire distributed to 15 IT companies, the study collected 24 responses from different departments within the same organizations. It explores their motivations, decision-making processes, and preferred AI applications. Findings indicate that most firms are in the early stages of adoption, driven mainly by client requirements and cost efficiency, with notable interest in analytics, automation, and chatbot solutions.

The questionnaire gathered data on organizational size, investment motives, perceived barriers, and technology preferences. The analysis shows that the main drivers of AI adoption include operational efficiency, competitiveness, and customer demand, while the primary obstacles relate to integration complexity, data quality, and financial constraints.

This paper contributes to the understanding of digitalization processes in emerging economies and offers practical insights for business leaders, policymakers, and educators aiming to encourage innovation-driven growth.

Keywords:

Artificial Intelligence (AI), Technology Adoption, IT Companies, North Macedonia, Innovation, Digital Transformation, Decision-Making

1. Introduction

Small and medium-sized IT enterprises (SMEs) play an essential role in the economic structure of both developed and emerging economies, contributing significantly to employment, innovation, and gross domestic product (OECD, 2021). Despite their importance, SMEs face persistent barriers when adopting new technologies, ranging from limited financial resources and technical expertise to resistance toward organizational change (Eurofound, 2022).

In the contemporary digital economy, the pace of technological advancement—particularly in artificial intelligence (AI), automation, and data analytics—has intensified the challenges for SMEs seeking to maintain competitiveness. AI adoption, in particular, demands not only technical investment but also structural, strategic, and cultural readiness (OECD, 2021; Mitkovski, 2015).

While large enterprises often have dedicated innovation budgets and R&D units, SMEs typically rely on incremental innovation and external collaboration to integrate new technologies (OECD, 2021; World Bank, 2023). For IT SMEs in emerging markets such as North Macedonia, these challenges are further amplified by limited public support mechanisms, skill shortages, and evolving regulatory frameworks.

This paper builds upon the holistic model proposed by (Mitkovski, 2015), which emphasizes the integration of technological, human, and organizational factors in achieving sustainable digital transformation. The study investigates how IT SMEs in North Macedonia adopt and integrate AI-driven technologies, exploring the motivations behind these investments, the obstacles faced during

implementation, and the strategic alignment required for long-term competitiveness.

By combining theoretical perspectives with empirical data collected through a nationwide survey, this paper aims to identify practical strategies that can help SMEs transition from traditional operations toward innovation-driven models. The findings provide actionable recommendations for managers, policymakers, and educators seeking to strengthen the digital transformation capacity of SMEs in the Western Balkans and similar economies.

2. Literature Review

The digital transformation of small and medium-sized enterprises (SMEs) has become one of the most widely studied topics in management and innovation research over the past decade. Scholars agree that SMEs face both unprecedented opportunities and complex challenges as they seek to incorporate digital technologies into their business models (Vial, 2019; OECD, 2021). The evolution from digitization to digital transformation involves more than the adoption of new technologies—it represents a profound shift in how organizations create value, structure operations, and manage human capital (Brynjolfsson & McAfee, 2017).

According to (Mitkovski, 2015), technological transformation in SMEs must be approached holistically, considering not only the introduction of new technologies but also their integration into organizational culture, leadership, and human resource management. His model emphasizes that a fragmented approach—focusing solely on technology—leads to sub-optimization, whereas aligning all subsystems enhances innovation capacity and long-term competitiveness. This theoretical framework provides the foundation for this study's analysis of how IT SMEs in North Macedonia adopt artificial intelligence (AI) and other advanced technologies.

The Organisation for Economic Co-operation and Development (OECD, 2021) stresses that SMEs adopting AI technologies often do so to improve efficiency, customer experience, and product quality. However, these efforts are frequently constrained by limited technical skills, data governance issues, and financial barriers. Similarly, the European Investment Bank (2023) found that only a small percentage of SMEs in the EU have fully integrated AI solutions, citing a lack of digital infrastructure and strategic planning as key obstacles.
Vial (2019) defines digital transformation as "a process that aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies." This view aligns with (Davenport & Ronanki, 2018), who argue that successful AI initiatives focus on targeted, high-value applications such as process automation, predictive analytics, and customer insight generation.

In the context of developing economies, research by (North and Varvakis, 2016) and the (World Bank, 2023) emphasizes that SMEs require systemic support, including access to funding, digital skills training, and government-backed innovation programs. These enablers are particularly critical in smaller markets such as North Macedonia, where the IT sector's capacity for innovation is often limited by external dependencies and labor market constraints.

The existing literature collectively supports the argument that technology adoption in SMEs must be treated as an organizational transformation process rather than a purely technical upgrade (Mitkovski, 2015; OECD, 2021; Vial, 2019). The holistic approach recognizes that leadership vision, employee engagement, and cultural readiness are as vital as financial and technological resources in achieving sustainable digital advancement.

This framework serves as the analytical foundation for the present research, which seeks to determine how IT SMEs in North Macedonia operationalize this holistic model in their approach to AI-driven technological transformation.

3. Methodology

This study adopts a quantitative research design, utilizing a structured questionnaire distributed to 15 IT companies across North Macedonia. A total of 24 responses were collected, as several companies provided input from multiple departments, such as management, IT, and R&D. The research focuses on understanding how small and medium-sized enterprises (SMEs) decide to invest in emerging technologies—particularly in artificial intelligence (AI)—and examines the motivations, influencing factors, and perceived barriers in this process (OECD, 2021; Vial, 2019).

The survey instrument was designed to capture insights into several dimensions of technology adoption:

(a) organizational size and structure;

(b) main activity of the company (software, consulting, telecommunications, etc.);

(c) level of AI adoption and technological readiness;

(d) motivational factors (e.g., efficiency improvement, competitive advantage, cost reduction);

(e) decision-making processes and leadership roles; and

(f) key challenges such as funding limitations, skill gaps, or system integration issues.

Each question was structured using a combination of multiple-choice, Likert scale, and open-ended formats to enable both quantitative and qualitative analysis. The questionnaire was developed based on established models of SME digital transformation (OECD, 2021; Mitkovski, 2015; North & Varvakis, 2016), ensuring alignment with recognized theoretical frameworks and comparability with similar studies.

4. Results

The results of the survey reveal how IT companies in North Macedonia are adopting Artificial Intelligence (AI) technologies and integrating them into their operations. The findings are presented in descriptive form, summarizing the overall trends from the 24 valid responses gathered across 15 participating companies.

4.1 Company Size

Among the surveyed IT companies, 45.8 % are small enterprises with 10–49 employees, forming the largest group in the sample. Medium-sized companies (50–249 employees) and large companies (250+ employees) each represent 20.8 %, while 12.5 % are micro companies with fewer than 10 employees. Together, small and medium-sized enterprises account for 66.6 % of respondents, reflecting the dominant structure of the IT sector in North Macedonia.

4.2 Business Activity

A majority of respondents (54.2 %) identified software development as their company's main area of activity. Another 29.2 % operate in IT services and consulting, while smaller shares are observed in telecommunications (8.3 %), hardware or IoT solutions (4.2 %), and AI or data analytics (4.2 %). These findings indicate that the Macedonian IT industry remains primarily software-driven, supported by a

strong consulting segment that facilitates client-side digital transformation.

4.3 AI Adoption Level

Regarding AI adoption, 41.7 % of companies reported actively using AI solutions, while 33.3 % are currently piloting AI projects. Another 12.5 % are in the exploration phase with no implementation yet, and 12.5 % already provide AI-based products or services. In total, 75 % of surveyed companies are either piloting or using AI solutions, confirming that adoption within North Macedonia's IT sector has moved beyond the exploratory stage.

4.4 Investment Motivations

The two most influential drivers of AI investment are cost reduction and efficiency improvement, both selected by 70.8 % of respondents. Process automation follows closely with 70.8 %, while market competitiveness and innovation were cited by 62.5 % of companies. Client or tender requirements influenced 37.5 % of companies, and compliance or reporting requirements were mentioned by only 4.2 %. Notably, none of the respondents identified access to grants or external funding as a key motivator. These findings suggest that AI adoption is primarily self-initiated and performance-driven rather than driven by external incentives.

4.5 Decision-Making Responsibility

Decision-making responsibility for AI investment is split evenly between CEOs or managing directors (33.3 %) and joint management teams (33.3 %). The R&D or innovation departments account for 16.7 %, while CIOs or IT managers represent 12.5 %. Only 4.2 % of decisions are attributed to operations managers. Overall, 66.6 % of AI-related investment decisions are made collaboratively or at the executive level, emphasizing the strategic nature of technology adoption.

4.6 Barriers to Adoption

The most frequently reported barrier is integration with existing systems, cited by 50 % of respondents. Limited data quality or availability (41.7 %) and lack of skilled professionals (37.5 %) follow closely, while 33.3 % reported unclear ROI as a challenge. Fewer companies mentioned high implementation costs (20.8 %), regulatory uncertainty (12.5 %), or lack of client demand (8.3 %). These results show that technical and operational barriers outweigh financial or regulatory ones, underscoring the importance of technical capacity and workforce readiness.

4.7 Preferred AI Technologies

Machine learning and predictive analytics were identified as the most relevant AI technologies, selected by 70.8 % of respondents. Chatbots and virtual assistants followed with 62.5 %, while natural language processing (37.5 %), robotic process automation (33.3 %), and recommendation systems (33.3 %) were also common. AI for cybersecurity (29.2 %), computer vision (25 %), and IoT data analytics (12.5 %) were less frequently chosen. This distribution highlights a clear preference for scalable, software-based AI tools that enhance efficiency, prediction, and customer experience.

4.8 Procurement Channels

Most companies (45.8 %) acquire AI or IT solutions directly from vendors, while 29.2 % develop them internally. Partnerships with other firms account for 16.7 %, and 8.3 % of companies acquire technology through public or private tenders. None of the respondents reported using government grants or donor programs as their main procurement channel. These results indicate a largely market-driven adoption process, with companies relying on commercial solutions and internal innovation rather than public

support.

4.9 Perceived Benefits

Half of the respondents (50 %) identified improved operational efficiency as the main benefit of AI adoption. One in five companies (20.8 %) reported developing new products or business models, while 12.5 % cited cost savings and another 12.5 % better decision-making through data insights. Only 4.2 % stated that they have not yet observed measurable benefits. The predominance of efficiency and innovation outcomes demonstrates that AI implementation is already delivering tangible organizational value.

4.10 Future Investment Plans

Looking ahead, 41.7 % of companies plan to slightly increase AI investments in the next year, while 37.5 % intend to increase them significantly. Only 8.3 % expect no change, and 12.5 % remain uncertain. None of the respondents plan to reduce investments. These responses indicate strong confidence in AI's long-term potential, with nearly 80 % of firms expecting to expand their AI budgets in the near future.

5. Discussion

The results of this research highlight the dynamic yet uneven progress of digital transformation within the IT sector in North Macedonia. SMEs in this sector are not merely adopting technologies reactively but are increasingly taking strategic steps toward integrating AI and automation into their core operations. These findings reinforce the notion that technology adoption among SMEs is primarily motivated by internal strategic objectives—such as cost efficiency, innovation, and maintaining competitiveness—rather than by external regulatory or client pressures (OECD, 2021; European Investment Bank, 2023).

Consistent with (Mitkovski, 2015) holistic framework, successful technology transformation within SMEs depends on the simultaneous alignment of technological, organizational, and human dimensions. Leadership plays a critical role in steering this transformation: two-thirds of the surveyed companies reported that the CEO or management team is directly responsible for technology investment decisions. This finding reinforces the idea that strong leadership vision and commitment to innovation are central to organizational readiness (North & Varvakis, 2016; Vial, 2019).

Another key insight is that while the majority of firms are motivated to adopt AI, barriers such as integration difficulties, data quality issues, and a lack of expertise persist. These challenges mirror trends across Europe and globally (Davenport & Ronanki, 2018; OECD, 2021), confirming that even in smaller markets, digital transformation is constrained not only by capital but also by organizational capacity and skills. The need for continuous employee training and digital literacy development, therefore, emerges as a critical success factor.

A particularly noteworthy finding is that 79.2 % of companies plan to increase AI-related investments within the next year. This figure underscores the growing recognition of AI as a strategic enabler of competitiveness rather than an experimental innovation. However, without corresponding investments in human capital—through targeted training and leadership development—such growth risks remaining superficial (World Bank, 2023).

This research also shows that Macedonian IT SMEs are increasingly aware of the strategic importance of innovation ecosystems. Many respondents expressed interest in collaborating with universities, training centers, and international partners to access knowledge and resources. This aligns with broader European digitalization strategies, which emphasize partnerships between the private sector, academia,

and public institutions to accelerate SME transformation (Eurofound, 2022).
Ultimately, the study confirms that a holistic approach to technological transformation, as described by (Mitkovski, 2015), remains the most effective framework for managing change in SMEs. Addressing technology adoption solely from a technical standpoint overlooks the essential human and cultural dimensions that determine success or failure. Integrating leadership vision, employee engagement, and long-term planning ensures not only short-term efficiency gains but also sustainable organizational evolution.

6. Conclusion

This research provides a comprehensive overview of how small and medium-sized IT enterprises (SMEs) in North Macedonia approach technological transformation through a holistic lens. The results reveal that digitalization and AI adoption among these companies are primarily driven by internal strategic objectives—most notably cost optimization, efficiency enhancement, and competitiveness—rather than external mandates or regulatory pressure (OECD, 2021; Eurofound, 2022).

Building upon (Mitkovski, 2015) holistic model, this study confirms that technological transformation in SMEs cannot be achieved through isolated technical interventions alone. Instead, it requires the coordinated alignment of technological, organizational, and human components. Effective leadership, employee engagement, and skills development emerge as critical success factors, as organizations that invest simultaneously in human capital and technological infrastructure demonstrate higher readiness for digital transformation (Vial, 2019; North & Varvakis, 2016).

The research also underscores the significance of training and capacity-building programs in bridging the digital skills gap within Macedonian SMEs. While most companies express a willingness to increase investments in AI, the absence of structured learning initiatives and advisory support poses a risk to the sustainability of transformation efforts. Public policies aimed at supporting SME digitalization should therefore prioritize capacity building, access to financing, and knowledge-sharing mechanisms between academia and industry (World Bank, 2023; European Investment Bank, 2023).

In conclusion, adopting a holistic approach to technology transformation significantly enhances the ability of SMEs to innovate and remain competitive in an increasingly digital world. By considering technological, organizational, and human factors together, IT SMEs in North Macedonia can navigate the complexities of AI adoption and achieve sustainable growth. The insights gained from this study contribute to both academic discourse and practical policymaking, providing a framework for understanding how emerging economies can foster innovation-driven development through the strategic integration of digital technologies.

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Analysis of the Internet Banking in the Macedonian Banking Sector and Other Countries

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Abstract:
The rapid advancement of information and communication technologies has significantly transformed the global banking industry, with Internet banking emerging as a key component of modern financial services. This paper analysis the development, adoption, and impact of Internet banking services within the Macedonian banking sector. It presents the current state of digital banking infrastructure, customer acceptance, and the strategic initiatives that are undertaken by banks to enhance service delivery through Internet platforms.
This paper presents a structured analysis of Internet banking in the Macedonian banking sector and comparative analysis in relation to the Internet banking in certain countries.

Keywords:
Banks, Services, Internet banking

1. Introduction

In recent years, Internet banking has emerged as a crucial component of the modern banking system, revolutionizing how financial institutions deliver services and interact with customers. The rise of digital technologies and the increasing penetration of Internet access have fundamentally reshaped customer expectations, pushing banks to innovate and provide convenient, secure, and accessible banking services online [1].
Internet banking refers to the use of the Internet to perform banking activities, such as checking account balances, transferring funds, paying bills, applying for loans, and more. With the availability of services for smartphones, Internet banking services have become more accessible and diverse. The Internet banking landscape in any country depends on several factors, including technological infrastructure, government regulations, consumer adoption, and the banking sector's readiness to embrace digital transformation.
Our country has a well-established banking sector, with a mix of local banks and international financial institutions operating in the country. The banking system is modernizing, with a growing adoption of digital banking solutions [2]. Macedonian banking sector has been gradually embracing digital transformation, with Internet banking services becoming increasingly widespread. While the adoption of Internet banking in the country lags behind that of more developed economies, Macedonian banks have made significant strides in modernizing their digital offerings, improving user interfaces, enhancing cybersecurity, and expanding online service availability [3,4].

Understanding the dynamics of Internet banking in Macedonia is essential not only for financial institutions seeking to remain competitive but also for policymakers, investors, and consumers navigating an increasingly digital financial landscape.

2. Methodology

This paper contains a descriptive and comparative research to analyze the development and adoption of Internet banking in the Macedonian banking sector, as well as its position relative to the

European Union and selected Western Balkan countries. The analysis is based on secondary quantitative data collected for the period 2023–2025.

Data were obtained from several authoritative sources, including the National Bank of the Republic of North Macedonia, the State Statistical Office, and the Macedonian E-Commerce Association. Additional information was gathered from Data Report (Digital 2025), EBRD and EU digitalization programs, and relevant academic and institutional studies. Comparative data for the EU and other countries (Serbia, Albania, Bosnia and Herzegovina, Kosovo, and Bulgaria) were sourced from Eurostat, Statista, Trading Economics, and national reports published between 2023 and 2025.

To ensure data reliability, the paper conducted cross-validation of figures from multiple independent databases and reports. Only consistent, up-to-date, and verifiable data were included in the analysis. The main variables examined included Internet penetration, percentage of individuals using Internet banking, digital payment volumes, and growth rates in online and mobile transactions. The results were presented using descriptive statistics and comparative tables to identify trends, disparities, and regional patterns in Internet banking adoption.

3. Analysis of the Internet banking in the Macedonian banking sector

In continue is an analysis of Internet banking in the Macedonian banking sector.

The current situation shows that there is an increase in the adoption of digital payments and channels, and there is a noticeable growth in the use of payment cards, POS terminals, e-commerce, mobile payment applications and electronically initiated payment orders [5].

Also, according to available data, mobile payment applications recorded an increase of ~44.3% year-on-year in the number of transactions. Citizens are increasingly using Internet banking to initiate payment orders and transfers [5]. As key infrastructure and regulatory initiatives are the Introduction of a National Digital Identity Service in partnership with Mastercard and Evrotrust, which enables remote identification, e-signatures, and reduces the need for physical visits [6]. Banks are also implementing more advanced digital platforms (e.g. “Digital Edge” for retail and corporate clients) [7].

There are several EU/EBRD programs (e.g. “Go Digital in Western Balkans”) that provide financing and technical assistance to SMEs and banks to adopt digital and green technology [8].

When it comes for the customer experience and satisfaction, there is a positive attitude among customers towards e-banking; many see clear benefits (convenience, speed, less need to visit branches) according to available surveys [9].

Key drivers for this current state are [8, 9, 10]:

1. The COVID 19 pandemic has accelerated the adoption of online and mobile banking, as well as in many countries.
2. Regulatory and technological enablers such as digital signatures, national e-card identification, PSD2-like regulations (or at least the intention to do so) are driving banks to modernize.
3. Public and private investment / international assistance (EU, EBRD) for digital transformation, especially for SMEs and banking infrastructure.
4. Consumer expectations: more tech-savvy people expect digital service, convenience.

The analysis of available data on recent trends of Internet banking in the Macedonian banking sector shows that there is a growing adoption of digital payment channels and continued transfer from cash to e-banking, mobile apps and online payment orders. Mobile payment apps and Internet banking are increasingly used by citizens for transfers and commerce. There is also an increase in e-commerce and online shopping. More and more Internet users are purchasing goods or services online. This is driving demand for secure, convenient payment and banking apps/interfaces [1].

Internet penetration, mobile device usage, network speeds are increasing. Fixed and mobile Internet download speeds are improving, supporting more sophisticated digital banking features. Regarding regulatory developments and fintech/open banking, laws and regulations are being adapted to enable

more innovations: payment services, open banking (sharing customer data according to regulation), e-money, etc. These are favorable for the expansion of Internet banking [11].
Banks in Macedonian banking sector are also advancing in digital maturity: adopting new technologies, automating processes, improving the user experience, offering remote/online services. [4].
The following table 1 shows some of the measurable indicators related to the Internet banking in the Macedonian banking sector and the data in the table are from the sources: [1,2,16].

Table 1:
Measurable indicators for Internet banking in Macedonian banking sector

Metric	Value / Trend
Internet penetration	~ 92.0% of population (early 2025) are Internet users
Households with Internet access	~ 90-ish percent, increasing from ~ 88% in prior year
Use of Internet banking	Increased to 40% of Internet users in 2024, up from about 32.8% in 2023
Growth in payment transactions by cards / POS / e-commerce	Year-on-year increases: cards usage (number & value) up ~ 17.2% / 16.2%; e-commerce payments up ~ 21.8%; POS payments up ~ 16.8%
Growth in digital payment orders via mobile apps / online banking	Mobile payment app transactions rose ~ 44.3% vs same period in 2023; Internet banking-initiated payment orders rose ~ 12.6%
Digital payments market size / projection	Estimated transaction value ~ US$1.21 billion in digital payments for 2025; projected to grow to ~US$3.06B by 2030
Banking system size & loans	Total assets of banking system ~ MKD 858,401 million; total loans ~ MKD 524,186 million. Households account for ~ 50% of loans; non-financial companies ~ 49%

The table shows that there is an increase in the use of online banking (from ~33% to ~40%), indicating growing user convenience/trust and better service offerings. Mobile applications are growing faster than online banking, or at least are experiencing higher transaction volume growth rates. Digital payments (cards, POS terminals, e-commerce) are expanding, but there may still be gaps in some areas. Infrastructure improvements (better speeds, more stable connectivity) are enabling more advanced banking services. Regulatory changes (e.g. PSD2, open banking, new payment services laws) will accelerate innovation and competition.

4. Comparative analysis with EU

The comparative analysis of the measurable indicators that were presented for internet banking in the Macedonian banking sector and the measurable indicators available for the EU are presented in the following table 2 and the data in the table are from the sources: [12,13,14,15].

Table 2:
Comparative analysis: North Macedonia and EU

Metric	North Macedonia	EU Average
Internet penetration / usage	~ 92% internet users	EU ~ 93%
Internet banking usage	~ 40% of internet users	~ 67% across EU. High-performing countries often 80-85%
Growth rates in digital payment transactions	e.g. mobile app transactions grew ~44.3%; POS/e-commerce also rising	Strong growth in digital wallet usage, contactless payments, real-time payments. But in many Western EU states the base line is already high, so growth rates are more incremental

Metric	North Macedonia	EU Average
Households with internet access	~ 90+%	~ 89-95% depending on region

Although internet access is high, the percentage of internet users actively using internet banking in North Macedonia is significantly lower than the EU average. This points to barriers such as trust, usability, awareness or perhaps a lack of attractive service offerings. The strong growth rates of payments via mobile apps, POS, e-commerce point to latent demand. When the trust/infrastructure or regulatory barriers are addressed, adoption could accelerate.

Many EU countries are already at a high level of adoption, so further growth is more related to incremental improvements (e.g. more advanced services, improved user experience, new payment methods) than to broad expansion. In contrast, North Macedonia has more space to expand its basic adoption.

The EU has a strong trend towards open banking, real-time payments, digital wallets, etc. For North Macedonia will be important not only infrastructure, but also legal/regulatory frameworks, security, consumer protection, and bank investments in digital platforms.

5. Comparative analysis with other countries

The comparative analysis of the measurable indicators that were presented for internet banking in the Macedonian banking sector and the measurable indicators available for the other countries (Balkans / Western Balkans) are presented in the following table 3 and the data in the table are from the sources: [16,17,18,19,20,21,22,23].

Table 3:
Comparative analysis with other countries

Country	Key Data / Metrics for Internet Banking	Notes
European Union (EU-27 / EU avg.)	~ 67.24% of individuals using internet for banking (December 2024) High usage in Nordic / Baltic / Western European states (Estonia ~ 83%, Sweden ~ 83%)	This is benchmark; reflects advanced digital adoption, high trust / infrastructure.
North Macedonia	~ 40% of internet users use internet banking	This is below EU average by ~ 25-30 percentage points; sizable gap though improving.
Serbia	In 2023, ~31.82% of individuals used internet banking (all individuals) according to Eurostat data. 4.6 million mobile banking users + 4.4 million electronic banking users by end-2024, showing growth	Serbia is also well below EU average in % usage of internet banking by individuals, though growth is strong. Mobile and e-banking users expanding rapidly suggesting narrowing the gap.
Bosnia and Herzegovina (BiH)	• Internet banking services offered widely; but in households, only ~ 20.1% use internet banking now (compared to ~ 7.8% in 2019). • 76% of households have internet access; ~ 78.8% used the Internet in past 3 months. • e-commerce penetration ~ 42% of population purchase online; many still prefer cash / POS / offline payment	BiH is far behind EU average on internet banking usage; has reasonable internet access and usage rates, but less uptake of banking/digital payments.
Albania	• Remote / internet banking transactions: record high in 2024; total remote transactions	Some progress (strong growth), but still substantially below EU average. Infrastructure

Country	Key Data / Metrics for Internet Banking	Notes
	increased ~ 22% year-on-year. • At end-2024, ~ 39% of active bank accounts accessible online (internet connected) vs ~ 34% in 2023. • However, overall percentage of individuals who used internet banking is among the lowest in Europe (< 28% in some earlier years)	& regulatory / trust issues perhaps more relevant.
Kosovo	• Internet penetration very high (~ 96.6%) as of early 2025. • Strong growth in electronic transactions: e-banking payments up ~ 17.3% for Jan-Sep 2024 vs same period prior year. • Use of online payments, especially among young (18-35) rising; large increase over past decade.	Kosovo shows promising infrastructure (internet penetration high), and growing transaction volumes. Yet usage of full suite of internet banking services by individuals still likely below EU average, though narrowing.
Bulgaria	Individuals using the internet for internet banking: ~ 31.33% (December 2024)	Far below EU average (~67%), suggesting that even within EU there are substantial internal disparities.

Based on this comparative data we conclude that most of the Western Balkans are significantly below the EU average (~ 67%) in terms of percentage of individuals using internet banking. Even among EU countries, those in Eastern / Southeastern Europe often are under the EU average. Countries like Serbia, Albania, Kosovo are showing fast growth in usage, active accounts, remote / electronic transactions. Because they start from a lower base, annual growth rates tend to be higher.

Many countries in the region have relatively high internet penetration (e.g. Kosovo ~ 96.6%, Bosnia & Herzegovina ~ 86.7%) but much lower share of people actually using internet banking. Thus, the reason for that is infrastructure (in many places) trust, service quality, regulatory / legal framework, digital literacy. There are differences between legal entities vs individuals, mobile vs internet banking n some places. Legal entities use internet banking more; individuals prefer mobile banking or use less. Also, mobile banking may grow at faster rates, showing that user preferences lean toward convenience and mobile first.

Card payments, POS usage, e commerce are increasing, but some countries still have significant usage of cash /physical payments. EU countries tend to have higher share of digital payments (cards, online).

From the available data in continue is some regional ranking among the analysis countries, from higher to lower in terms of internet banking adoption:

1. Serbia – relatively strong growth and number of users, though still below EU average in % of population
2. Kosovo – very high internet access, growth in transaction volume
3. North Macedonia – moderate, around ~40%, i.e. in a middle position among the Western Balkans
4. Albania – growing fast, but still lower adoption by individuals using internet banking
5. Bosnia & Herzegovina – lower, many households with access, but relatively low active usage by individuals.
6. Bulgaria also shows lower internet banking usage among its population

6. Discussion

The comparative analysis of Internet banking adoption across North Macedonia, the European Union, and other Western Balkan countries reveals that the variation in usage rates cannot be explained solely by technological availability or Internet access. Although North Macedonia and its neighbors exhibit relatively high levels of Internet penetration (above 85–90%), the percentage of individuals

actively using Internet banking remains significantly lower than the EU average. This disparity reflects a complex interaction of institutional, cultural, and behavioral factors.

One of the most significant determinants is trust in digital financial systems. In many Western Balkan countries, a persistent reliance on cash and face-to-face banking reflects limited public confidence in the security of online financial transactions. Concerns regarding cybercrime, data privacy, and fraud continue to discourage users from fully embracing online banking services. In contrast, EU member states—especially in Northern and Western Europe—benefit from long-standing regulatory oversight, strong consumer protection laws, and higher public trust in digital infrastructure, which collectively foster a more mature digital banking culture.

Regulatory environments also play a pivotal role. While EU countries operate under harmonized frameworks such as the Payment Services Directive (PSD2), which encourages open banking and secure digital authentication, most Western Balkan states, including North Macedonia, are still in the process of aligning their legislation with EU standards. The lack of a unified digital identification system, limited interoperability between banks, and slow implementation of open banking principles delay the growth of Internet banking usage. North Macedonia has made recent progress through initiatives like the National Digital Identity Service and the adoption of digital signatures, yet these measures are still in early stages compared to the EU.

Socio-cultural factors further influence adoption rates. In the Balkans, traditional attitudes toward personal banking—preferring in-branch interactions and paper documentation—remain common. Digital literacy levels also vary across regions, affecting users' willingness and ability to engage with online platforms. By contrast, EU countries with high Internet banking usage typically have higher levels of financial education and digital competence, supported by public and private digital inclusion programs.

7. Conclusions

Internet banking is transforming the way people interact with financial institutions. It offers numerous advantages in terms of convenience, speed and cost savings. However, security concerns and digital literacy challenges must continue to solved to ensure a safe banking experience for all. As technology advances, we can expect Internet banking services to become even more integrated, secure and user oriented. Compared to other countries, the Macedonian banking sector is following global banking trends, but will need additional digital investments, better cybersecurity practices, and more financial products to compete effectively in the digital banking space. The Macedonian banking sector has seen significant growth in Internet banking and digital payment channels. The growth is related to the use of Internet banking services, but also to regulatory and infrastructural support. There is a significant foundation such as high Internet penetration, increased e-commerce, growth of mobile payments, etc. However, challenges remain in ensuring fair adoption, trust and easy to use services. For the banking sector to fully exploit Internet banking are still needed continued investment, innovation and customer-focused regulatory measures.

Future research could focus on examining user behavior and demographic factors influencing digital banking adoption through data collection, such as surveys or interviews. Regulators and banks should collaborate on national strategies to enhance financial literacy, expand rural access to digital services, and foster innovation through fintech partnerships. Such coordinated efforts would not only increase Internet banking adoption but also contribute to broader economic digitalization and financial inclusion in North Macedonia and the Western Balkan region.

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Circular Economy in Manufacturing Processes: A Comparative Analysis of the EU and Serbia

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Abstract:
This paper analyzes the development and implementation of the circular economy (CE) concept in manufacturing processes, focusing on a comparative analysis between the European Union (EU) and Serbia. The circular economy represents an important instrument for achieving sustainable development and resource efficiency through closing material and energy loops. In the EU, CE has become a cornerstone of the European Green Deal and the 2020 Circular Economy Action Plan, serving as a driver of competitiveness and climate neutrality. Serbia, as a candidate country for EU membership, has begun aligning its legislative and strategic frameworks with European standards. However, significant challenges remain, including insufficient infrastructure, low recycling rates, and weak institutional capacities. This paper highlights best practices, regulatory frameworks, and key challenges, emphasizing the role of digital technologies and decision-support systems in facilitating the transition to circular production. The results suggest that the integration of CE principles into manufacturing and ICT systems can significantly improve resource efficiency and competitiveness in Serbia.

Keywords:
Circular Economy, Manufacturing, EU Integration, Sustainable Development, ICT, Decision Support Systems

1. Introduction

The global economy is increasingly facing challenges related to resource scarcity, environmental degradation, and climate change. The European Union has placed the circular economy at the center of its sustainability strategy, as outlined in the European Green Deal and Circular Economy Action Plan (2020). The transition from a linear model (take–make–dispose) to a circular model aims to extend product life cycles, minimize waste, and maximize resource efficiency. For Serbia and other Western Balkan countries, implementing circular economy principles represents both a legal obligation and an opportunity for modernization and economic resilience.

This paper aims to analyze the current state of circular economy implementation in Serbia and compare it with EU practices, focusing particularly on manufacturing processes. The research identifies key challenges and opportunities, and proposes the use of ICT tools and business intelligence systems to support data-driven decision-making in circular production planning.

In the context of the global transition toward sustainable development, the circular economy represents an important element of industrial transformation. Its implementation contributes to reducing pressure on natural resources and enhancing economic competitiveness through innovation, efficient material use, and digital technologies. Comparing the approaches of the European Union and Serbia allows for the identification of alignment levels, institutional challenges, and opportunities for improving production systems toward sustainable Industry 4.0. Thus, this paper contributes to a better understanding of the circular economy as both a development policy and an instrument for European integration.

2. Methodology

This paper applies a qualitative comparative analysis based on desk research of strategic documents,

legal frameworks, and academic literature. The comparison between the EU and Serbia was conducted using predefined criteria: (1) regulatory alignment, (2) institutional capacity, (3) adoption of CE practices in manufacturing, and (4) the role of digital technologies. No statistical modelling was performed. Instead, the analysis relied on thematic indicators such as recycling targets, waste management performance, and documented industry-level initiatives. This approach allows a structured comparison while keeping the focus on manufacturing processes and practical CE implementation.

3. Theoretical Background

The circular economy is an alternative to the traditional linear model, designed to keep materials, products, and resources in use for as long as possible while minimizing waste generation [1]. It relies on the "R" strategies: Reduce, Reuse, Recycle, and Recover, which aim to optimize resource utilization throughout the product life cycle [2]. Modern approaches expand these to include Refuse, Rethink, Repair, Refurbish, Remanufacture, and Repurpose [3].

Digital transformation plays a crucial role in achieving CE objectives. The integration of ICT systems, data analytics, and smart manufacturing enables companies to track material flows, assess environmental impacts, and plan production based on real-time data[4].

The linear model is based on resource extraction, production, consumption, and disposal, leading to unsustainable resource depletion [5]. Conversely, the circular model emphasizes regenerative processes where waste becomes input for new production cycles. This system relies heavily on data-driven monitoring, digital twins, and IoT technologies to optimize energy use and material recovery[6].

The development of the circular economy concept is closely connected to the United Nations Sustainable Development Goals: SDG 9 - Industry, Innovation and Infrastructure and SDG 12 – Responsible Consumption and Production[7].

In relation to SDG 9, CE fosters the development of sustainable industry through innovations in product design, more efficient use of resources, integration of renewable energy sources, and the creation of a new generation of "green" jobs[8]. These processes stimulate industrial modernization and support the shift toward low-carbon, technology-driven production systems[9].

Regarding SDG 12, CE enables the transition toward responsible consumption and production patterns by reducing waste generation, optimizing material flows, and encouraging both producers and consumers to adopt sustainable behavior[10].

The implementation of circular principles contributes to measurable environmental, economic, and social benefits:

- Reduction of the ecological footprint through lower CO_2 emissions and decreased water and energy consumption;
- Greater economic resilience by reducing dependence on raw material imports and stimulating local production;
- Social inclusion through the creation of new employment opportunities in repair, recycling, and remanufacturing sectors[11].

Overall, the circular economy represents the operationalization of sustainable production, transforming the theoretical goals of the SDGs into concrete business models and technical practices that enable long-term sustainability[12].

4. Analysis of Circular Economy Implementation in Industrial Manufacturing: EU and Serbia

4.1 Circular Economy in the European Union

The EU has developed an advanced framework for implementing CE through legislation, policies, and financial instruments. The European Green Deal (2019) and Circular Economy Action Plan (2020) define CE as a critical tool for achieving climate neutrality by 2050 [13]. Important legislative instruments include:

- Waste Framework Directive (2008/98/EC): Establishes waste hierarchy and defines obligations for prevention, reuse, and recycling.
- Packaging and Packaging Waste Directive (94/62/EC): Sets recycling targets by material type.
- Landfill Directive (1999/31/EC): Limits the disposal of biodegradable waste[14].

EU member states have achieved significant progress through national CE strategies. For instance, Belgium's Circular Flanders program connects the public sector, private companies, research institutions, and citizens. Its activities focus on material recycling, reuse, and the development of secondary raw material markets[15].

Germany's GreenTech Innovation program represents a national initiative supporting innovation in green technologies, including financial assistance for startups and small and medium-sized enterprises (SMEs) through grants and subsidies. The main focus areas include energy efficiency, renewable energy, eco-design, and waste reduction [16].

4.2 Circular Economy in Serbia

Serbia is in the early stages of implementing circular economy principles but has made progress through strategic and legislative initiatives. The Roadmap for Circular Economy in Serbia (2020) marked a milestone, defining national priorities for waste reduction, recycling, and sustainable production [17]. Important policy frameworks include:

- Waste Management Program (2022–2031)
- Law on Waste Management (2016 Amendment) introducing the concepts of by-products and end-of-waste status
- National Sustainable Development Strategy

Despite this progress, several barriers persist: insufficient recycling infrastructure, limited investment, fragmented regulations, and low public awareness [18]. Additionally, data management systems are underdeveloped, limiting effective policy monitoring. Integrating ICT solutions such as smart waste tracking, digital logistics systems, and environmental data analytics could significantly improve operational efficiency and policy evaluation [19].

Concrete examples of circular economy practices in Serbian manufacturing include:

Brzan Plast d.o.o. – Plastic Recycling. Processes PET packaging and plastic film waste into regranulate, producing construction films and sacks while achieving up to 50% cost savings compared to virgin materials. Environmental benefits include pollution reduction and prevention of plastic incineration. This model has replication potential in agriculture, construction, and local communities [20].

Newpen d.o.o. – Pencil Production from Recycled Newspapers. Manufactures graphite and colored pencils from old or unsold newspapers, reducing wood consumption and promoting social value. The model can be integrated into school programs, the souvenir industry, and sustainable product initiatives [21].

Strauss Adriatic d.o.o. – Energy Recovery from Coffee Production Waste. Uses coffee husks to produce heating briquettes, replacing fossil fuels with biomass, lowering CO_2 emissions, and utilizing industrial organic waste. The approach is applicable in food and other organic-waste-generating industries such as milling, bakery, and fruit processing [22].

These examples demonstrate that although CE adoption in Serbia remains limited relative to EU levels, viable and scalable circular practices are emerging within traditional manufacturing.

4.3 Comparative Analysis: EU vs. Serbia

The comparative analysis highlights key differences in the legal and institutional frameworks of the EU and Serbia. While the EU enforces binding directives with clear recycling and waste reduction targets, Serbia relies on voluntary or partially harmonized policies. Table 1 summarizes the main areas of comparison.

Table 6:
Comparative Overview of EU and Serbian CE Framework

Aspect	EU Framework	Serbian Framework	Compliance Level
Waste Management	Directive 2008/98/EC	Law on Waste Management (2016)	Medium
Recycling Targets	EU 55% by 2025, 65% by 2035	No mandatory national targets	Low
Extended Producer Responsibility	Directive 94/62/EC	Partial implementation	Low
Public Awareness & Education	CEAP education programs	Limited educational initiatives	Medium

Serbia's path to EU alignment involves improving institutional capacity, strengthening inspection mechanisms, and increasing investment in recycling infrastructure. Collaboration between universities, industry, and government can accelerate innovation and adoption of digital technologies to enable sustainable manufacturing systems.

Implementing circular economy principles requires a holistic approach that combines technological innovation, regulatory adaptation, and cultural transformation [23]. ICT tools such as enterprise resource planning (ERP), Internet of Things (IoT), and artificial intelligence (AI) can support efficient material tracking, predictive maintenance, and energy optimization [24]. Moreover, integrating decision support systems can enhance data-based planning in production and logistics[25].

For Serbia, the digitalization of circular processes offers an opportunity to overcome structural challenges by improving transparency, reducing costs, and optimizing resource use. EU funds, such as IPA and Horizon Europe, can provide financial support for pilot projects focused on green technologies and digital transition[26].

Table 2:
CE Tools/Indicator Adoption Rates: Serbia vs. EU

Indicator	EU	Serbia
Circular Material Use Rate (share of recycled material in total material use)	~ 12.2% in 2024.	~ 1.7% in 2021.
Municipal Waste Recycling (or recovery)	EU-wide recycling rates are significantly higher; packaging-waste recycling targets are about 62%.	Recycling rate for municipal solid waste was only 15.5% in 2023.
CE Business Adoption (Construction / C&D Waste)	Many EU companies in the same sector generate more than 75% of their revenue from circular waste-management activities.	In a study of Serbian construction & demolition firms, 80% of companies earned < 10% of their revenue from waste management or recycling, indicating very low business integration of circular models.

These figures highlight a substantial gap between the EU and Serbia in the adoption of circular economy tools, indicating that Serbia requires stronger investment, improved infrastructure, and targeted business incentives to accelerate its transition toward a fully operational circular economy.

5. Conclusions

The transition toward a circular economy (CE) remains a central strategy for sustainable industrial development and environmental protection in both the European Union and Serbia. The EU has established a comprehensive policy and regulatory framework that combines innovation, digitalization,

and competitiveness, leading to moderate adoption of CE tools with relatively high recycling rates. In contrast, Serbia is still in the early stages of this transition.

Despite these challenges, Serbia is demonstrating emerging operational progress. Case studies from Serbian industry are adopting by-product reuse which illustrate that circular practices are taking root and provide practical benchmarks for broader adoption. The examples show that, although CE implementation remains fragmented, tangible improvements are already achievable at the company level.

The success of Serbia's transition depends not only on aligning legislation with EU standards but also on fostering industry readiness, institutional coordination, and societal engagement. Systemic change is required in product design, material sourcing, and value measurement, supported by digital tools, decision-making systems, and targeted investments. Strengthening infrastructure, promoting business incentives, and building capacity through education are essential to accelerate adoption.

Ultimately, the circular economy in Serbia is more than closing material loops, it represents a shift toward knowledge-driven innovation, sustainable value creation, and a culture where competitiveness and environmental responsibility coexist. By combining EU-aligned regulation with practical, industry-level implementation and strategic digitalization, Serbia can significantly accelerate its manufacturing transition to a circular, sustainable, and resilient industrial model.

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Transforming Human Resource Management: The Role of AI Technologies

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Abstract:
Artificial Intelligence (AI) is progressively being integrated into HRM practices across organizations, reshaping the way of managing employees. It is transforming the way work is being performed. The aim of this paper is to explore the possibilities of using AI in contemporary Human Resource Management practice, to investigate its role in HRM, as well as to highlight the need for managerial readiness in response to evolving labour market demands. The research methodology is based on secondary data sources, focusing primarily on reviewing the existing literature in this field. Research has found that AI has a significant impact on different HRM processes, such as planning, recruitment, selection, training, learning and development, talent management and retention etc. By automating routine administrative functions, AI allows HR professionals to focus on strategic priorities and people-centered initiatives. Since it enables HR managers to gain better insight into employee work, behaviour and feelings, by leveraging AI technologies, organizations can unlock the full potential of their workforce. When thoughtfully implemented, AI can streamline operations, enhance decision-making, and deliver personalized employee experiences—ultimately driving innovation and shaping a more sustainable and equitable future of work. The significance of this paper lies in its contribution to deepening the theoretical and practical understanding of the possibilities for AI application in HRM.
Keywords:
Human resource, employee, AI, artificial intelligence, recruitment, selection

1. Introduction

Every dimension of work is increasingly becoming dependent on technology. Automation is transforming the nature of work and the competencies it requires. Artificial Intelligence (AI) is transforming the way work is being performed and driving innovation across industries. Together with machine learning, AI has become integral to digital working environment. AI in business refers to intelligent systems that learn, react, and perform human-like tasks [1]. Using vast datasets, such as text, audio, images, video, and numbers, AI supports problem-solving and decision-making. It's dynamic, adapting through sensing, cognition, and action using a range of modern technologies.

Nowadays, AI and other AI-based technologies are used in different fields. One of them is human resource management (HRM). Businesses increasingly recognize that AI can replace human labor in many domains, enhancing accuracy, profitability, and operational efficiency. Current estimates suggest that approximately 50% of workplace tasks could be automated using existing digital and AI technologies [2]. With HRM evolving to a strategic driver of organizational success, addressing these issues becomes critical to sustaining competitive advantage and operational effectiveness.

Research has found that AI has a significant impact on different HRM processes [3], such as planning, recruitment, selection, training, learning and development, etc. The aim of this paper is to explore the possibilities of using AI in contemporary Human Resource Management practice as well as to investigate its application and role in different HRM processes. The research methodology is based on secondary data sources, focusing primarily on reviewing the existing literature in this field. The significance of this paper

lies in its contribution to deepening the theoretical and practical understanding of the possibilities for AI application in HRM.

2. Use of AI in specific HRM processes

AI is progressively being integrated into HRM practices across organizations, reshaping the way employees are being managed within organizations around the world. Over the past decade, AI tools have expanded within HRM [4]. With AI refining HRM processes growing complexity, the HR sector is undergoing digital transformation. AI technologies are changing how work is structured, enhancing resource use, decision-making, and problem-solving. However, theoretical backgrounds in this field are still underdeveloped [5].

In the field of HRM, AI is implemented with an aim to identify, critically evaluate, and replicate cognitive functions of a human and use the available data to derive meaningful insights that optimize human resource utilization in support of organizational goals and strategic objectives [6]. AI learns dynamically from input quality, shaping its decisions and performance. These capabilities are increasingly embedded in HRM tools and subfields, transforming how work and workforce interactions are managed.

A key strategic aim of integrating AI into HRM is to attract and prepare talent for emerging roles shaped by technological advancement. As AI continues to displace traditional job functions across industries, proactive workforce development becomes essential [7]. More and more, HR managers are relying on AI to design HR strategies to address employee well-being on one hand and organizational productivity, on the other hand [1], [4]. AI was found to have a positive impact on various HRM processes, such as:

- HR planning,
- recruitment and selection,
- onboarding,
- training,
- learning and development,
- managing employee performance,
- talent management,
- retention etc. [6], [8], [9], [10].

AI platforms enhance **HR planning** by identifying trends, forecasting turnover, and detecting skills gaps. These insights enable HR professionals to design workforce plans aligned with future organizational needs. By examining big datasets, finding patterns, and creating predictive analytics, AI empowers HR professionals to make knowledgeable, up-to date, data-based decisions [11]. This approach reinforces the HR-related decision quality and enables organizations to forecast future workforce needs and talent gaps in a timely and proactive manner [12].

AI was first adopted in **recruitment and selection** to enhance efficiency and accuracy of these processes. It now supports multiple stages of the recruitment and selection, including sourcing, screening, as well as interviewing applicants. One of key advantages of AI lies in streamlining routine tasks—such as resume screening and candidate sourcing—saving time and resources while enabling HR professionals to focus on higher-value strategic initiatives [13]. AI significantly advances recruitment and selection process, through automating repetitive tasks like screening applications submitted by the candidates [14]. AI-based Applicant Tracking Systems (ATS) match candidate profiles to job description and job specifications, while tools like ChatGPT assist recruiters with preparing job descriptions, detecting bias in job advertisements, defining the interview questions, and reading the candidate resumes.

AI simplifies and accelerates **onboarding process** by providing new employees responses to common inquiries [6]. Onboarding AI-assisted platforms generate an engaging employee experience by automating administrative tasks such as completing forms, sharing organizational policies and scheduling training

programs.

In addition, it is important to mention the role of AI in **learning and development**. AI provides personalized learning experience, facilitates learning and development process through creating automated content adapted to employee individual needs and preferences, predictive analytics and chatbot-based learning support.

AI-based platforms can be used for identifying leadership potential within organization. By leveraging employee data, AI permits employees to map out their personalized future **career paths** [6]. AI is assisting **talent management** and retention through data-driven approaches to employee performance, career development and succession planning.

Use of AI facilitates communication within organization through providing automatic responses to routine employee requests as well as generating different documents (job descriptions, different policies, employee handbooks etc.). AI provides the possibility for organizations to offer tailor-made employee experiences, from individual career paths to personalized feedback, increasing employee engagement and satisfaction.

3. Benefits of implementing AI in HRM

AI represents a major opportunity within the modern workplace. AI-assisted HRM is increasingly viewed as a strategic necessity for organizational survival and growth [5]. AI should enable enhance HR service delivery and user experience, standardize services to minimize inconsistencies, align HR with business strategy, improve responsiveness to changes, reduce costs and increase flexibility for both employees and the organization [1].

The benefits of implementing AI in human resource management activities are summarized in Table 1.

Table 7:
Benefits of implementing AI in HRM

HRM activity	Benefits
HR Planning	Skill gap analysis and forecasting turnover
	Predictive modelling for future skill needs
	Increased quality of HR decisions
Recruitment & Selection	Automated resume screening and candidate matching
	Reduced bias and faster hiring process
	Improved candidate experience
Onboarding	Personalized and engaging onboarding journey
	AI chatbots for answering common inquiries and guiding new employees
Learning & Development	Learning platforms tailored to individual needs
	Chatbot-based learning facilitates learning and development process
	Supports the design of individualized career pathways
Talent management	Facilitated talent forecasting and succession planning
	Facilitated identification of leadership potential

As mentioned previously, AI may enhance the efficiency of recruitment processes, improve employer brand, optimize recruitment strategies, increase the quality of the candidate pool, lessen bias, and improve the hiring experience for both managers and candidates, [3], [15]. AI supports HRM by automating routine administrative tasks, therefore enabling staff to focus on strategic responsibilities that require human expertise [3].

AI is transforming HRM by handling routine tasks quickly, efficiently and effectively. By digitalizing

routine administrative tasks, AI enables HR professionals to focus on strategic priorities within HRM processes.

The integration of AI with HRM is reducing the gap between people and ICT, providing new manners to increase productivity and efficiency. HR professionals are increasingly focusing on harmonizing labor-intensive and automatic tasks in order to generate a more user-friendly working environment. AI-assisted HR technologies offer different short-term and long-term benefits, increasing organizational performance and flexibility [16].

AI allows HR managers to gain better understanding into employee performance, behavior and emotional state [15]. By leveraging AI technologies, organizations can unlock the full potential of their workforce, driving innovation and sustained competitive advantage in today's evolving business environment.

The research has shown that AI represents a huge possibility for the development of HRM, rearranging administrative tasks and enabling a more strategic focus. While the benefits of integrating AI in HRM are highlighted, certain limitations of its implementation should be addressed. This transformation brings some ethical challenges that demand careful oversight [18]. HR directors must critically assess potential risks related to algorithmic bias, fairness, transparency [3], data privacy issues as well as the need for human oversight. AI should be managed responsibly in order to avoid the previously mentioned challenges. A more balanced outlook could reflect both the opportunities and challenges of AI implementation in HRM activities.

4. Conclusions

AI is reshaping the future of human resource management. The future of HRM is increasingly digital and virtual, with AI driving sustainable competitive advantage through enhanced human capital and Industry 4.0-aligned practices [17].

However, research in this field remains fragmented [5]. AI offers HRM advanced tools to modernize various HRM processes, including recruitment and selection, training and development, performance evaluation, talent retention etc. When thoughtfully implemented, AI can streamline operations, enhance decision-making, and deliver personalized employee experiences—ultimately driving innovation and shaping a more sustainable and equitable future of work.

If current trends persist, HR management will undergo substantial transformation, while future HR managers may be tasked with overseeing both human and artificial intelligence as integrated components of the workforce. To fully harness the potential of AI, organizations need a creative and adaptive HRM approach—one that embraces technological change while remaining grounded in human values [15].

This paper may assist HR professionals in preparing for AI-enabled HRM systems in the future [19]. However, the paper has some limitations. It is based on theoretical exploration rather than empirical study. In order to overcome these limitations, ffuture research may focus on investigating the perception of HR professionals with experience in using AI in HRM systems. Another option could focus on presenting specific case studies of organizations which implement these practices with an aim to assess outcomes and ethical considerations.

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The Role of Caching in Real-Time Systems – A Case Study: Application of Redis in Monitoring Economic Indicators

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Abstract:
The advancement of technology and the increasing reliance on real-time economic indicator monitoring systems highlight the need for rapid and reliable data processing. Eliminating latency and optimizing performance are essential for supporting effective economic decision-making. This paper investigates the role of caching in real-time systems, with a particular focus on Redis as a mechanism for improving performance and responsiveness. Using data retrieved from the World Bank API, the study conducts a comparative analysis of two models: one implementing Redis and one without it. The findings reveal significant improvements in response time and overall efficiency when caching is applied. From a methodological perspective, the research employs Python for implementation, Airflow for orchestration, and Power BI for visualization. Results indicate that Redis not only reduces system response time but also lowers server load, thereby enhancing system scalability and efficiency. The study contributes to the literature by providing empirical evidence on the effectiveness of caching, offering practical insights for the development of robust real-time monitoring systems in economics.

Keywords:
Caching, Redis, Real-Time Monitoring Systems, API Calls, Data Visualization.

1. Introduction

Real-time systems do not allow for "delayed" interactions, as they must deliver results and output to users in the shortest possible time. Latency in video streaming, online gaming, real-time display of data values, or live results can significantly degrade the user experience. Therefore, effective data handling while ensuring speed, high performance, and accuracy is essential for creating modern responsive systems. By storing copies of frequently accessed data close to users, reducing the load on databases or data warehouses, and minimizing data retrieval times, caching plays a key role in system design, making systems more scalable, faster, efficient, and precise in delivering user output. Whether implemented on the client or server side, caching enhances the user experience by significantly reducing system response time and the need for constant server access.

Consequently, this study investigates the role and significance of caching in real-time systems through an analysis of Redis implementation in economic key indicator monitoring systems. Due to the nature of such systems and the continuous need to process large volumes of real-time data, techniques and methods are required to accelerate processes, reduce data traffic and server load, and simultaneously maximize resource utilization, efficiency, speed, and scalability. This paper emphasizes caching as a mechanism that minimizes the need for repeated data retrieval from databases and complex resource-intensive computations by storing copies of frequently accessed data in temporary locations for rapid user access.

Specifically, the research examines the effects of caching on data extraction, cleaning, transformation, and loading (ECTL) processes in real-time economic monitoring systems by analyzing execution time, API call frequency, and visual data representation. The underlying hypothesis is that Redis caching significantly improves and optimizes real-time systems, particularly monitoring systems, by accelerating and enhancing ECTL processes. Accordingly, the dissertation is structured into five sections. The first section provides a detailed review of existing scholarly research, analyses, practices, and professional literature on the topic. The second section outlines the methodological framework

applied in this study. The third section presents the research results, while the fourth section discusses and compares these findings with existing scientific contributions. The final section summarizes the conclusions drawn from the results and offers recommendations for further research.

2. Literature Review

In the era of modern technologies, where large volumes of real-time data are processed, caching increasingly becomes an indispensable concept in the design of contemporary systems. As noted by Mao et al., caching is employed to improve system performance by reducing data latency due to access times and decreasing server-side load, while simultaneously providing "fresh" data through the definition of an optimal Time To Live (TTL) for cached data before it is replaced with new data [1]. According to Génèrès, Lauer & Fabre [2], even minor errors in real-time systems can lead to delayed delivery of relevant data or results to users. Therefore, caching not only optimizes processes but also ensures that accurate and relevant data is delivered.

To achieve optimal caching, it is necessary to evaluate data "popularity," i.e., how frequently data is accessed, as well as the dynamics of its refresh [3]. Researchers investigating latency reduction strategies and response time improvement in such systems emphasize the importance of awareness regarding data popularity and user behavior through access trend analysis to minimize delays and server load [4]. Aydın & Kekevi [5] highlight that in systems handling large volumes of real-time data, such as monitoring systems, efficient extraction, cleaning, transformation, storage, and analysis are crucial for delivering timely and valuable insights.

Although numerous caching technologies exist with differences in structure, operational characteristics, and performance across applications, many authors underscore the importance of Redis in caching. According to some studies, the extensive capabilities and high performance of Redis provide response times in milliseconds and support millions of requests per second, making it suitable for real-time operations such as monitoring and analytics, media streaming, instant messaging, and gaming [6]. Others note that Redis's advanced functionalities, high scalability, and flexibility stem from its layered architecture, which groups data and prioritizes it based on access frequency [7].

Comparative analyses with Memcached—the second most commonly used caching tool—by two research groups led by Faridi (using machine learning) and Almeida, respectively, indicate that Redis outperforms in terms of data structure flexibility, response speed, and clustering capabilities, making it suitable not only for databases but also for data warehouses [8] [9]. Kanthed [10] demonstrates that these features make Redis the preferred choice for complex caching, monitoring and analytics systems, session management, and data storage. Previous research and implementations further indicate that Redis enables high concurrency, availability, and speed in applications such as high-speed railway monitoring systems [11] and optimizes resource utilization while significantly reducing transaction processing and response times in online order processing systems for restaurants serving over 15,000 users daily [12].

Given its wide range of applications and significant benefits, this study focuses on caching techniques in real-time data systems by analyzing the role and importance of Redis in economic indicator monitoring systems.

3. Methodology

The focus of this research is the role and impact of caching on the performance and responsiveness of real-time data processing systems, with particular emphasis on economic indicator monitoring systems. The aim of the study is to demonstrate the positive impact of caching on real-time systems, making them more efficient, powerful, and faster as a result of reduced data handling time. The main research problem concerns the investigation of the effects of caching using Redis on the ECTL processes within real-time economic monitoring systems, including their execution time, API call frequency, and visual data representation, all directed towards testing the stated hypotheses. The primary hypothesis posits that Redis caching enhances real-time systems, particularly monitoring

systems, by increasing the speed and efficiency of ECTL processes. The second hypothesis aims to demonstrate that caching reduces both the number and response time of frequent API calls, thereby improving system responsiveness. The final hypothesis suggests that caching large volumes of complex data significantly improves visual representations, which are part of dashboards and user perception. For this study, secondary data from official sources—the World Bank Group—were utilized, covering various economic indicators, countries, and time periods, and stored in JSON format [13]. Specifically, using the Python programming language, a workflow implementing ECTL processes was developed and executed in two modes: without and with caching. One of the most widely used caching systems, Redis, was employed for storing and caching NoSQL key-value data to highlight its importance in real-time systems. Task execution and process monitoring were managed using the Apache Airflow platform. Primary data were also collected by measuring ECTL execution times and API response times in both operational modes. Through repeated ECTL experiments with and without caching, data suitable for performance comparison and evaluation were obtained.

A framework was implemented to automate extraction, transformation, and loading processes, measure key performance indicators, and store results in CSV format. Real-time economic monitoring systems were based on visualizations integrated into dashboards for monitoring and analysis. Statistical analyses were conducted on execution results with and without caching, along with evaluations of responsiveness and perceptions of the generated visualizations.

The real-time monitoring system comprised the following components:

- **API Data Source:** Publicly available World Bank API providing economic indicator values;
- **Data Storage:** Data stored in a PostgreSQL database;
- **Caching Layer:** Implemented using Redis (key-value based), representing a core part of the study;
- **Process Orchestration:** Processes integrated and synchronized using Apache Airflow for ECTL control and monitoring;
- **Dashboard and Analysis:** Operated in Power BI, providing the primary system functionality.

4. Results and discussion

For the purposes of this research, and following the example of the market monitoring system by Eddelbuettel [14], a real-time economic indicators monitoring system was implemented. While Eddelbuettel [14] focuses on specific approaches for integrating caching with Redis within his system using the R programming language, the present study aimed to analyze the impact of Redis caching within an economic monitoring system, utilizing Python due to its extensive library support and robust data processing capabilities. Unlike his system, which is limited to financial data, the system examined here processes various types of economic data (economic indicators). PostgreSQL was used as the data warehouse, Apache Airflow for orchestrating ETL processes, and Power BI for the visualization underpinning the monitoring system.

The system was evaluated in two modes—without and with Redis caching—to compare performance and assess the hypotheses. The practical implementation of this research can be divided into several steps:

1. **Data extraction, cleaning, transformation, and loading (ECTL):** Data on various economic indicators (e.g., GDP, unemployment rate, inflation, import and export of goods and services as a percentage of GDP, foreign direct investment, and other publicly available reports) were extracted via API calls to the World Bank (World Bank Group). The data were then cleaned by removing unnecessary entries, transformed through proper formatting and parsing, and loaded into the PostgreSQL data warehouse. This step was executed both with and without Redis caching, repeating the procedure multiple times:
   1.1. **Without caching:** Data were retrieved directly from the World Bank API, cleaned, transformed, and loaded into the warehouse each time.
   1.2 **With caching:** Instead of querying the World Bank server, the Redis server stored copies of the cleaned and formatted data, making them immediately available for subsequent processing steps. **Data storage:** Processed data were stored in the PostgreSQL data warehouse. In the caching layer implemented with Redis, a key-value copy of the

data was maintained to enable faster access.

2. **Process orchestration:** Since the monitoring system relies on multiple processes, these were synchronized and monitored using Apache Airflow, ensuring precise workflow control.
3. **Indicator visualization:** At the core of the system is the visualization implemented in Power BI, providing an interactive dashboard that enables intuitive real-time monitoring of indicator values.

All workflows were executed in both modes (with and without caching) through repeated testing, and results were saved in a separate CSV file for further analysis to determine the impact of caching on this type of system.

A specific example of testing the system without caching involved executing Python scripts defining the ECTL processes. The main workflow script was invoked with the operation mode set as an input argument (in this case, without_cache).

```
=== DOCS ETL BENCHMARK START (WITHOUT_CACHE) ===
-- Step 1: Fetch & Cache
Step 1 time:   131.88s
Fetch phase: Redis hits:   0
Fetch phase: Redis misses: 100
Fetch phase: Hit ratio:    0.00%

-- Step 2: Transform & Load
Step 2 time:   0.43s

Total ETL time: 132.31s
=== DOCS ETL BENCHMARK END ===


=== INDICATORS ETL BENCHMARK START (WITHOUT_CACHE) ===
[CACHE MISS] wb:MK:NY.GDP.MKTP.CD — fetching from WB API
[CACHE MISS] wb:MK:SL.UEM.TOTL.ZS — fetching from WB API
[CACHE MISS] wb:MK:FP.CPI.TOTL.ZG — fetching from WB API
[CACHE MISS] wb:MK:SP.POP.TOTL — fetching from WB API
[CACHE MISS] wb:MK:NE.EXP.GNFS.ZS — fetching from WB API
[CACHE MISS] wb:MK:NE.IMP.GNFS.ZS — fetching from WB API
[CACHE MISS] wb:MK:BX.KLT.DINV.WD.GD.ZS — fetching from WB API
[CACHE MISS] wb:MK:DT.ODA.ODAT.GN.ZS — fetching from WB API
[CACHE MISS] wb:MK:GC.TAX.TOTL.GD.ZS — fetching from WB API
[CACHE MISS] wb:MK:GC.XPN.TOTL.GD.ZS — fetching from WB API
-- Step 1: Fetch & Cache
Step 1 time:   4.01s
Fetch phase: Redis hits:   0
Fetch phase: Redis misses: 10
Fetch phase: Hit ratio:    0.00%

-- Step 2: Transform & Load
Step 2 time:   0.81s

Total ETL time: 4.82s
=== INDICATORS ETL BENCHMARK END ===
```

Figure 1: Execution of ECTL Processes Without Caching

Figure 1 presents the logs from the execution of the respective processes without caching. It can be observed that during the extraction, cleaning, transformation, and loading (ECTL) of the data related to the economic indicator reports, there is no interaction with Redis—Redis hits are 0, Redis misses are 100, and the hit ratio is 0%, indicating that all requests are made directly to the data warehouse. The total processing time for the report data in this particular test amounts to 131.88 seconds. Similarly, for the indicator data, API calls are made directly to the data warehouse, which takes 4.82 seconds in total. Each time the data is accessed, a direct API call to the World Bank is performed, resulting in repeated loading and transformation. The execution of these processes is monitored using Airflow:

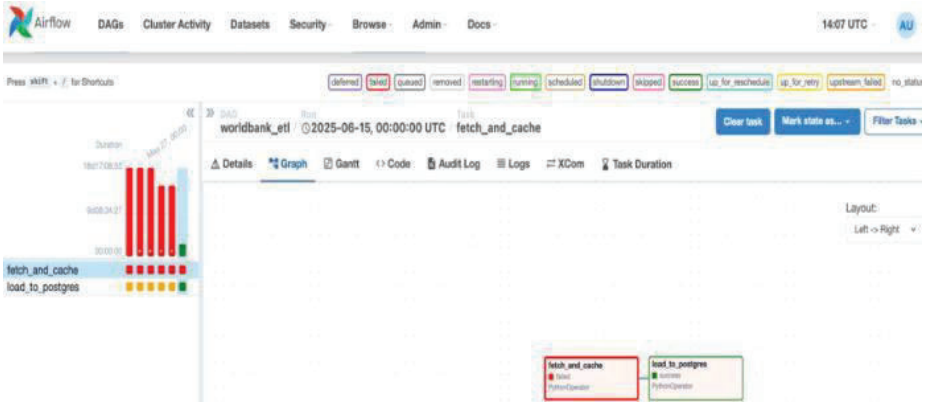


Figure 2: Orchestration of Processes with Airflow

As shown in Figure 2, the workflow consists of two processes – one for loading and caching, and

the other for storing data in the PostgreSQL database. These processes communicate with each other depending on which operational mode is active at the moment. The active process – storing in PostgreSQL – is highlighted in green, while the inactive process is shown in red.

Once the data is properly loaded, it can be visualized to allow real-time tracking of changes over time. For this purpose, an interactive dashboard was implemented in Power BI, featuring several types of visualizations as illustrated in Figure 3.

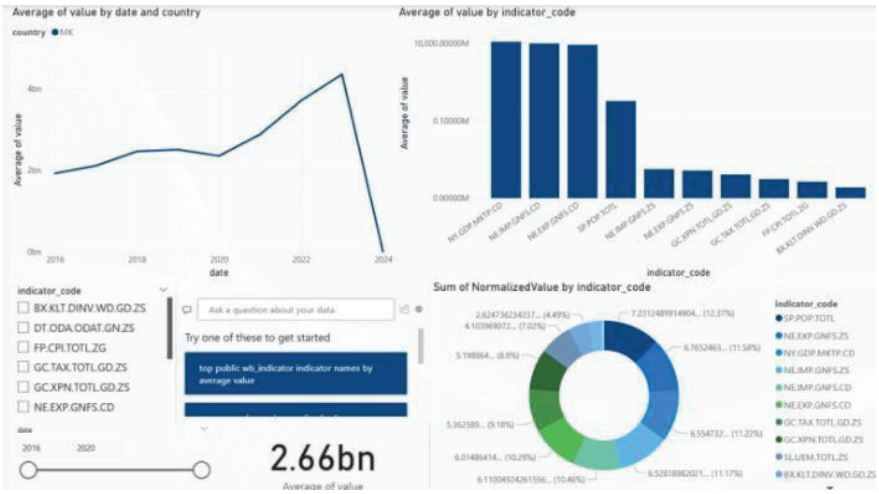


Figure 3: Real-Time Monitoring of Economic Indicators with Power BI

The monitoring system in real time includes line charts, bar charts, and pie charts to track trends in economic parameters, cards or metrics for Key Performance Indicators (KPIs), a Q&A section, as well as segmented filters by year and indicator (Slicers) (Figure 3). When the system operated without caching, the visualizations experienced delayed refresh and interaction, particularly when resetting filters.

The same workflow principle applies when the system operates with caching, with the ECTL scripts executed using the argument with_cache. An example of testing with Redis caching yielded the following results:

```
=== DOCS ETL BENCHMARK START (WITH_CACHE) ===
[CACHE HIT] wb:gdp:100
-- Step 1: Fetch & Cache
Step 1 time:    0.03s
Fetch phase: Redis hits:    1
Fetch phase: Redis misses: 0
Fetch phase: Hit ratio:     100.00%

-- Step 2: Transform & Load
Step 2 time:    0.35s

Total ETL time: 0.38s
=== DOCS ETL BENCHMARK END ===


=== INDICATORS ETL BENCHMARK START (WITH_CACHE) ===
[CACHE HIT] wb:MK:NY.GDP.MKTP.CD
[CACHE HIT] wb:MK:SL.UEM.TOTL.ZS
[CACHE HIT] wb:MK:FP.CPI.TOTL.ZG
[CACHE HIT] wb:MK:SP.POP.TOTL
[CACHE HIT] wb:MK:NE.EXP.GNFS.ZS
[CACHE HIT] wb:MK:NE.IMP.GNFS.ZS
[CACHE HIT] wb:MK:BX.KLT.DINV.WD.GD.ZS
[CACHE HIT] wb:MK:DT.ODA.ODAT.GN.ZS
[CACHE HIT] wb:MK:GC.TAX.TOTL.GD.ZS
[CACHE HIT] wb:MK:GC.XPN.TOTL.GD.ZS
-- Step 1: Fetch & Cache
Step 1 time:    0.01s
Fetch phase: Redis hits:    10
Fetch phase: Redis misses: 0
Fetch phase: Hit ratio:     100.00%

-- Step 2: Transform & Load
Step 2 time:    0.21s

Total ETL time: 0.22s
=== INDICATORS ETL BENCHMARK END ===
```

Figure 4: Execution of ECTL Processes with Caching

Figure 4 illustrates that when the system operates integrated with Redis, which stores copies of the most frequently accessed data, the processes handling report data take only 0.38 seconds (380

milliseconds), while the indicator data processes take 0.22 seconds (220 milliseconds). During this execution, the number of Redis hits was 100, and misses were 0, resulting in a 100% hit ratio. In a single test, caching the economic report data made this process approximately 347 times faster (131.88 / 0.38 ≈ 347), and caching the indicator data accelerated their processing 22 times (4.82 / 0.22 ≈ 22). Moreover, the data were retrieved directly from the Redis cache without sending any requests to the World Bank API, allowing visualizations to refresh without noticeable delay.

To obtain more robust results, multiple tests were conducted in both modes of operation, producing the following outcomes:

Table 1:
Execution Time With and Without Caching

Process Type	Average Time Without Caching	Average Time With Caching	Improvement
Reports	129.21 seconds	0.47 seconds	274×
Indicators	4.61 seconds	0.25 seconds	18×

Table 1 demonstrates that when the real-time economic indicator monitoring system employs Redis caching, it takes on average 0.47 seconds (470 milliseconds) to extract, clean, transform, and process the report data, and only 0.25 seconds (250 milliseconds) for indicator data. This represents an improvement in system speed by 274 and 18 times, respectively. In the context of the importance of fast data processing for improving real-time system performance, as highlighted by Kekevi & Aydin [5], these findings strongly support the first hypothesis: Redis caching enhances real-time systems, particularly monitoring systems, by accelerating and increasing the efficiency of ETL processes, making them more resilient to load.

Regarding API calls and response time, it was determined that without caching, approximately 124 API requests were made with an average response time of 834 milliseconds (8.34 seconds), whereas with caching, only 11 API requests were required with an average response time of about 57 milliseconds (0.57 seconds):

Table 2:
Number of API Calls and Average Response Time

Metric	Without Caching	With Caching	Difference
Number of API Calls Average	124	11	91% reduction
Response Time (ms)	834 ms	57 ms	14.6× improvement

These results (Table 2) confirm the findings of Faridi et al. (2023) regarding the convenience and adaptability of Redis when working with data stores and its ability to minimize unnecessary API requests. In this case, caching reduced API calls by 91%, significantly decreasing the average response time by 14.6 times, thereby validating the second hypothesis: Redis reduces API calls and improves system responsiveness.

The analysis of the interactive Power BI dashboard showed the following:

Table 3:
Power BI Dashboard Analysis

Metric	Without Caching	With Caching	Difference
Refresh Time	6.8 seconds	0.7 seconds	90% faster
Rendering of Visuals, Filters, and KPI Cards	Delayed	Instant	Significant UX improvement

Importantly, as highlighted by Mao et al. [1], minimizing data latency is critical, while Génèrès, Lauer & Fabre [2] emphasize that untimely delivery of key data reduces the accuracy and functionality of real-time systems, directly impacting the user experience. The implementation results (Table 3) llustrate this effect: without caching, the dashboard refreshes in 6.8 seconds, resulting in delayed rendering of visual elements. In contrast, Redis caching reduces refresh time by 90% (to 0.7 seconds), enabling instantaneous rendering. Accordingly, the third hypothesis is validated: caching is a key mechanism for fast and efficient rendering of visual representations, enhancing accuracy, interactivity, and user experience quality in real-time systems.

5. Conclusion

The findings of this study indicate that caching, particularly through the deployment of Redis, constitutes a fundamental mechanism for the enhancement of real-time systems, with pronounced effects on monitoring infrastructures, by substantially improving operational efficiency, responsiveness, and overall user experience. A comparative performance analysis of the system operating with and without Redis caching demonstrated that ETL execution times, the frequency of API requests, and response latency are markedly reduced, thereby ensuring elevated processing speed, system stability, and intuitive usability.

The empirical results reveal substantial performance gains: extraction, cleaning, transformation, and loading of economic report data were accelerated by a factor of 274, while processing of economic indicators was expedited by 18-fold; API requests decreased by 91%, and dashboard refresh rates improved by 90%. These outcomes substantiate the primary hypothesis and underscore caching as an indispensable component of contemporary real-time systems. By enabling rapid and seamless access to data, minimizing latency, and maximizing operational throughput, Redis caching facilitates the construction of robust systems capable of handling large-scale, real-time datasets across diverse domains, including economics, healthcare, and public administration.

Furthermore, the integration of process orchestration tools, exemplified by Apache Airflow, alongside visualization platforms such as Power BI, demonstrates that caching operates not in isolation but as part of a comprehensive ecosystem that efficiently processes and visualizes real-time data to support informed decision-making.

Future research should investigate strategies for dynamic cache refreshing, the implementation of caching in Big Data environments, and the utilization of artificial intelligence—particularly machine learning—to anticipate data “popularity,” thereby enabling more efficient and optimized caching mechanisms tailored to real-time operational demands.

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A Comparative Methodological Framework for Semantic Enrichment of Time Series Forecasting: Beyond the Balkans Case Study

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Abstract:
This research introduces a robust methodological framework that builds upon and extends our prior investigations into knowledge extraction from time series data within the broader context of digital transformation. Using the Balkans as a case study, we employ a comparative methodological design to evaluate diverse forecasting techniques—VAR, ARIMA, LSTM, and Prophet—integrated with semantic enrichment strategies. The proposed framework seeks to address critical methodological gaps in interdisciplinary research that bridges machine learning, econometric modeling, and semantic technologies. By systematically comparing ontology engineering approaches and assessing semantic enrichment methodologies, we develop a generalizable decision-support framework tailored for researchers engaged in knowledge extraction from time series data. Our findings demonstrate that semantic enrichment significantly enhances interpretability while maintaining forecasting accuracy across different methodologies. Consequently, this study establishes methodological standards and transferable guidelines that can inform and advance future interdisciplinary research in this domain.

Keywords:
Research Methodology, Time Series Forecasting, Semantic Enrichment, Knowledge Extraction, Ontology Engineering, Comparative Analysis.

1. Introduction

Building on earlier works — "Extracting Knowledge from Time Series Data: Digital Trends in the Balkans" [1] and "Digitalization of the Balkan Countries Before and After Covid-19" [2] — which combined Vector Autoregression (VAR), k-means clustering, and semantic enrichment via knowledge graphs, this study extends the framework by addressing its methodological limitations. The integration of econometric forecasting with semantic technologies presents challenges in balancing interpretability, theoretical rigor, and methodological precision. To resolve these tensions, the present research introduces a comparative framework that aligns quantitative accuracy with semantic depth, strengthening interdisciplinary analysis of time series data. Specifically, the study aims to:

1. Compare VAR, ARIMA, LSTM, and Prophet models when integrated with semantic enrichment techniques.
2. Evaluate ontology engineering approaches (UPON Lite, NeOn, Methontology) based on criteria including development time, domain coverage, formal rigor, usability, ecosystem support, and capacity to enhance semantic knowledge extraction.
3. Develop a hybrid decision-support framework linking data characteristics and research goals to optimal model–enrichment combinations.
4. Assess transferability across domains and regions, identifying adaptation requirements tied to data quality and availability.

Through this integrated design, the study advances a refined methodological foundation for interdisciplinary research in time series forecasting and knowledge extraction

2. Literature Review

Econometric modeling based on Vector Autoregression (VAR) has advanced through improvements in lag selection, structural identification, and extensions to multidimensional systems, with factor-based approaches proposed to address dimensionality challenges [2] [3]. Similarly, ARIMA models remain relevant due to enhancements in automatic selection algorithms and integration with machine learning, as demonstrated in large-scale forecasting competitions [4] [5].

Deep learning approaches such as LSTM and N-BEATS efficiently capture complex temporal dependencies, maintaining interpretability while outperforming traditional models [6] [7]. Prophet has also proven robust in non-stationary environments and effective across diverse forecasting scenarios [8] [9].

In ontology engineering, agile methodologies such as UPON Lite, NeOn, and OOPS! emphasize accessibility, collaboration, and quality assessment, advancing beyond conventional frameworks [10] [11] [12]. Closely related, knowledge graphs—particularly temporal ones—play a central role in linking data to meaning, with advances in embeddings, time-aware reasoning, and graph neural networks improving predictive capacity [13] [14] [15] [16].

Hybrid approaches combining statistical and machine learning models highlight the complementary strengths of these paradigms, underscored by forecasting competitions and subsequent studies. Key contributions include hybrid exponential smoothing with neural networks, guidelines for rigorous validation, and integration of domain knowledge and semantic features to enhance both accuracy and interpretability [17] [18] [19] [20] [21] [22].

Recent econometric developments address structural breaks and mixed-frequency challenges through regime-switching, TVP-VAR, and MF-VAR models, allowing adaptation to shifting economic conditions and effective incorporation of high-frequency data [13] [13] [23] [22]. Finally, interpretability in predictive modeling has become increasingly emphasized, with SHAP and related frameworks providing robust methods for explaining machine learning outcomes in time-series contexts [24] [25].

3. Materials and Methods

This study focuses on comparative methodologies for time series forecasting and semantic enrichment in knowledge extraction. It examines the performance of forecasting models (VAR, ARIMA, LSTM, Prophet) combined with semantic techniques to identify optimal configurations for interdisciplinary research. A quantitative comparative approach was applied, integrating statistical and machine learning methods on digital indicators to ensure forecasting accuracy, while qualitative evaluation addressed interpretability and theoretical consistency through expert assessment.

1. Data Split and Validation: A rolling-origin evaluation with an 80/20 chronological split at the country–indicator level, repeated across horizons to reduce variance.
2. Accuracy Metrics: RMSE, MAE, and MAPE computed per series and aggregated via macro-averages.
3. Computational Efficiency: Training and prediction times measured on identical hardware, with median values across repetitions reported.
4. Interpretability Score: Evaluated on a 10-point rubric by two experts (Cohen's κ reported), covering model transparency (0–4), driver attribution (0–3), and theoretical consistency (0–3).
5. Statistical Testing: Paired t-tests with Bonferroni correction and Cohen's d for effect size; normality checked via Shapiro–Wilk, with Wilcoxon tests used when violated
6. Ontology Assessment Criteria: Ontology-based approaches were evaluated according to: (i) development time to first usable prototype, (ii) domain coverage (percentage of competency questions satisfied), (iii) formal rigor (consistency and reasoning support), (iv) usability for non-ontologists (System Usability Scale, SUS, score), and (v) ecosystem and tooling support. In addition, the ontology engineering assessment focused on examining the effectiveness of different ontology engineering approaches in supporting semantic knowledge extraction and enhancing data interpretability, ensuring that the resulting ontologies provide transparent, consistent, and reusable representations of the domain.

Furthermore, the interdisciplinary nature of the study allows for a statistical comparison of forecasting accuracy and relevance, simultaneously contrasting the performance of the applied methodologies. For this purpose, secondary data have been utilized from the World Bank Group [27] and the UN E-Government Knowledgebase [28], covering several indicators of the digitalization process:

1. E-Participation Index – measures citizen engagement in governmental digital processes,
2. E-Government Index – assesses government capacity to deliver digital services,
3. Online Service Index – indicates the quality and accessibility of governmental online services,
4. Human Capital Index – measures digital literacy and IT skills of the population,
5. Telecommunications Infrastructure Index – evaluates the development of ICT infrastructure.

The dataset spans a period of ten years (2014–2024) and includes several Balkan countries: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Montenegro, North Macedonia, Serbia, and Slovenia. The implementation of the study is structured in several phases:

1. Data preparation and preprocessing: Time series data from the World Bank and UN E-Government Knowledgebase were normalized (0–1) for comparability. Missing values were imputed using Multiple Imputation by Chained Equations (MICE) as the main method, supported by KNN and forward/backward filling. Min–max normalization was applied per indicator, and sensitivity analysis showed <2% variation in accuracy metrics.
2. Stationarity testing: Augmented Dickey-Fuller (ADF) and KPSS tests are employed to assess stationarity. In cases of non-stationarity, first-order differencing is applied, followed by repeated testing.
3. Application of forecasting models: Four forecasting models are selected for comparative evaluation:
   a. VAR (Vector Autoregression): capable of analyzing multiple complex indicators and their interdependencies, with optimal lag order determined by AIC and BIC criteria,
   b. ARIMA (Autoregressive Integrated Moving Average): optimized via AIC and BIC criteria to balance accuracy and parsimony,
   c. LSTM (Long Short-Term Memory): a deep neural network composed of multiple hidden layers trained on historical sequences to capture complex nonlinear dependencies,
   d. Prophet: designed for automatic trend detection in the presence of disruptions and incomplete data.
4. Semantic enrichment and knowledge extraction: To enhance interpretability of forecasting results, semantic models are incorporated through three ontology engineering methodologies: UPON Lite (rapid implementation with domain expert support), NeOn (collaborative and formally oriented), and Methontology (structured with conceptual clarity). These methodologies are used to construct a knowledge graph, representing indicators, countries, and their trends as entities linked by temporal relations.
5. Evaluation and comparative analysis: Forecasting accuracy is assessed using Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE). Computational efficiency is evaluated by measuring training and prediction time. Statistical robustness is validated using t-tests with Bonferroni correction, along with the calculation of 95% confidence intervals.

This framework thus provides a systematic approach for selecting the optimal methodological combination, ensuring greater statistical reliability and practical applicability across other regions and domains.

4. Results

The empirical evaluation conducted within this study offers a comprehensive comparative analysis

of forecasting methodologies, semantic enrichment approaches, and integration protocols. This section presents the results in a systematic manner, with a particular emphasis on both quantitative accuracy measures and qualitative interpretability dimensions. The following subsections highlight performance differences, semantic enhancements, and cross-domain transferability, while integrating figures and tables to contextualize the findings.

The forecasting performance of the VAR, ARIMA, LSTM, and Prophet models was evaluated using a dataset drawn from regional economic indicators in the Balkans. The results highlight clear trade-offs between accuracy, interpretability, and computational efficiency. Table 1 provides an overview of key performance metrics, while subsequent figures illustrate the forecasting trajectories.

Table 1:

Comparative forecasting accuracy across methodologies

Methodology	RMSE	MAE	MAPE	Interpretability Score
VAR	0.023	0.018	4.2%	9/10
ARIMA	0.031	0.024	5.1%	8/10
LSTM	0.019	0.015	3.8%	4/10
Prophet	0.026	0.020	4.5%	7/10

Source: Authors' calculation

As demonstrated in Table 1, the LSTM network achieved the lowest RMSE and MAE values, confirming its superior raw predictive accuracy. However, its interpretability score was markedly lower compared to traditional statistical models. In contrast, the VAR model provided a balanced trade-off, combining high interpretability with competitive accuracy. The Prophet model offered robustness across heterogeneous time series patterns, while ARIMA excelled in contexts dominated by univariate dynamics.

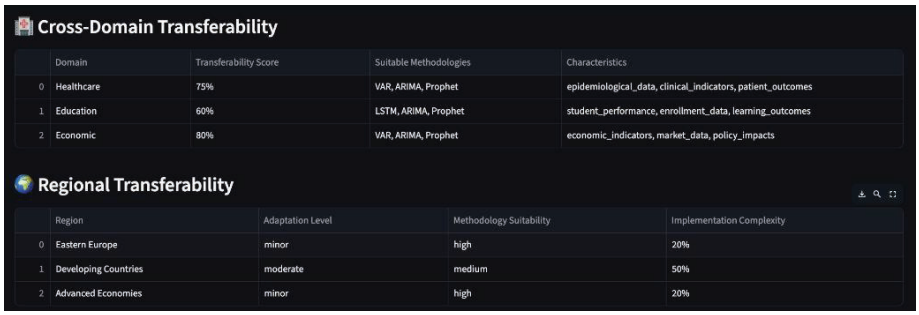


Figure 1. Forecasting trajectories for different methodologies.

Figure 1 illustrates that while deep learning methods capture intricate nonlinearities, classical approaches remain valuable due to their transparency and theoretical grounding. These results emphasize that methodological selection should depend not solely on accuracy, but also on interpretability and contextual requirements.

To evaluate the added value of semantic enrichment, we assessed how interpretability and knowledge integration were enhanced when ontological approaches were applied. Table 2 compares interpretability scores before and after semantic enrichment, revealing consistent improvements across all methodologies.

Table 2:

Improvements in interpretability through semantic enrichment.

Methodology	Baseline Interpretability	With Enrichment	Improvement
VAR	7/10	9/10	+29%
ARIMA	6/10	8/10	+33%
LSTM	2/10	6/10	+200%
Prophet	5/10	8/10	+60%

Source: Authors' calculation

The results underscore the transformative role of semantic enrichment, particularly for black-box methodologies such as LSTM, where interpretability improvements were most pronounced. Ontology-driven contextualization enabled a more nuanced understanding of the models' outputs, bridging the gap between computational efficiency and policy relevance.

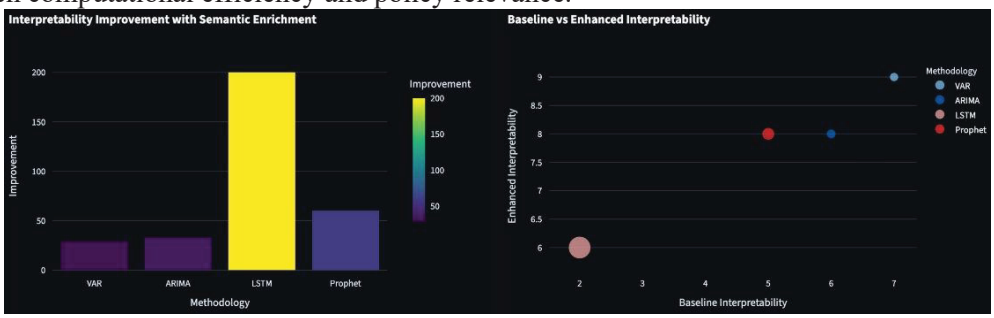


Figure 2. Semantic enrichment workflow applied in the experimental setup.

Figure 2 depicts the semantic enrichment workflow, illustrating how domain-specific ontologies were employed to formalize and contextualize forecast results. This integration not only improved interpretability but also supported the construction of knowledge graphs capable of capturing domain relationships.

The evaluation of ontology engineering methodologies further demonstrated that lightweight approaches such as UPON Lite yielded significant efficiency gains, without compromising usability or compliance with schema requirements. Table 3 summarizes the comparative assessment of three methodologies.

Table 3:

Comparative ontology engineering assessment.

Approach	Development Time	Domain Coverage	Formal Rigor	Usability
UPON Lite	Fast (2 days)	85%	Medium	High
NeOn	Slow (2 weeks)	95%	High	Low
Methontology	Medium (1 week)	90%	High	Medium

Source: Authors' calculation



Figure 3. Ontology engineering methodology application.

Figure 3 illustrates the practical application of ontology methodologies, confirming that UPON Lite offered a unique advantage in terms of rapid prototyping and accessibility for domain experts. While NeOn excelled in formal rigor, its steep learning curve limited practical uptake. Methontology provided a balanced alternative, but its tooling limitations constrained broader applicability.

Beyond individual methodological evaluations, the framework was assessed for its adaptability across domains and regions. Cross-domain results demonstrated that healthcare, education, and economics each benefited from different methodological strengths. For instance, LSTM was highly effective in educational forecasting, while VAR retained theoretical robustness in economic contexts.

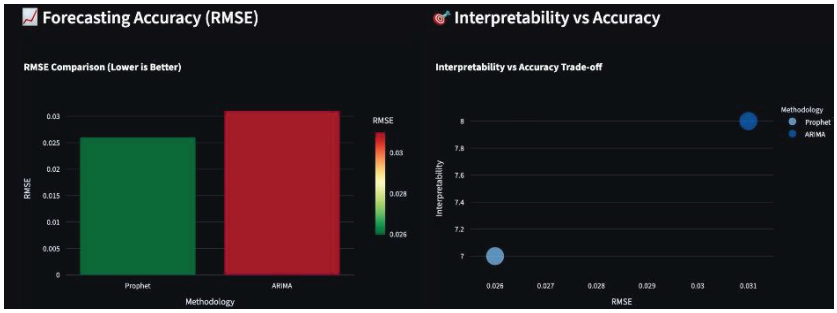


Figure 4. Cross-domain transferability of the proposed framework.

Figure 4 demonstrates the framework's versatility, where methodological selection was adapted to domain-specific requirements. Similarly, regional transferability confirmed applicability in Eastern Europe, advanced economies, and developing countries, albeit with varying adjustments to data quality and availability.

Semantic Enrichment Impact Assessment

Impact of semantic enrichment on interpretability across methodologies

	Methodology	Baseline Interpretability	Enhanced Interpretability	Improvement
0	VAR	7/10	9/10	29%
1	ARIMA	6/10	8/10	33%
2	LSTM	2/10	6/10	200%
3	Prophet	5/10	8/10	60%

Figure 5. Regional adaptation of forecasting and enrichment methodologies.

In conclusion, the results of this comprehensive evaluation provide strong evidence that methodological selection should be guided not solely by accuracy metrics, but also by interpretability, semantic enrichment potential, and cross-domain adaptability. The findings underscore that hybrid approaches, underpinned by semantic formalization, represent a critical pathway toward more transparent, context-aware, and transferable forecasting systems.

Overall, the presented results reaffirm the necessity of integrating methodological rigor with semantic formalization, thereby ensuring that forecasting models evolve beyond numerical accuracy to embody interpretability, transferability, and policy relevance—criteria that will define the next generation of computational social science.

5. Discussion

This study demonstrates that integrating forecasting methodologies with semantic enrichment substantially improves model interpretability while maintaining high predictive accuracy. The VAR + UPON Lite combination emerged as the most effective, balancing transparency and forecasting performance, whereas LSTM and Prophet provide advantages for capturing nonlinear and seasonal patterns. These findings highlight the importance of selecting methodologies aligned with data characteristics and research objectives.

Ontology engineering approaches further influence outcomes: UPON Lite offers rapid development and high usability for domain experts, while NeOn and Methontology provide formal rigor at the cost of complexity. This suggests potential for hybrid strategies that combine strengths across methodologies.

Despite its promising results, the study has certain limitations. Model performance depends on data quality and the computational demands of hybrid approaches, which may restrict scalability. Moreover, the absence of standardized evaluation metrics for semantic enrichment can hinder objective comparison across domains. Future work should address these challenges by exploring automated data quality assessment, lightweight optimization methods, and establishing shared benchmarks for reproducibility.

Overall, the proposed framework provides both theoretical and practical contributions, enhancing the applicability of forecasting and semantic technologies across multiple knowledge domains.

6. Conclusion

This study proposes an integrated framework for systematically comparing forecasting methods with semantic enrichment. The analysis of VAR, ARIMA, LSTM, and Prophet shows that semantic integration substantially improves interpretability and applicability, with gains between 29% and 200%. The VAR + UPON Lite combination emerges as the most effective, balancing accuracy and transparency.

The framework is broadly transferable across domains such as healthcare, education, and economics, offering guidelines for selecting methods suited to specific data and objectives. It contributes academically by setting standards for integrating econometrics, machine learning, and semantic technologies while ensuring rigorous validation.

Looking ahead, the framework can inform industry standards, educational curricula, and academic–industrial collaboration, establishing a foundation for future interdisciplinary work at the intersection of forecasting and semantics.

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Practical Tensor Decompositions for NLP Embeddings with TT, Tucker, and CP

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Abstract:
Transformer models devote a large share of parameters to token embedding matrices, creating memory and latency bottlenecks for training and deployment. This paper provides a concise, practice-oriented review and mini-tutorial on tensor decompositions for compressing NLP embedding layers. We focus on Tensor Train (TT), Tucker, and CP decompositions applied to Transformer embeddings in the 2020–2025 period. We distinguish training-free factorization from fine-tuned or end-to-end tensorized embeddings, summarize typical compression–accuracy trade-offs, and give rank-selection and implementation tips that convert parameter savings into real latency and memory gains. Empirical results from peer-reviewed studies indicate that TT-based embeddings can achieve multi-fold parameter reductions with negligible accuracy loss, that post-training TT/MPO with light fine-tuning reduces the number of trainable parameters dramatically during adaptation, and that hybrid tensorization combined with distillation can even improve quality in some machine translation settings. A compact checklist and table of representative results are included to help practitioners choose a decomposition and training regime for embedding-heavy NLP models.

Keywords:
tensor train; Tucker; CP/CANDECOMP-PARAFAC; tensorization; embeddings; model compression; transformers; BERT; GPT; NLP

1. Introduction

Large vocabularies and high hidden dimensions make embedding layers a dominant parameter and memory component in modern NLP models. Practical compression must reduce storage, bandwidth, and latency while maintaining downstream quality. Tensor decompositions re-express a 2D embedding matrix as a multi-dimensional tensor with small factor "cores," enabling dramatic parameter savings via TT, Tucker, or CP factorizations. Unlike unstructured pruning or scalar quantization, tensor methods expose algebraic structure that compilers and kernels can exploit for speed.

This paper is a short, practice-oriented note, not a full SLR (Systematic Literature Review). We synthesize peer-reviewed results on tensorizing embedding layers only, offer conservative guidance on method choice and ranks, and outline traps and implementation details that matter in real deployments. A broader, Kitchenham-aligned SLR will follow and include attention and feed-forward tensorization.

Motivation and Research Gap

Although tensor decompositions have been explored in several recent studies, most available results are scattered across different architectures and are presented through highly technical formulations. Current publications typically focus on *either* theoretical tensor properties *or* single-task demonstrations, but they do not provide a practice-oriented synthesis of how TT, Tucker, and CP behave **specifically on NLP embedding layers** under different training regimes. Moreover, no existing work consolidates compression–accuracy trade-offs, rank-selection heuristics, and implementation details into a unified guide aimed at practitioners. This paper addresses this gap by systematizing peer-reviewed empirical findings (2020–2025) and translating them into practical recommendations for real-world NLP deployment.

Contributions

This work provides three main contributions. First, it offers a structured comparison of Tensor Train, Tucker, and CP decompositions applied to NLP embedding layers and distinguishes between training-free, fine-tuned, and end-to-end tensorization regimes. Second, it analyzes five representative studies from the recent literature by discussing their methodological similarities and differences, as well as their empirical effects on compression and accuracy. Third, it summarizes practical considerations for applying tensor decompositions in real-world NLP systems, including rank-selection heuristics, runtime implications, and the relationship between parameter savings and wall-clock efficiency. These contributions provide a focused, practice-oriented foundation that complements broader systematic literature reviews planned for future work.

2. Background and related work

A token embedding matrix of size V×dV \times dV×d can be reshaped into a higher-order tensor and factorized using several classical tensor decomposition techniques. Tensor Train, also known as Matrix Product Operator, represents the matrix as a sequence of three-dimensional cores whose parameter count increases approximately linearly with the chosen Tensor Train rank. Tucker decomposition expresses the embedding through a smaller core tensor and a set of factor matrices, allowing the ranks along each mode to differ and providing flexibility in capturing anisotropic structure. CP decomposition represents the embedding as a sum of rank-one outer products, which yields a highly compact representation but often requires careful initialization due to its sensitivity during optimization.

Embedding layers are particularly suitable for tensor decomposition because they typically contain a large proportion of the model parameters and encode redundant patterns arising from subword co-occurrence statistics. This redundancy enables substantial reductions through low-rank tensorization while preserving the functional behavior of the embeddings, especially when accompanied by modest fine-tuning or distillation as demonstrated in several recent studies [1–3].

Several related approaches pursue similar goals but fall outside the scope of tensor decompositions. Kronecker factorization and low-rank matrix approximations based on singular value decomposition have been used to compress embedding layers as well, although they rely on different algebraic structures. These methods are mentioned here only for contextual positioning and are not included in the central analysis of this work.

3. Method categories and descriptions

3.1. Training-free tensorization of pre-trained embeddings

Training-free tensorization reshapes a pre-trained embedding matrix into a higher-order tensor and factorizes it without modifying the remaining model parameters. The primary goal of this approach is to reduce memory footprint and storage cost while preserving the representational capacity learned during large-scale pre-training. Since this procedure does not rely on parameter updates, the choice of tensor ranks must remain conservative to prevent a loss of expressiveness. Although NLP-specific studies on fully training-free tensorization are relatively limited, research in adjacent domains such as recommender systems and graph neural networks indicates that substantial compression can often be achieved with little or no degradation in quality. These results suggest that training-free tensorization is a promising strategy in scenarios where computational resources for fine-tuning are constrained or where deployment considerations require minimal changes to the original model architecture.

3.2. Fine-tuned or end-to-end tensorized embeddings

Fine-tuned and end-to-end tensorized embeddings integrate tensor decomposition directly into the learning process. Tensor Train embeddings trained from scratch frequently achieve multi-fold reductions

in embedding parameters while preserving accuracy across a variety of NLP tasks. A related line of work factorizes the embedding layer of a pre-trained model and updates only the newly introduced tensor cores during downstream fine-tuning, which substantially decreases the number of trainable parameters and reduces the computational cost of adaptation. Hybrid models extend this approach by combining tensor decompositions with small dense residual components and often employ knowledge distillation to stabilize training. These models not only compress embeddings but in certain cases also achieve quality improvements such as higher BLEU scores in machine translation. Consequently, fine-tuned and hybrid tensorized embeddings are suitable for settings where limited fine-tuning compute is available and where greater compression or accuracy retention is required.

3.3. Choosing TT vs Tucker vs CP for embeddings

Tensor Train has emerged as the most consistently stable and empirically supported method for compressing large embedding matrices, largely due to its flexible rank control and favorable optimization properties. Tucker decomposition provides greater control over mode-specific ranks and is advantageous when the underlying embedding structure is anisotropic, although its core tensor introduces additional computational overhead. CP decomposition offers the most compact representation in theory, but its optimization can be sensitive to initialization and often requires careful regularization. The choice among these decompositions therefore depends on the expected structure of the embedding space and the computational constraints of the application, with Tensor Train frequently serving as a reliable default in large-scale NLP models.

4. Analysis and discussion

Across the reviewed studies, a consistent pattern emerges regarding the relationship between compression and downstream quality. End-to-end Tensor Train embeddings typically achieve reductions of two to ten times in the size of the embedding layer while preserving accuracy on text classification and language modeling tasks. Post-training factorization methods such as MPO or Tensor Train decomposition maintain competitive performance even when only a small percentage of the parameters are updated during fine-tuning. Hybrid models that combine tensorized embeddings with small dense components and a distillation objective can deliver both efficiency and quality improvements, as demonstrated in machine translation. These results highlight the practical usefulness of tensor decompositions for NLP embeddings, although they also indicate that the extent of achievable compression depends strongly on model architecture, rank selection, and the availability of fine-tuning compute.

Rank selection plays a central role in determining the quality-efficiency trade-off. Empirical studies show that beginning with conservative ranks and evaluating several candidate configurations yields more stable behavior than attempting aggressive compression from the outset. Tensor Train decompositions are generally easier to tune because their ranks increase parameter count smoothly, while CP ranks can produce sudden drops in representational capacity. For this reason, most studies adjust Tensor Train ranks gradually and monitor validation curves as a practical guideline.

The implementation of tensorized embeddings affects not only parameter count but also runtime characteristics. Actual speedups depend on the efficiency of the kernels used for factorized lookup and reconstruction. For meaningful evaluation, it is therefore necessary to report parameter count, wall-clock latency, peak memory consumption, and downstream accuracy together. Combining tensor decompositions with quantization can further reduce storage and improve throughput, although these combined methods require careful tuning to avoid compounding sources of approximation error.

Table 1. Summary of Tensor Decomposition Approaches for Embedding Layer Compression (2020–2025)

Paper	Decomp.	Training Regime	Target	Reported Compression	Accuracy Effect	Venue/Year

Hrinchuk et al. [1]	TT	End-to-end (from scratch)	Embeddings	≈2–10× (embedding)	≈parity or slight gains	Findings EMNLP 2020
Liu et al. [2]	TT/MPO	Post-training + fine-tune (aux cores)	Embeddings + other	Large reduction in trainable params (~90%)	≈parity after FT	ACL 2021
Li et al. [3]	Hybrid TT (+dense residual)	From scratch + distillation	Embeddings + other	Model smaller; runtime ↑ (≈1.27×)	↑ BLEU vs baseline	EMNLP 2022
Yin et al. [4]	TT	From scratch	Recsys embeddings	Up to ≈112×	≈parity	MLSys 2021
Yin et al. [5]	TT	From scratch	GNN embeddings	≈1.6k×–80k×	≈parity or better	KDD 2022

Comparative Analysis of Representative Studies.

The five papers in Table 1 represent distinct approaches to tensorizing embedding layers. Hrinchuk et al. [1] introduce TT-Embedding and demonstrate that end-to-end Tensor Train training provides stable optimization and achieves a two to ten times reduction of embedding parameters with minimal loss in accuracy. Liu et al. [2] extend this approach by applying MPO and Tensor Train post-training factorization and updating only auxiliary cores during fine-tuning. This reduces the number of trainable parameters by roughly ninety percent while retaining accuracy.

Li et al. [3] combine Tensor Train with a small dense residual and use knowledge distillation. This hybrid strategy yields both model-size reduction and improvements in BLEU score for machine translation.

The results reported by Yin et al. [4] and Yin et al. [5] in recommender systems and GNNs demonstrate that Tensor Train can scale to extremely large embedding tables. They achieve between one hundred and eighty thousand times compression with little or no accuracy loss. Although these domains differ from NLP, the results indicate that Tensor Train remains stable even under aggressive compression, which supports its applicability to NLP embeddings.

Overall, these studies suggest that Tensor Train provides the most empirically reliable performance. MPO-based fine-tuning significantly reduces adaptation cost. Hybrid approaches can even improve output quality. However, the literature provides limited evidence regarding Tucker and CP performance on NLP embeddings and almost no systematic comparison between these methods. This identifies an open research direction.

5. Future directions

Several open questions remain regarding the practical use of tensor decompositions in NLP. Automatic rank selection and mode-wise rank scheduling could reduce the dependence on manual tuning and make tensorized embeddings more broadly accessible. Further research on optimized kernels is needed to ensure that parameter savings translate into measurable improvements in wall-clock inference time. Although evidence from other domains suggests that training-free tensorization may be viable, more extensive NLP-specific experiments are required to validate this systematically. Finally, combining tensor decompositions with quantization or distillation represents a promising direction for obtaining compound efficiency gains.

6. Conclusions

Tensor decompositions provide an effective and empirically validated approach for compressing embedding layers in Transformer-based NLP models. Tensor Train in particular offers a favorable balance between compressibility and stability, and both end-to-end and post-training strategies demonstrate that considerable parameter reductions can be achieved with limited impact on downstream quality. Hybrid tensorized models that incorporate distillation or small dense components can even outperform dense baselines in specific tasks. These findings underscore the practical value of tensorization for embedding-heavy NLP models and motivate further investigation of its applicability to additional components of the Transformer architecture, including attention blocks and feed-forward networks.

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Applying semantic web technology in IoRT: A Review

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Abstract:
This paper provides an overview of semantic web concepts, distinguishing them from World Wide Web, and examines their impact on Internet of Robot Thinks technologies. Here it provides a review of semantic web technologies, their applications across various industries, and their role in achieving practical objectives. It further explains how the application of semantic web technology in robotics can enable automation across different environments, even without direct spatial awareness. Moreover, the application of semantic web technologies increases the opportunities for automating robots, facilitation coordination between robots and humans. Additionally, the paper explains how employing deep learning algorithms, cloud computing, and IoT enhances the opportunities for applications and expands the capabilities of robotic systems.

Keywords:
SWT, IoRT, RaaS, DL

1. Introduction

To advance from performing fixed mechanical tasks in factories to operating autonomously in various environments, robots need to understand their surroundings and the context of their tasks. The Internet of Things (IoT) enables robots to monitor events by collecting data from various sensors, while semantic technology helps them understand the context of things, places, and words around them. Semantic technology provides the capability for communication and coordination between robots by interpreting the messages they send and receive.

Also, World Wide Web is designed to be understood by human beings but not from machine beings while the semantic web is the extension of the web, thus the computer cannot give any meaningful information from the content of WWW. This comparation is illustrated in Figure 1. For semantic web to function effectively, the computer must use decentralized information with compromises, adhering to specific roles to provide automatic results. [2] Software agents gather information from various pages and then provide sophisticated information automatically for end users.

The Web app is designed to present the content of information which is not understandable for a processing machine. The Semantic Web utilizes technologies such as RDF and XML to publish information in websites, making it readable by processing machines. [1]

The first chapter explains the concept of semantic web, how it differs from the world wide web, and the functions it provides. It also describes key technologies such as URI, XML, RDF, and ontologies within the scope of semantic web. The second chapter provides a review of papers that present the IoRT as a combination of robotics and the Internet of things (IoT), highlighting its impact across different fields. It also describes how robots increase intelligence and autonomy through semantic web technologies, helping to interpret and coordinate interactions between robots.

It also reviews two use cases: one showing how a robot fulfills a user's request to close a screen in the kitchen based on user preferences, and another demonstrating robot coordination in moving an object from one room to another. The fourth chapter describes the application of semantic web in IoRT.

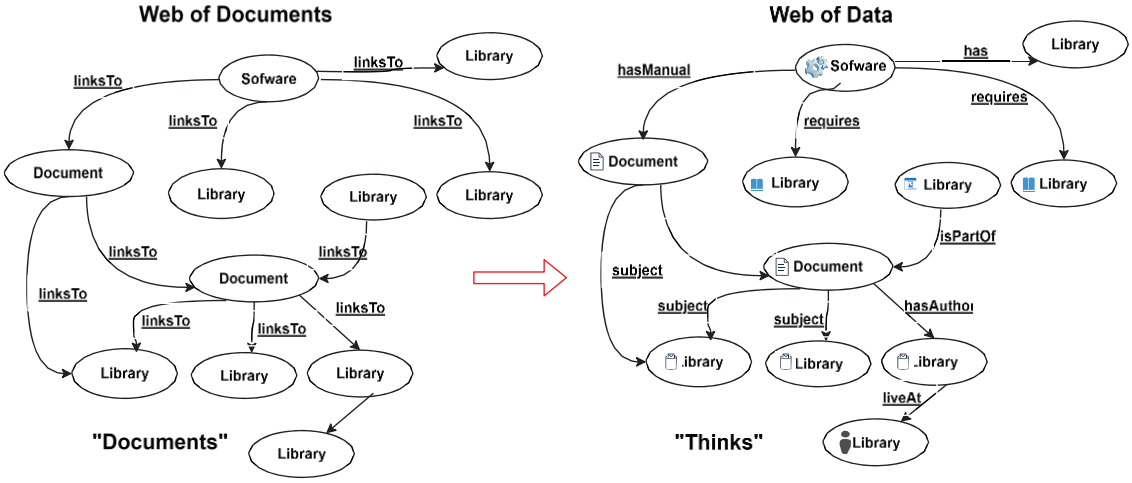


Figure 1: The Semantic Web — From Web of Documents to Web of Data

It highlights the functions of semantic web technologies and their potential uses. The chapter also emphasizes that implementing semantic web in the field of robots can enable communication and coordination between robots and humans.

2. Semantic Web

The Semantic web is a concept of web understanding from both machine processing and human beings, by structuring the document in a way that is understandable to machines. Web Ontology Languages like DAML+OIL extend the RDF model and provide fundamental technologies that enable Semantic Web. Semantic web is an extension of www and enables processing machines to understand its contents of web (Web Content). The Web currently comprises multiline lines and multi-pages documents, which are interpreted line by line and thought databases. Furthermore, it presents individual web pages using the schema URI of those documents. [1]

If a user searches for a free appointment at any clinic, the Semantic Web can go beyond simply providing keyword-based results from specific pages. Instead, it can utilize intelligent agents to offer comprehensive results. These agents can locate free appointments in nearby clinics, specifying available dates and considering criteria such as proximity and user preferences, all without relying on advanced AI systems. The World Wide Web, in its current form, functions primarily as a network of interconnected documents linked from page to page. It serves as a medium for presenting information designed for human reading and understanding, rather than for processing by machines. This design focuses on human interaction and accessibility, making it less suitable for direct machine interpretation or automated processing. The Semantic Web, to provide accurate answers to user requests, must have access to a collection of data structured according to specific rules.

2.1. Technologies

2.1.1. Uniform Resources Locator (URI)

In order to identify one part of the web it is used URI, which is a fundamental component of WEB. URI enable each piece of information within a document to be described as unique and encoded within

world wide web.

2.1.2. Resource Description Framework (RDF) and RDF Schemas

RDF is a mockup language used to describe the information and resources. RDF helps in filtering and analyzing web data. Semantic web uses RDF to describe resources and employs different models for data. RDF uses XML tags to be read and understood from a computer, not from a human being. The key components of RDF schemas are resources, classes and property. RDF provides the natural way to description the objects and relationships between them. An example of RDF is illustrated in Figure 2, which represents a natural way of describing object relationships for instance, room1 contains a table and has a size of 15. [2]

2.1.3. Extensible Markup Language (XML)

XML is designed to communicate on the web by using mockup, which increases data mining, and makes data readable by machines. XML is similar to HTML in that it allows the creation of tags such as <mobile ip>, to identify the content of a document. However, XML does not provide extra information about meaning of these tags

A RDF could represent three main components: Objects, subjects and verbs which could be identified using XML. [2]

2.1.4. Ontologies

One issue in semantic web is that single identifiers from different databases could have different meanings. To address this issue, semantic web uses ontology, which is a framework for defining the relationships between entities. While ontology, as a discipline, traditionally studies the nature of things in Semantic We, it plays the critical role in resolving these ambiguities. Ontologies are documents that describe how items are related to each other.

There could be a case when two different databases may contain the column HomeStreet and another database column home address which have different names but same meaning. Therefore, when the computer reads those fields, it does not know that they have the same meaning as human beings. The terms defined in XML code document used in web page can linked to terms in an ontology document

Therefore, in Ontologies, it is defined that “Home Street” and “Home Address” as “living addresses”, indicating that they have the same meaning. This is also illustrated in Fig. 2, where 'DORE1' and 'DORE_no1' denote the same meaning for both robots in the use case involving two robots performing a table-moving task. Ontologies also improve the accuracy of web search engines and enhance the precision of ambiguous words.

3. Related Work

The author in [6] has described the advantages of Internet of Robot Thinks. It presents the robot overview, its current stage of evaluation, and its potential to assist humans in everyday activities. Also, the author has presented the layers of architecture for the IoRT. The paper also presents the fields where IoRT can be applied, such as medicine, natural disaster, and agriculture. It explains how these applications can be implemented and highlights the benefits they offer.

In this paper, the author has cited three laws of robotics based on Issac Asimov works. Here is highlighting the challenges of data processing in security as a critical issue. The paper also explains how the smart society enabled by IoRT can be beneficial in the future. In [3] the author has explained that IoRT as a Robot that by using artificial intelligence could perform complex tasks by collecting various types of data. Also, it explains the architecture of IoRT, which the author has divided into three tiers.

The author also explains how the integration of robots can be applied in smart environments, such as

smart homes, smart cities, smart healthcare, and more. The integration of robots in IoT creates the IoRT which has applied in Healthcare, Education, Military emergency/disaster response and in different industries such as Automate Agriculture, UAVs, Civil infrastructure, emergency situations etc. DL Algorithms have found significant implementation in semantic aspects, image classification and object detection, by utility sensors for perception like cameras and LiDAR and methods for analysis like semantic segmentation and object detection. Furthermore, the author has classified that semantic segmentation is a technique for object identification within the images, a method used by various systems to establish distances. To achieve this result, the author explains that deep learning algorithms, image processing, and cloud computing are used.
The phases of object detection are twofold: the bounding box phase and the object recognition phase. The paper also presents a comparison between single-robot and multi-robot systems, highlighting the advantages and disadvantages of each.

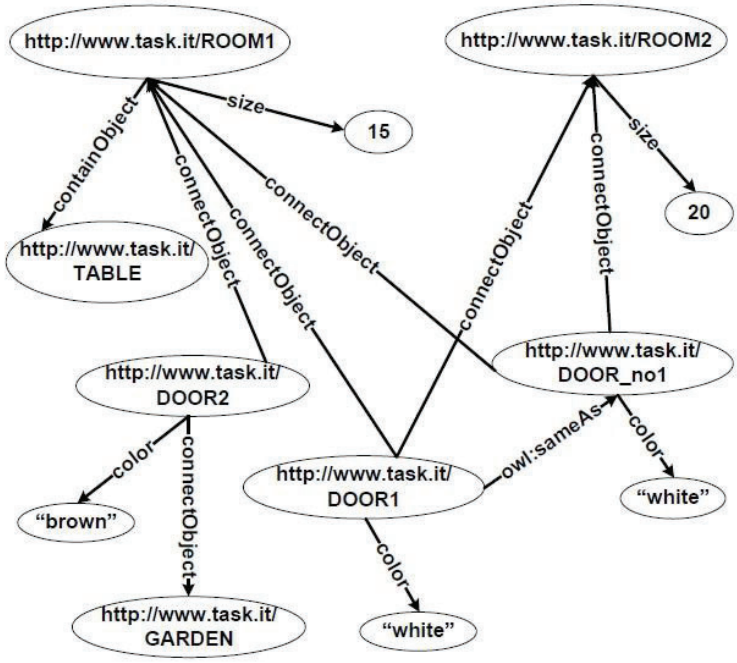


Figure 2: The RDF Graf illustrating the movement of tasks in use case, apart from [7]

The author in [7] presents a comparison between the early robot systems and modern ones, which offer enhanced interaction with humans and other robots. It is clarified that the autonomy and intelligence of a robot can be achieved using SWT (Semantic Web Technology). SWT provides a framework that enables resource sharing between different devices. Implementing SWT can help communication and coordination between robots by interpreting senders or receiving messages from robots. A robot can share and acquire knowledge from other robots, which can then be used to facilitate collaboration with both other robots and human beings. Some frameworks that enable communication between robots include: KnownRob, RoboEarth and RoboDB. KnownRob is a robotic operating system that offers tools for precision and accuracy. RoboEarth facility in knowledge generation, saving and reproducing data on the web. RoboDB is a database of the series of ontologies which enables creation and description of characteristics of robots in a structured way.
Here the author has highlighted the frameworks which demonstrate the scenario of changing the place of table from one room to another by utilizing two robots. While explaining the scenario, the authors use the components of SWL, such: XML, RDF and OWL. For description of the component, relation between the objects and distances within the object it is used the Ontologies.

In [8] the author has explained the historic concepts of centralization systems, advantages and disadvantages of Robot-as-Service (RaaS). Here, the author highlights the concept of automating connections between robots and discusses its expansion due to technological advancements. All of this

has a positive impact on the economy and the well-being of society (by also helping in different rescue operations during natural disasters) and automation of many processes in daily businesses. It is presented as responsible possible services for monitoring Cloud Robot and frameworks that provide robotic tools enabling integration among robots. As disadvantages of RaaS, the author has highlighted the Centralization, Transparency and Security systems.

In the future the author has presented the possibility to replace RaaS with p2p technology, thus, the replacement of Cloud with Blockchain technology, which is considered more cost-effective. It provides enhanced security and avoids the risks associated with a Single Point of Failure (SPF). A notable disadvantage of Blockchain in comparison to Cloud is its relatively low speed.

In [9] the author describes Cloud Computing as the combination of Cloud Computing technology and Robotic. Cloud Computing consists of three fundamentals models such as: SaaS, PaaS and IaaS. It also describes the ability of Robots (by doing sensitive and repeated tasks such as soldering and packaging) and his limits (memory and storage spaces). Certain limitations can be addressed and improved using Cloud Computing. Here is presented RaaS (Robot-as-a-Service) which refer to robots like Police, Waiter, Health Care, which are distributed across different locations and have access through the Cloud Robot platform. It clarifies some frameworks for software management, the most well-known are RAS, Raozuta, SCMR and DaVinci. Here it divides the robots in two types: the classic one and cloud-enabled and explains the benefits of Robots from Cloud. Cloud-enabled is also divided into stand-alone and networking.

The paper also explains the tasks that robots can perform, such as object grasping, object identification, SLAM (Simultaneous Localization and Mapping), monitoring, and networking.

In [10], the author discusses the benefits that cloud computing offers to companies and governments. The paper highlights the major cloud providers, the services they offer, and their key characteristics. It describes robot and mobile robot activities. It explains its applications in the medical, military, and security sectors, as well as in the fields of home care and healthcare. Cloud also could help in the lifespan of AUV. It is explained that cloud resources, along with data collected by various sensors, enable robots to identify different objects. Cloud robots can enable communication between robots as well as between robots and human beings.

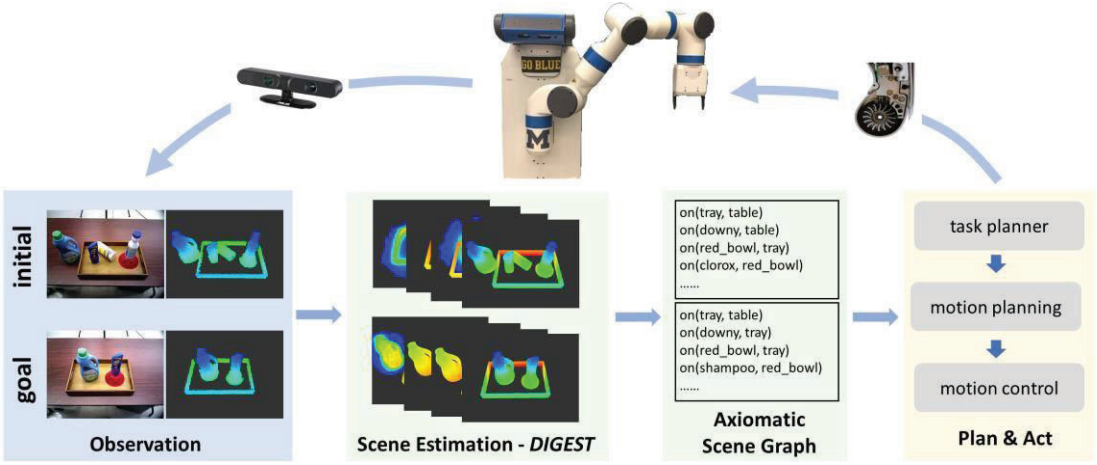


Figure 3: The goal-directed programming process is described in three stages, adapted from [11]

In [11] The author presents a use case illustrating how a robot manipulates clustered scenes in a goal-directed manner using Semantic Robot Programming (SRP). It demonstrates how the SRP enables robots to achieve user goals. This process relies on a continuous perception–action loop, in which perception involves object clarification to support interactions to achieve the goal. Therefore, this process remains unclear for robots. As a solution, it employs semantic mapping between objects using axiomatic scene graphs, as illustrated in Fig. 3, leveraging the advantages offered by robots.

4. Semantic web in IoRT

IoRT(Internet of Robot Thinks) is a combination of Robotic and IoT, enabling the monitoring of

events and collection of data from various sensors. This data is then processed to determine next intelligent actions. IoRT is an intelligent robot which can monitor and perform routine and complex tasks by using AI to process data that was collected from various sensors. IoRT, also utilizes the advance of technology in saving, process and security, except IoT and Cloud. IoRT consists of two important components:

The first service is the information detection service, which involves monitoring and recognizing change, and the second service involves creating movements and interaction with other entities.

Robotic has a significant application in the field of IoT. The robot can be considered an intelligent physical capable of performing tasks autonomy, with actions and qualities that allow it to function without being affected by the surrounding space. Robot automatization is a growing trend, driven by the widespread use of the internet, mobile devices, sensors, video cameras, deep learning algorithms, driverless vehicles and high-performance satellite internet.[9]

Mobile robots are famous for their ability to move across different locations without boundaries. Their movement can be autonomous. They could also move to different locations without predefined conditions, such as AGV. [9]

This application has become now common in various industries such as health, military and security. Robot automatization can also contribute to human well-being and security by performing repetitive daily hard tasks and could be helped in space, particularly in dangerous environments when for humans may be a risk. Robots have been used for far to perform specific tasks in various factories, but nowadays, their role is becoming more interactive, either by helping humans or collaborations with other Robots. If it could arrive, it would provide the opportunity to be automatic and intelligent, which is quite challenging. Then the Robot could have the chance to adapt to respond to the different environment.[5] Additionally, an important issue here is the ethics and safety of services for the robot. For these issues, the three laws of robotics by Isaac Asimov are well known, outlining the ethical principles governing the relationship between robots and humans. Then, the rights over the ownership of the robot and the rights regarding the use of its data. In order to achieve this automatization, it utilizes semantic technology. Semantic technology in the world of technology is used in the context of understanding things, places and other entities [4]. Implementation of semantics in the field of Robotics can help robots communicate and coordinate Robots through interpreting and sending messages or accepting messages by other robots.

Semantics is a technique of computer vision which can extract information in images, such as Sky, forest, Vehicle, Human, etc. and labeling the object that identifies.

The purpose of object identification is to represent the scene and enhance the understanding of the image content to identify objects and the connection between them, the robot uses sensors such as cameras and LiDAR [5] [3]. Identifying semantic objects from images can help to fulfill various tasks. Therefore, the detection and recognition of objects in images can significantly improve robots' ability to understand the tasks, making it essential for tasks to fulfill. These tasks could be different functions in industries that could request robots to fulfill [4]. Except for object identification, robots can also perform other tasks, such as grabbing objects, SLAM, monitoring and networking with other robots. Robots, by utilizing sensors such as cameras or LiDAR, can detect objects and connections between them across different spaces.

The goal of using a robot could also involve object manipulation in a cluster scene based on the user's objective. To achieve this user's goal, a series of actions and perceptions must be implemented using Semantic Robot Programming. SRP provides a general, abstract level of robot programming by employing a declarative approach in axiomatic way, aimed at achieving the user goal. Two types of scenes must be known as the robot in the beginning of the process, the goal scene and the initial scene. Then, based on the initial scene and goal, SRP will plan the executive sub-phase in the direction of the goal [11].

It is planted for each subphase to evaluate the actual scene by including labeling the object, ranging the weight of objects, position of objects and corner of objects. Then, a different algorithm is applied for each of these [11].

5. Conclusions

In conclusion, this study has reviewed the impact of web semantics on internet robot technology, highlighting their significance and implications for future developments in the field. This review highlights the semantic web is designed to be understood by machines, enabling computers to process and retrieve information in a decentralized format, and to produce sophisticated results automatically without the explicit use of artificial intelligence. To achieve such automation, the semantic web leverages RDF as a markup language, XML as the structural framework for communication, and ontologies as formal documentation that define the relationships between items.

The integration of robots into the Internet of Things has given rise to the Internet of Robotic Things (IoRT), which has found significant applications in areas such as smart homes, smart cities, and healthcare. If this field utilizes artificial intelligence, it could undertake complex and repetitive tasks currently performed by humans, with potential applications in healthcare, education, military operation, and emergency response.

By utilizing semantic web technologies, robots can automate communication with humans by accurately interpreting messages. In order to enable networking between robots and others, cloud resources are utilized. By utilizing cloud computing, robots can offer diverse services (such as: SaaS, PaaS, IaaS) and overcome limitations such as storage capacity and processing power. Robots employ various attributes, such as cameras, LiDAR sensors, and SLAM systems, to gather information and perform specific tasks. Regarding the regulation and governance of robots in relation to human beings, it is important to note Isaac Asimov's three fundamental laws of robotics.

The application and extension of semantic web technology in IoRT have greatly facilitated the use of cloud computing, providing opportunities for networking with other robots, enhanced processing power, and access to additional resources. However, the use of cloud computing also introduces potential limitations, including single points of failure, centralization, and security concerns. As a potential solution to these challenges, technology could be considered point-to-point (p2p) technologies.

The challenge for robotics is to consider Isaac Asimov's Three Laws of Robotics, which address the ethical principles governing the relationship between robots and humans. Also, the rights over the ownership of the robot and the rights regarding the use of its data. Data processing and security are also critical issues.

This review is limited to the impact of semantic implementation in the Internet of Robotic Things (IoRT) and does not address issues such as data quality, interoperability, and consistency in ethical development, which remain open challenges for future research.

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Development and Functional Design of “Smart” Surgical Masks Based on IoT Technology

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Abstract:
The development of surgical masks from basic mechanical barriers to smart diagnostic systems marks an important step forward in personal protection technology. This paper presents the construction and functional principle of "smart" surgical masks connected to the Internet of Things (IoT). Such masks combine a traditional multi-layer filtration structure with built-in sensors, microcontrollers and wireless data transmission modules, which enables continuous monitoring of physiological and external parameters in real time. The device measures and analyzes respiration rate, humidity, and temperature, while triboelectric nanogenerators (TENGs) provide self-powered power without the need for an external power source. The collected data is transmitted via Bluetooth or Wi-Fi connection to mobile applications or health systems, where it is further processed with the help of artificial intelligence algorithms. Special emphasis is given to the application of nanomaterials with antimicrobial and self-sterilizing properties that improve filtration and hygiene. In this way, smart masks move from the role of passive protection to active diagnostic devices that connect the user to digital health networks. However, challenges such as component miniaturization, energy autonomy, and privacy protection still remain key to their widespread application.

Keywords:
“smart” surgical masks; Internet of Things (IoT); triboelectric nanogenerator (TENG); antimicrobial nanomaterials; wearable diagnostics

1. Introduction

For more than a century, protective surgical masks have played a key role in preventing the spread of infections and protecting the wearer's respiratory system. Their basic function (filtration of particles and microorganisms) has long been based exclusively on the physical principles and structure of fibers. However, in recent years, with the accelerated development of materials science and digital technologies, masks have gone from simple means of personal protection to advanced, interactive devices that integrate sensors, electronic components and the ability to communicate with external systems [7, 9].

The COVID-19 pandemic acted as a strong impulse for the accelerated development of new approaches to respiratory protection, as it indicated the need for intelligent, self-contained systems that not only protect the user, but also monitor their physiological state in real time. This trend led to the emergence of the concept of *"smart"* surgical masks, which represent a combination of material engineering, microelectronics and information technologies [1, 3, 16].

Unlike conventional masks, which achieve their effectiveness by applying multi-layered filtration structures and possibly nanotechnological coatings with antimicrobial action (graphene, TiO_2, ZnO), smart masks function on a completely new principle. They contain built-in microcontrollers, sensors

and wireless communication modules, which enable continuous monitoring of breathing parameters, temperature, humidity and concentration of gases in exhaled air [9, 21].

Data collected while wearing the mask are processed inside the microprocessor unit and can be transmitted in real time via Bluetooth, Wi-Fi or RF connections to mobile applications or health databases [10, 22]. In this way, the mask is no longer a passive barrier, but an active diagnostic device that connects the person with the digital health ecosystem and becomes part of the wider Internet of Things (IoT) network.

The development of smart surgical masks represents a new direction in the evolution of personal protective equipment: devices that not only filter particles, but also interpret data about the user and his environment. Such technology opens up opportunities for application in medicine, industry and everyday life, while at the same time raising questions about energy autonomy, system reliability and privacy protection of collected information.

2. Evolution and Development of Surgical Face Masks

2.1. Historical Development of Surgical Face Masks

The first forms of protective masks date back to the 17th century, when the French doctor Charles de Lorme designed the so-called a mask with a beak, which contained aromatic plants and medicines intended to filter "infected air" during plague epidemics. That simple but functional concept was the forerunner of modern respiratory protection. True surgical masks appeared in the early 20th century, when doctors began wearing gauze cloths during operations to prevent contamination of the surgical field [24].

In the 1930s, multi-layer filters based on cellulose and synthetic fibers were introduced, which significantly increased the efficiency of particle retention. Later, the development of polymer fibers and the method of *"spunbond"* and *"melt-blown"* production enabled the mass production of three-layer and four-layer masks, which are most commonly used in medicine today [13].

These classic surgical masks are composed of an outer hydrophobic layer, a middle filtration layer and an inner, soft layer that comes into contact with the skin. Their goal is to prevent the transmission of droplets and aerosols, while preserving breathing comfort.

2.2. Implementation of New Technologies

The development of nanotechnology has opened a new chapter in the construction of protective masks. Nanomaterials with antimicrobial, antistatic, and self-sterilizing properties, such as silver (Ag), copper oxide (CuO), zinc oxide (ZnO), and titanium dioxide (TiO_2), have begun to be incorporated into the fiber structure [19, 20].

These additives will facilitate the breakdown of microorganisms through photocatalytic reactions or the release of metal ions, thus extending the protective capability of the surgical mask. Concurrently, biodegradable materials such as polylactic acid (PLA) have been introduced which maintain the electrostatic properties need for effective filtration, while being more eco-friendly [12].

Beyond advancements in materials, the 2020s have seen the introduction of digital components into the structure of protective equipment. Researchers have begun combining nonwoven fabrics with microsensors, microcontrollers, and IoT modules to enable real-time monitoring of breathing parameters and environmental conditions [9, 21]. These systems are capable of measuring temperature, humidity, CO_2 concentration, and respiratory frequency, transforming the mask from a passive protective barrier into an active diagnostic device.

2.3. Transition to the "Smart" Concept

With the advent of recent studies, a new phase of development has begun: IoT-based smart masks equipped with microchips, sensors, and automatic tightening systems [21, 22]. These prototypes generally combine Arduino or ESP32 microcontrollers with temperature, humidity and pressure sensors, and the collected data wirelessly sent for artificial intelligence analysis. In this way, the mask becomes a smart device that can respond to the user's breathing changes, to maintain an optimal face fit and warn of misuse. By combining material and electronic advances, the modern surgical mask transitions into a complex system that integrates filtration, detection and communication, which serves as the foundation for understanding the construction and operational parameters of "smart" masks.

3. Construction and Operating Principle of Smart Surgical Face Masks

3.1. Structure and Main Components

Smart surgical masks (Figure 1) are a combination of a classic filtration structure and a built-in electronic system that enables measurement and data transfer in real time. In its basic form, the mask consists of three mechanical layers and one functional electronic module [21, 22, 23]:

- **Outer layer** (made of waterproof polypropylene (*"spunbond"*), which protects against moisture and drops)
- **Middle layer** (filtration material produced by the melt-blown process, responsible for retaining particles and microorganisms)
- **Inner layer** (hypoallergenic material in contact with the skin, in which sensors are integrated)
- **Electronic subsystem** (located on the frame of the mask and connected to the microprocessor unit)

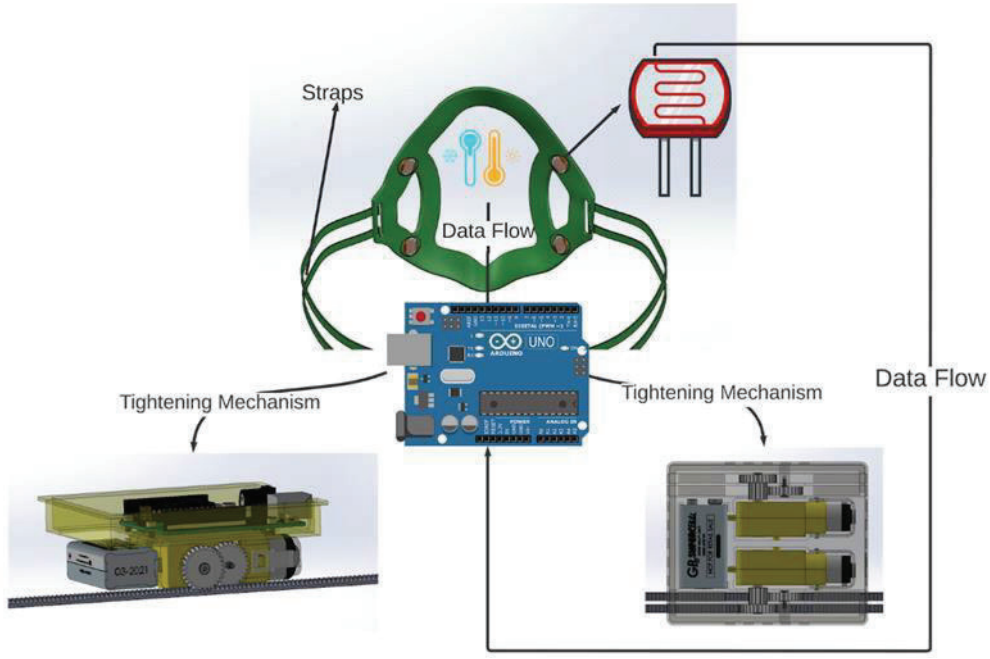


Figure 1 "Smart" Surgical Face Mask [23]

The electronic subsystem of the device includes a microcontroller that is in charge of controlling sensors and processing the gathered signals. The sensors are built in to continually measure the temperature, humidity, pressure, and CO_2 variation of the internal mask environment and user inhalation and exhalation measurements. Furthermore, the device incorporates tightening mechanics that have a servo motor that will mechanically tighten and loosen webbing to create a comfortable fit. The system gets its power from a micro-battery or from a triboelectric nanogenerator (TENG) that converts the

user's breathing/physical movement into useable electrical energy while the mask functions independently [4, 15, 23].

3.2. Principle of Operation of Smart Surgical Face Masks

The operating principle of the smart surgical mask is based on the continuous collection and analysis of data on the state of the user and the environment. When the mask is placed on the face, the temperature and humidity sensors register the conditions in the space between the mask and the skin, while the CO_2 sensor measures the concentration of exhaled gas and the rhythm of breathing [16, 21, 23].

The collected signals are transmitted in the form of analog data to the microcontroller, where they are digitally converted and processed in real time. The system uses algorithms to detect changes in breathing and adjusts the tension of the straps using a servo motor if the mask does not fit evenly [22].

The processed data is then transferred via Bluetooth or Wi-Fi connection to a mobile device or computer system for visualization and analysis. In this way, two-way communication is achieved: the user receives information about the quality of breathing and the conditions in the mask, while the system can independently react to changes, such as an increase in humidity or temperature.

The flow of information in the "smart" surgical mask takes place in several consecutive stages that together form a closed system of monitoring and data processing. First, the sensor layer registers physical changes such as temperature, humidity, pressure and carbon dioxide concentration in the space between the face and the mask. These values represent basic parameters that indicate breathing conditions and user comfort [21]. At that point, the microcontroller takes the analog signals from the sensors, converts them into digital data and processes them (noise filtering, calibration and temporarily store) [22, 23]. The wireless communication module (Bluetooth, Wi-Fi or RF) transmits the processed data to external devices, mobile applications or IoT platforms where the data is displayed visually [9, 10]. Finally, artificial intelligence algorithms are applied to recognize breathing patterns, detect deviations or irregularities to provide user feedback in the form of warnings or recommendations [4, 15]. So a mask works as an integrated system that, in addition to taking measurements, interprets physiological data in real time to convert into usable digital information for medical diagnostics and health monitoring.

4. Applications of "Smart" Surgical Face Masks

4.1. Current Research and Development

The development of smart surgical masks is in the phase of intensive research and experimental prototypes. Contemporary works are mainly focused on the development of IoT-based systems that combine classical filtration layers with electronic components and the possibility of wireless data transmission [21-23].

Research shows different models of masks that use temperature, humidity and pressure sensors connected to microcontrollers such as Arduino Uno or ESP32, which enables monitoring of breathing parameters and microclimate inside the mask. Collected data are transmitted in real time via Bluetooth connection to IoT platforms for processing and analysis [21].

Also, models with automated tensioning mechanisms are being developed that detect inadequate fit and independently adjust the tension of the straps in order to achieve better comfort and stability during wearing [22].

In addition, a special line of research is directed towards the development of self-sustaining systems that use triboelectric nanogenerators (TENGs) to generate electricity from the user's breathing and movements. Such models do not require external battery power and enable long-term and sustainable sensor operation [4, 15]. This technology opens up the possibility of applying masks in situations where charging batteries is impractical, as well as in areas where long-term functionality and stability of protective equipment is required.

4.2. Potential and Future Applications

Smart surgical masks have a wide range of possible applications, including medical diagnostics, industrial safety and everyday use.

In medicine, smart masks can be used for continuous monitoring of breathing of patients in the postoperative period or in persons with respiratory diseases. By integrating with hospital information systems, it is possible to detect changes in breathing frequency, temperature and degree of oxygen saturation, which enables a quick reaction of the medical staff [9, 10, 21].

In industrial conditions, smart masks can be part of a system for monitoring the working environment, where they detect the presence of harmful gases (VOC, CO_2) and warn the user about exceeding the safety limits [16, 17].

In everyday application, the concept of "smart masks" is already present through commercial models such as MaskFone and AirPop Active+ Halo, which integrate breathing sensors and wireless audio components connected to mobile applications. However, more advanced versions that include multiple sensors, automated customization, and AI analytics are still under development and laboratory testing [22].

4.3. Limitations and Challenges

Despite the great potential, the application of smart masks faces a number of challenges. First of all, it is necessary to solve the issue of energy autonomy, it can be said that the durability of the battery and the sustainability of the TENG system are still not at the level for commercial application [4, 15].

Another challenge is the miniaturization of components and the integration of sensors into the thin and flexible structure of the mask, without impairing breathing comfort [6, 7].

In addition to technical aspects, there is also the issue of privacy and data security, because masks collect physiological information about the user that can be sensitive [14, 20].

Therefore, the current works are mainly of a research nature, and market implementation is expected in the coming years, after the standards and regulations for this category of medical IoT devices are defined.

5. Conclusion

“Smart” surgical masks constitute a new generation of protective measures that extend the role of a traditional mechanical barrier. By adopting sensors, microchips and wireless communication systems, it is possible to continually monitor breathing, temperature, humidity and air quality. In this sense, the mask functions as an active diagnostic device, linking the user with the digital environment and providing individualized protection and monitoring [9, 10, 21].

While commercial models equipped with basic sensors and IoT functions have recently appeared in the marketplace, advanced models with more integrated modules and automatic adjustments remain in the research stage [22]. Future development will focus on miniaturization of components, energy self-sustainability and user privacy protection. The potential for smart masks as an important component of the Internet of Medical Things system and modern digital healthcare will then become possible.

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Development of a smart sleep monitoring ecosystem

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Abstract:
This work presents an actively developing integrated software and hardware system for sleep analysis aimed to improve overall sleep quality. The project combines multimodal sensing (movement, cardiopulmonary signals, environmental parameters and others) with data pipelines and learning-based inference to deliver factor-level explanations and action able recommendations. A formal system model defines components, interfaces, and data flows, guiding implementation, testing, and planned extensibility. Given limitations of current consumer and ambulatory technologies, the architecture targets more reliable inference by fusing physiological and environmental data streams and adapting models to each user via machine-learning–based personalization (including calibration/transfer learning). Intermediate closed tests with prototype devices evaluate signal robustness, interoperability, and feasibility of home deployment; development proceeds iteratively with testing and planned validation against synchronized PSG. The system is designed as an expandable ecosystem intended for practical use and future clinical and commercial scaling.

Keywords:
sleep monitoring ecosystem, machine learning, transfer learning, personalized smart control, internet of things, development, modelling, architecture

1. Introduction

Sleep deficits and disturbances represent a global public-health problem that consumer wearables do not adequately solve. Sleep quality and duration are tightly linked to physical and mental health, cognition, productivity, and social functioning [1], [2], while insufficient or fragmented sleep remains common in the general population [3]. Major guidelines recommend at least 7 hours of sleep per day for adults to maintain health and well-being, and practical assessment relies on operational thresholds of sleep quality (see table 1).

Table 1:
Sleep quality norms

Indicator	Norm	Acceptable for older adults
Sleep latency Awakening	≤ 15 minutes	31–60 minutes
(> 5 minutes) Time awake	2 times/night	≤ 3 times
after sleep Daytime sleep	≤ 20 minutes	31–60 minutes
	≤ 20 minutes	≤ 100 minutes

Clinically, polysomnography (PSG) remains the gold standard, but its laboratory setting limits scalability and ecological validity. Outpatient alternatives—actigraphy and self-report—are widely used yet either lose accuracy in disordered sleep or introduce systematic bias. Modern wearables combine accelerometry and photoplethysmography to infer sleep–wake and stage surrogates, but they often misclassify sleep onset/offset and ignore environmental context [4].

Representative production systems include Apple Watch and Samsung Galaxy Watch, Fitbit (Google) and Garmin wearables, Oura Ring, WHOOP, Withings Sleep Analyzer/Mat, and Eight Sleep smart mattresses. These solutions primarily infer sleep from accelerometry and PPG (with limited peripheral temperature in some devices) and provide app-level scores and coaching; however, they generally lack calibrated environmental sensing and factor-level explainability. Consequently, accuracy

tends to degrade at sleep onset/offset and under atypical conditions, and personalization remains constrained [4].

This work targets a dedicated sleep ecosystem that extends beyond wrist-worn sensing to multi modal, in-home monitoring: ambient air quality (CO_2/TVOC), humidity, temperature, illumination, and noise, together with physiological signals such as movement, heart rate/variability, and skin temperature [5], [6], [7]. The system is designed to produce transparent, factor-level recommendations that explain what likely degraded sleep and why.

Sleep is inherently multifactorial, psychological, behavioral, so the medical determinants are substantial. The research scope here is limited to technical factors measurable by software/hardware platforms as a testable hypothesis that improving observable environmental and physiological correlates can raise overall sleep quality.

Research methods include literature selection, synthesis, requirements analysis, and modeling of the proposed system architecture with data-driven components.

2. Problem Statement

It is known sleep phase disorders can lead to poor health, decreased cognitive function, and an increased risk of chronic diseases [1], [2]. Chronic sleep deprivation is associated with an increased likelihood of cardiovascular disease, metabolic disorders (e.g., diabetes), and mental disorders, including depression. Moreover excessive sleep can also be harmful and is associated with an increased risk of stroke and obesity [2]. Background on diagnostic modalities and wearable algorithms is summarized in the theoretical background. Having identified the advantages and disadvantages of software and hardware methods of sleep research, an experiment was undertaken to create a proprietary system for monitoring human condition. In this approach, an additional control element is the comprehensive monitoring of the microclimate of the room in which the person sleeps [5], [6]. This comprehensive approach is used to build our own "sleep ecosystem" using the Internet of Things (IoT) and machine learning [7]. Taken together, this ecosystem will allow building analytics of a person's physical condition after waking up and organizing a monitoring system and subsequently controlling the indoor microclimate to improve the quality of life of a specific consumer [6]. Graphically, the complexity of this approach can be expressed as a cube, the faces of which represent the components of a single interconnected system (see Figure 1).

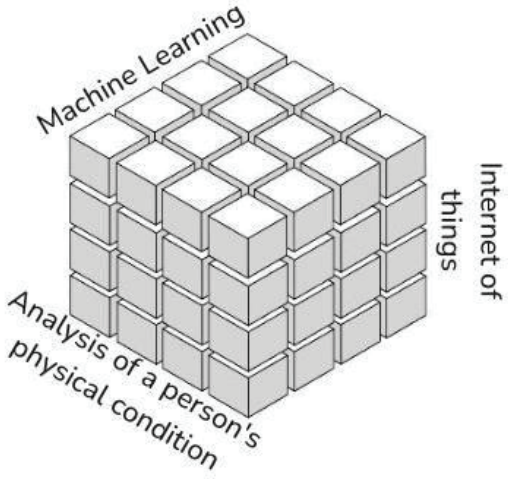


Figure 1: Graphical representation of the complexity of the approach

3. Theoretical background

Polysomnography (PSG) remains the "gold standard" of sleep assessment, recording EEG, eye movements, muscle tone, respiration, and other signals in a laboratory setting; however, the "first-night effect" and resource demands limit scalability and ecological validity. The first-night effect denotes transient alterations in sleep architecture and reduced sleep efficiency on the initial laboratory night due

to unfamiliar environment and instrumentation, often attenuating on subsequent nights.

Outpatient methods include actigraphy and questionnaires. Usually actigraphy achieves 89–98% accuracy in healthy adults but degrades in sleep disorders; questionnaires provide subjective estimates and tend to overestimate total sleep time by about 15–20 minutes.

Consumer wearables leverage accelerometry and photoplethysmography (and occasionally peripheral temperature) to infer sleep–wake and stage surrogates, enabling at-home monitoring [4]. Limitations include misclassification of sleep onset/offset, poor sensitivities to brief arousals with minimal movement, and the absence of external context markers (e.g. lights), which reduces reliability.

The review of sources in the field of somnology and the experiment show that the combination of wearable devices for monitoring a person's physical condition and the microclimate surrounding them is a promising direction in somnology for increasing the objectivity of research in natural conditions [4], [5]. Although polysomnography remains the "gold standard" for clinical diagnosis and detailed study of sleep architecture, its laboratory limitations—the first night effect and low availability for long term observation — justify the demand for outpatient and wearable solutions for large scale epidemiological and long-term cohort studies [4].

The multimodal data acquisition strategy improves the informativeness of signs compared to actigraphs, which increases the analytical ability of models to detect clinically relevant events, such as episodes of apnea and heart rhythm abnormalities, while simultaneously assessing the impact of external factors on sleep quality [4], [8].

4. Research process and discussion

The intended roadmap toward a working prototype consists of but not limited to:

- problem definition and requirements elicitation;
- system modeling and architecture design (hardware, software, data, interfaces);
- data interfaces and storage schema design;
- firmware development;
- backend data pipeline and APIs;
- baseline analytics and ML implementation;
- user interface and visualization;
- modular integration and closed tests;
- field trials and validation against reference measures;
- iteration and deployment planning.

The project was divided into complementary workstreams executed by specialists who are the authors of this paper:

- hardware architecture modeling and hardware implementation — Konstantin Zheltov;
- software architecture and automated testing — Kirill Zhilenkov;
- scientific article arrangement and literature synthesis — Andrey Dorofeev;
- strategic research planning and final structuring of research results — Irina Kuznetsova.

Before full scale implementation, system modeling and key design decisions were performed, followed by modular intermediate closed tests to de-risk integration. This article focuses on these initial steps—modeling and architecture design—and their closed tests to ensure that subsequent development and open testing demonstrate system integrity and stable performance.

4.1. Sleep monitoring ecosystem architecture design

The architecture consists of two networked devices that acquire physiological and environmental signals for sleep monitoring. The physiological sensing node integrates an ESP 32 microcontroller with MAX30102 PPG/SpO_2, AD8232 ECG, a piezoresistive temperature sensor, and a GY 521 accelerometer–gyroscope; two sensing points are used (arm and chest). The overall hardware config uration is summarized in Figure 2.

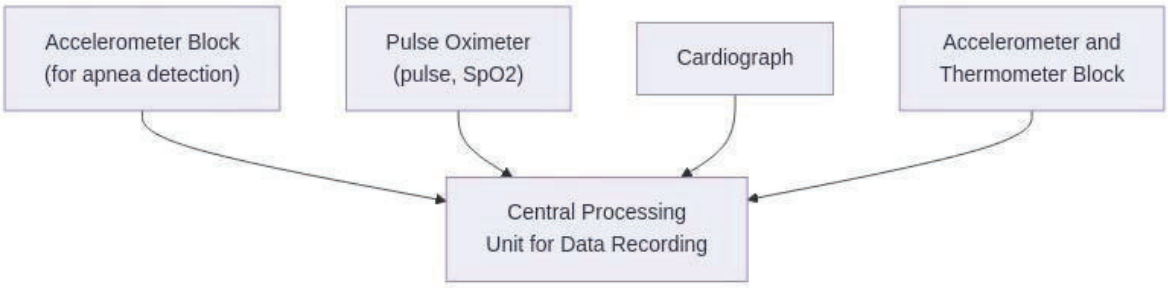


Figure 2: Block diagram of a human condition monitoring device

The second device, packaged as a decorative lamp, monitors ambient conditions using CCS811 (air quality), DHT11 (temperature and humidity), a microphone (acoustic noise), and BMP280 (barometric pressure), and provides dimmable lighting with a tri-color status indicator for microclimate quality (see Figure 3).

Within the system architecture, this lamp represents an external device class with dedicated hardware that both acquires ambient data for persistent storage in the platform and informs decision mechanisms at the per-user scope (e.g., context-aware feedback or actuation). It is used here to evaluate the flexibility and designed-in expandability of the ecosystem by demonstrating interoperability with other components and readiness for additional device classes.

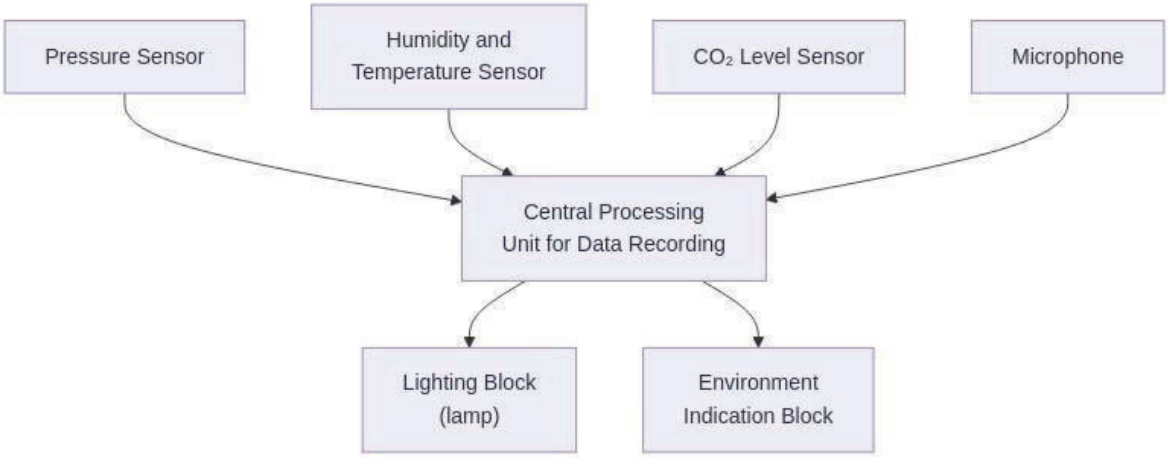


Figure 3: Microclimate monitoring unit

The software architecture is documented with diagrams that capture runtime interactions and static structure. The sequence diagram outlines the end-to-end flow of health monitoring (see Figure 4). Here, end-to-end flow denotes the complete data path from on-body and ambient sensors through transmission, buffering, preprocessing, model inference, persistence, and feedback to the user or actuators. The diagram specifies components, message ordering and timing, and nominal/ error paths (retries, timeouts) and interface contracts, which enables latency budgeting and de-risked integration planning.

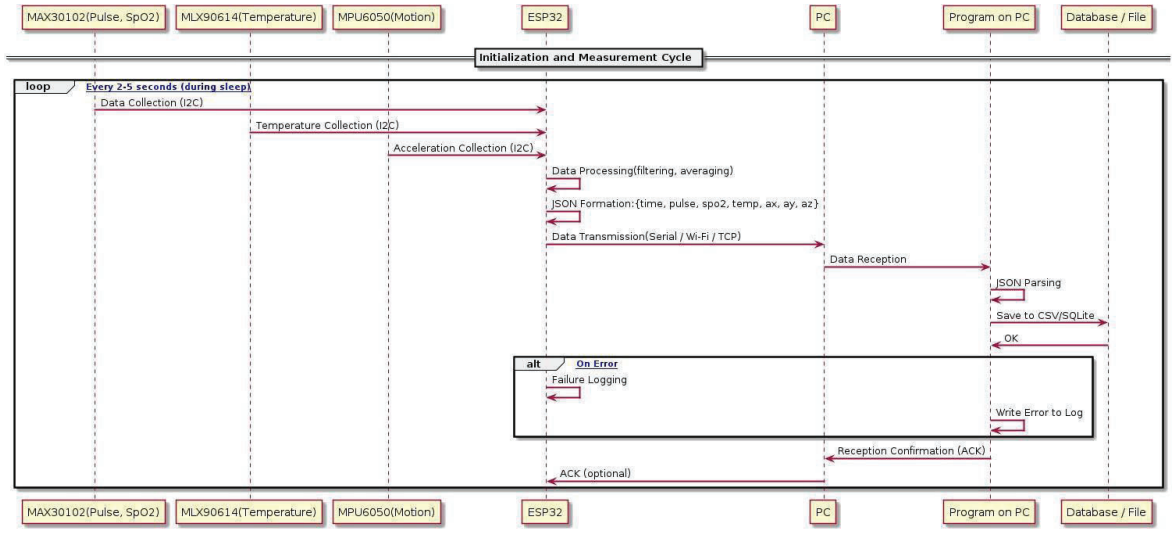


Figure 4: Sequence diagram

The application comprises four subsystems deployed on a monitoring and data processing server (data accumulation and machine learning):

1. Human physical condition monitoring unit:

- PulseOximeter — working with a pulse oximeter: reading pulse and SpO_2;
- Thermometer — working with a thermometer: measuring body temperature;
- MotionSensor — working with an accelerometer;
- SensorManager — orchestrates data collection from all sensors, controls the measurement cycle;
- DataProcessor — filtering, averaging, data validation;
- DataPacket — forming the data structure (JSON);
- Transmitter — sending data to the server (Wi Fi);
- Logger — collects errors and system status; • SleepMonitor — sleep monitoring: activity detection.

2. Microclimate monitoring unit:

- EnvironmentSensor — basic interface for environmental sensors;
- BMP280Sensor — pressure measurement;
- CO2Sensor — CO_2 concentration measurement;
- NoiseSensor — noise level measurement;
- DHTSensor — temperature and humidity measurement;
- EnvironmentManager — manages all microclimate sensors, data collection.

3. Data recording and storage subsystem:

- DataReceiver — receives data from monitoring units;
- DataParser — parsing JSON packets, integrity check;
- DataManager — data flow management, buffering;
- EnvironmentAnalyzer — comfort assessment based on temperature, humidity, pressure, CO_2;
- AirQualityMonitor — classification of air quality by CO_2/TVOC level;
- EnvironmentPlotter — visualization of microclimate parameters;
- SleepAnalyzer — data analysis: sleep phases, anomalies (apnea, increased heart rate);
- RealTimePlotter — visualization of data in real time;
- AlertSystem — alert generation;
- Logger — local logging of application events.

Machine-learning methods are required to integrate heterogeneous, noisy signals and to model nonlinear relations between physiology, environment, and sleep outcomes. The planned pipeline performs per-modality feature extraction, multimodal fusion, and task-specific inference: sleep staging, apnea detection, prediction of nightly sleep quality, and attribution of environmental impact.

Personalization is introduced via calibration and transfer learning to accommodate inter-individual variability and to strengthen the actionability of recommendations [4], [7], [8].

1. Machine learning subsystem:

- FeatureExtractor — feature extraction from raw data;
- MultimodalFusion — combining health and microclimate data into a single feature vector;
- MLModel — abstract model interface;
- SleepPhaseClassifier — classifies sleep phases;
- ApneaDetector — detects episodes of apnea based on a drop in SpO_2 and lack of movement;
- SleepQualityPredictor — predicts the final sleep score (regression method);
- EnvironmentImpactAnalyzer — determines which environmental factors most strongly affect sleep;
- ModelTrainer — trains models on historical data;
- ModelStorage — loads/saves models. Interacts with the database and file subsystem.

Figure 5 shows the component structure and interfaces between the machine learning subsystem and the other subsystems of the monitoring complex.

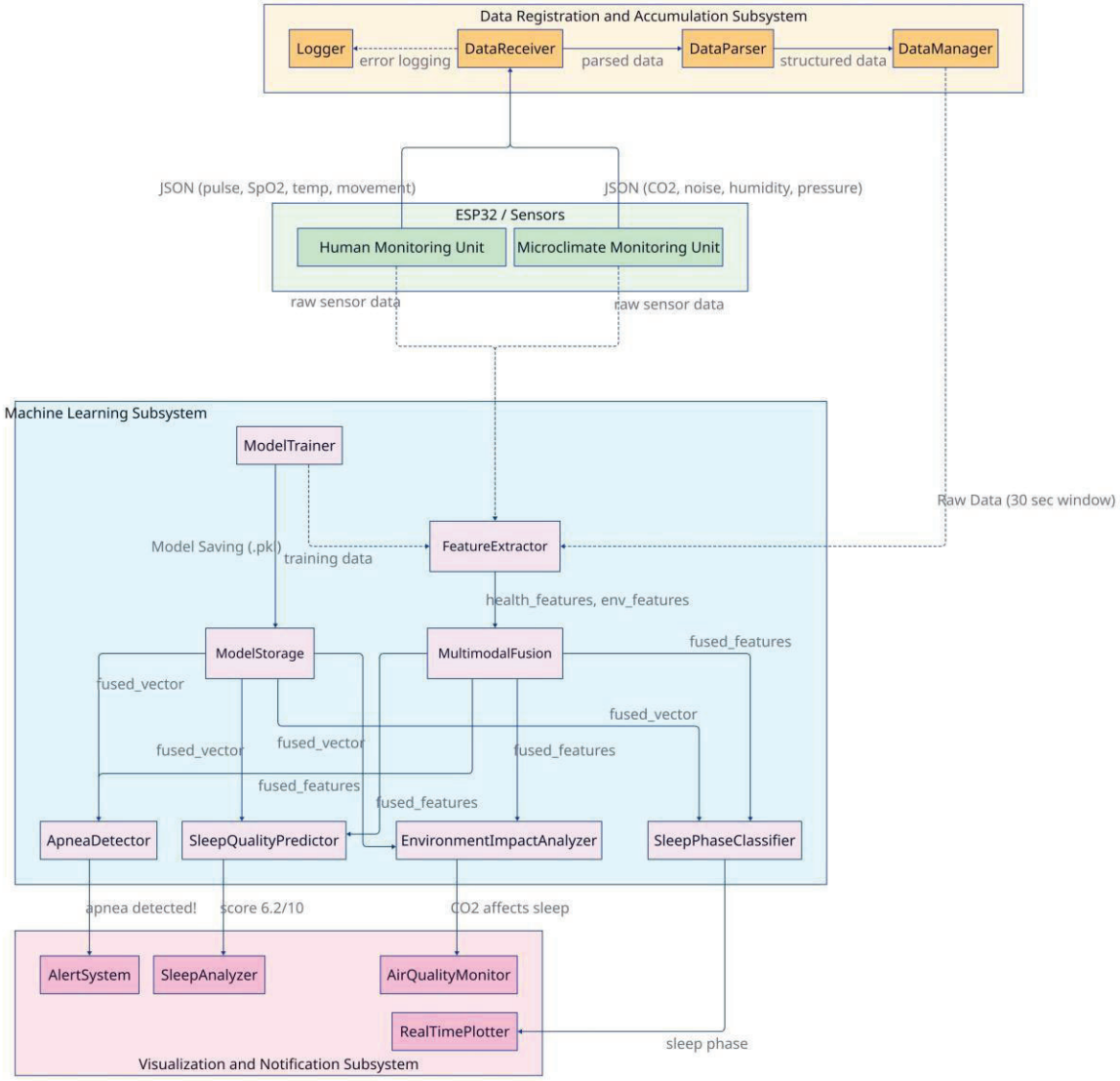


Figure 5: UML component diagram

The IoT logical diagram summarizes component interactions, data flows, and actions (see Figure 6).

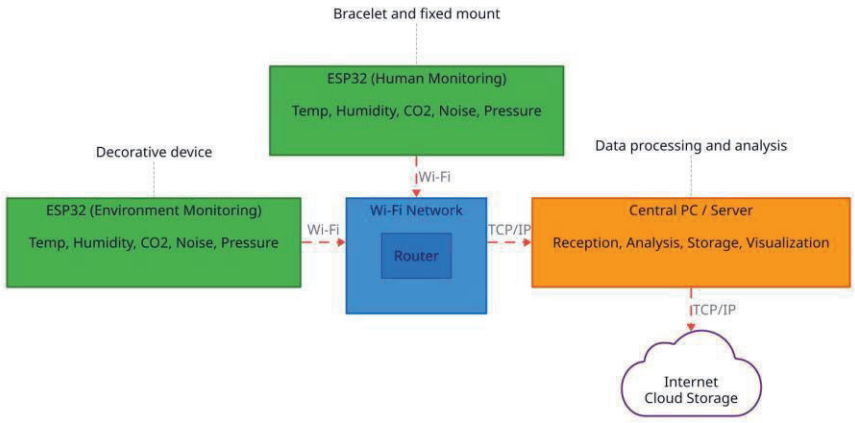


Figure 6: Logical diagram of the IoT monitoring network

4.2. Intermediate closed tests

Closed tests were conducted under controlled conditions to validate subsystem behavior and interfaces before field studies. A lightweight real-time visualization with periodic updates was used to verify signal quality and timing (see Figure 7), and all signals were persisted to the database. The device was subjected to environmental perturbations—elevated noise, exposure to alcohol spray (volatile compounds), illumination changes, and temperature shifts—to establish boundary and acceptable ranges for subsequent machine-learning calibration [4], [7].

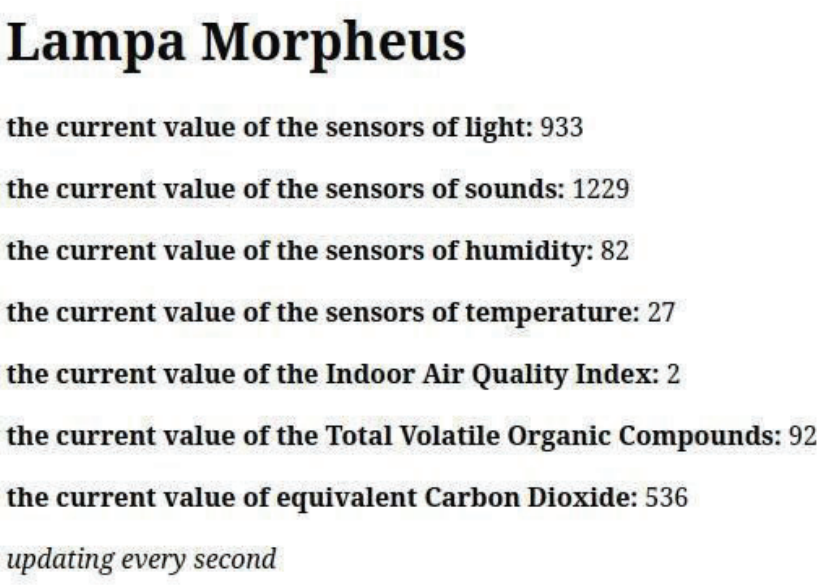


Figure 7: Derivation of numerical indicators for testing purposes

Parallel monitoring was performed with a software–hardware actigraph as an additional comparator. For operator feedback, a minimalist web interface provided real-time display of processed indicators (see Figure 8).

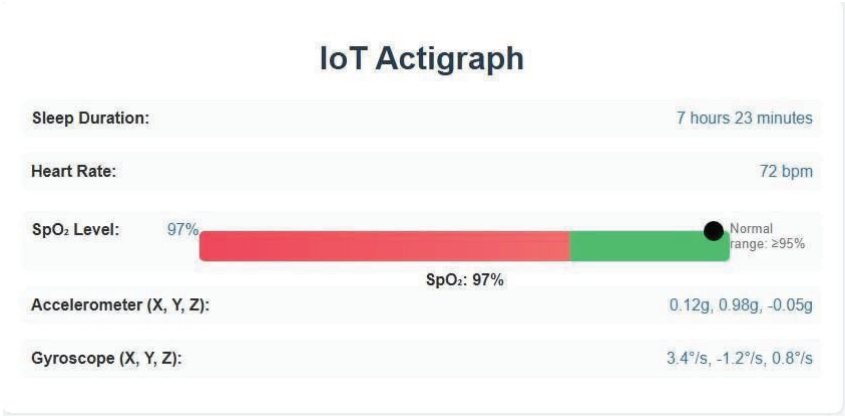


Figure 8: Visualization of indicators

Comparisons of sleep onset and offset times indicated that commercial wearables deviated from the software–hardware system predominantly within ±10 minutes. For one representative participant, deviations were small and occurred more frequently during late bedtimes or when behavioral artifacts accompanied sleep onset (see Figure 9).

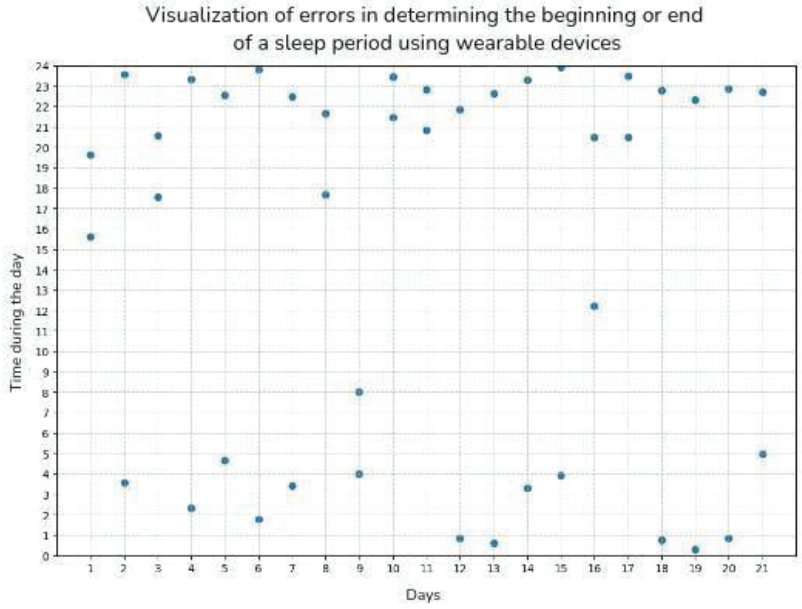


Figure 9: Diagram visualizing deviations of wearable device metrics from manually logged data

5. Results

This work established a multimodal sleep-monitoring architecture and produced an integrated prototype that demonstrates feasibility in realistic conditions:

- modeled and designed the system architecture (hardware, software, data, interfaces) and documented the end-to-end flow and components (see Figure 4, Figure 5, Figure 6);
- implemented a two-device prototype: a physiological sensing node (ESP-32 with MAX30102, AD8232, temperature, GY-521; arm and chest placements) and an ambient lamp unit (CCS811,
- DHT11, microphone, BMP280) with status lighting (see Figure 2 and Figure 3);
- defined data interfaces and storage; implemented a minimal data pipeline and real-time visualization for operator feedback (see Figure 7, Figure 8);
- conducted intermediate closed tests under environmental perturbations to establish boundary and acceptable ranges for calibration and to verify subsystem interoperability and designed-in expand ability;

- performed a preliminary comparison with commercial wearables, observing predominantly ±10-minute deviations for sleep onset/offset (see Figure 9).

A subset of tasks remains in active development and will proceed iteratively with regular unit and integration testing to achieve the project goal and strengthen the practical solution to the problem stated in the beginning of the article.

6. Conclusion

This work demonstrates a practical, extensible architecture for multimodal sleep monitoring that integrates physiological and environmental signals to produce factor-level insights and actionable recommendations. By focusing on technical, measurable determinants of sleep, the approach offers a tractable path to improve outcomes at home while remaining complementary to clinical diagnostics and care pathways, thereby motivating an extensible design.

Accordingly, the system is designed for expandability: external device classes (e.g., the ambient lamp) interoperate via defined interfaces, contribute data to persistent storage, and influence per-user decision mechanisms by leveraging Machine Learning, enabling third parties to adopt the platform as a foundation for their own complex sleep-related systems or to design compatible devices that join the presented ecosystem.

In support of this practical orientation, the project is being developed as a commercial product, and a part of the software has already been registered in the Russian state software registry.

Looking ahead, although this article covers early phases of a larger program, the development trajectory is clear. The results from intermediate closed tests indicate the potential for positive user impact in forthcoming field studies, contingent on continued iterative development with regular unit and integration testing and validation against reference measures.

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Review of Analysis of Traditional Complexity Metrics and Their Applicability to IoT Devices

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Abstract:
This paper presents an analysis of traditional software complexity metrics with the goal of identifying which of these metrics are most relevant for evaluating software quality in embedded systems and IoT devices. The study focuses on three common metrics which are Lines of Code (LOC), Halstead Complexity, and Cyclomatic Complexity metrics. Focus is given on exploring their basic concepts, calculation methods, and practical strengths and weaknesses. By reviewing these metrics in the context of embedded and IoT software development, this work aims to help researchers and developers better understand their applicability and limitations when applying them to embedded systems and IoT devices.

Keywords:
Analysis, Software Metrics, IoT, Embedded Systems

1. Introduction

Software quality metrics are used to evaluate the quality of the software and software source code. As embedded systems and IoT devices are limited in hardware specifications such as central processing unit's operating frequency, storage size, processing power and available memory, it is important to write optimized software that will fit the required use, while maintaining energy efficiency and decent performance. Depending on the context of use, aim should be in writing the source code that is reliable, fast in terms of execution speed, yet small in size but easy to upgrade, with great test coverage.

Understanding the differences in code quality between traditional software systems and Internet of Things (IoT) systems is very important for defining effective development and maintenance strategies. IoT systems operate under different scenarios, including limited hardware resources and distributed network architectures, which requires a specialized approach to code quality assessment. For example, inadequate coding practices in IoT applications, such as those found in smart city infrastructures, can introduce severe security vulnerabilities, resulting in data exposure and other critical risks. The dynamic operational environment of IoT devices further demands a focus on specific quality attributes, including scalability and adaptability [1].

Over the years, many software metrics were widely used to evaluate the quality of the software and software source codes, but they are not yet fully understood. The growth of the software is considered as the growth of the source code complexity as well. Regardless of various metrics that can be applied to measure the quality of software, different approaches and results can not always be compared [2].
However, comparing IoT and non-IoT systems is not an easy task, due to their difference in code and structure [1].

2. Previous work

Software development involves the steps of planning, designing, building, and testing. Measuring complexity in these steps is important in order to create efficient and good software. The IEEE standard defines software complexity as a scientific base for software engineering. Understanding software code is directly tied to how complex it is. However, how hard it is to study the software also matters in software creation. Therefore, software complexity can be defined as the amount of work needed to write, maintain, and run the code [3]. Regarding the software code metrics, they are systematically classified based on various quality attributes, including size, complexity, coupling, cohesion, redundancy, test coverage,

readability, security, heterogeneity, and maintainability [4].Software metrics provide quantitative measures of software attributes and serve as essential tools for quality assurance. Many metrics have been proposed over the years, but their effectiveness for modern programming paradigms is not yet fully established. However, for procedural programming, established metrics like McCabe's Cyclomatic Complexity and Halstead's Software Science have proven effective at identifying code that is difficult to understand, test, or maintain [5].

Speaking about software complexity itself, two main types can be determined which are static metrics and dynamic metrics. Focus of static metrics is oriented towards the early phases of software development life cycle with a goal to calculate amount of effort needed to develop and maintain the code, while dynamic metrics are used for late stages of software development life cycle, and they are designed to capture dynamic behavior of a system. Measuring the software complexity however, can be further divided into specific metrics that are Size based Metrics (related to measuring complexity of software by size attributes such as line numbers, volume… etc.), Control Flow based Metrics (related to measuring aspects of control structures of a program) and Data Flow based Metrics (related to data flow as well as data dependency) [2].

2.1 Lines of Code Metrics

Lines of Code, also known as Source Lines of Code [6], metric is one of the oldest, most basic, and most common measures for calculating program size. Lines of Code refers to the number of instructions in a program, known as Source Lines of Code, which excludes comments and blank lines. However, Lines of Code has been criticized for its inability to account for functionality and cohesiveness, its lack of counting standards, and its dependence on both programming language and programmer style. Alternative measures based on line counting include thousands of lines of code, thousands of delivered source instructions, counts of bytes or characters, and non-commented lines of code. Despite these variations, all line-based metrics share fundamental limitations [5].

According to [7], there are several tools for evaluating lines of code metrics, which are based on measuring different terms of "lines of code":

- **LocMetrics** provides comprehensive code analysis, measuring total lines (LOC), blank lines (BLOC), comment lines (CLOC), mixed code-comment lines, logical lines (SLOC-L), and McCabe complexity. The tool calculates physical executable lines (SLOC-P) by excluding blanks and comments, generating per-file metrics with project-wide accumulation and comment word histograms.

- **LineTally** supports over 60 programming languages with customizable language definitions. It distinguishes between code lines, comment lines, mixed lines, and blank lines, providing both counts and percentages. The tool processes code rapidly and exports reports in CSV, HTML, and TXT formats.

- **SourceMonitor** (Version 3.5) tracks both code quality and quantity metrics. Supporting C++, C#, Java, Visual Basic, Delphi, and HTML, it offers method-level and function-level analysis for detailed code examination and comparison across project versions.

- **Universal Code Lines Counter** delivers decent project analysis by counting code lines, blank lines, and comments across multiple files simultaneously. Featuring an intuitive interface, it presents results in both tabular and graphical formats (pie charts) and supports numerous languages with configurable language settings.

- **Any Code Counter** provides flexible source file analysis with support for all major programming languages and user-defined language configurations. The tool ensures accurate counting results with multiple export format options for reporting and analysis.

2.2 Halstead Complexity Metric

Software science, as defined by Halstead, advanced beyond simple line counting by proposing a

method to determine program size based on its fundamental components. Halstead's metrics analyze a program by counting the distinct operators and operands, along with their total occurrences throughout the code. These counts are used to calculate properties such as Program Vocabulary, Length, Estimated Program Length, Potential Volume, Effort, and Difficulty. An important factor is that they address several weaknesses of the basic line of code metric by defining a computer algorithm as a collection of tokens [5].

Halstead's definition of an "operator" is broader than in conventional programming languages like C++ or Java. It doesn't include only standard symbols like arithmetic and logical operators but also elements such as brackets, punctuation, and function names, which are not typically classified as operators in standard language definitions. This approach reveals that while core operator categories like Assignment, Arithmetic, Logical, and Relational operators are consistent across major languages, others vary. For example, increment and decrement operators exist in C++ and Java but not in Python. Therefore, Halstead's model groups operators into five universal categories applicable to all major languages: Assignment, Arithmetic, Logical, Relational, and a final category for language-specific elements like brackets and function calls [8].

According to [8], operators can be classified as:

- **Assignment Operators**: These handle value assignment, including basic assignment (=), compound operators (+=, -=), and increment/decrement operators (++, --).
- **Arithmetic Operators**: These perform mathematical operations using symbols like +, -, *, and / for addition, subtraction, multiplication, and division.
- **Logical Operators**: These evaluate Boolean logic using operators like AND (&&, and) and OR (||, or).
- **Relational Operators**: These compare values using operators such as <=, >=, ==, and != to establish relationships between operands.
- **Other Operators**: This category includes programming elements like brackets, parentheses, function calls, and other structural tokens that Halstead classified as operators.

However, according to [3], metrics like Halstead's complexity have limitations, particularly with large programs.

2.3 Cyclomatic Complexity Metric

Cyclomatic Complexity Metric, originally named McCabe Cyclomatic Complexity Metric is one of the basic but important metrics to be evaluated [9]. Cyclomatic complexity is a metric that quantifies the complexity of a program's code by analyzing its control flow. It is based on a control flow graph, which is a diagram representing all the possible paths the execution can take through a piece of code [10] and provides a systematic method for creating test cases that cover every logical pathway in a code module. This approach ensures that every decision point in the code is tested under both true and false conditions, significantly increasing the chance of finding hidden bugs and providing better validation of all possible execution paths [11].

According to [2], this metric provides a value of the control flow and can be represented by a formula:

$$V(G)=E-N+2P$$

where V (G)= Cyclomatic Complexity,
E= the number of edges in a graph
N= the number of nodes in graph
P= the number of connected components in graph

However, original formula for Cyclomatic Complexity can be extended to assess the complexity of an entire class across all of its methods, by making a summary of Cyclomatic Complexities for each individual method of the class [12].

As a summary of evaluated metrics on Lines of Code, Halstead and Cyclomatic Complexity, a brief overview table is formed to present the brief summary and noteworthy factors of said metrics.

Table 8:
Overview of Complexity Metrics

Complexity Metric	Brief summary	Pro's for usage in IoT devices	Con's for usage in IoT devices
Lines of Code Complexity	Complexity of measuring lines of code is focused to determine the final size of the program. However, it may depend on the programming language used in development process, as well as the programming style.	This metric is very simple to understand, easy to calculate and interpret, which makes it accessible for both beginner and experienced developers. It may indicate the areas of code that need refactoring for better maintainability.	Compiler optimization should be considered when developing low level code, due to optimization techniques, which may modify the final code translated to binary. For example, compiler may perform inline functions, regardless of function not being set as inline, which will increase actual line count, and reduce size, but will decrease overhead on function calls.
Halstead's Complexity	The summary of Halstead's Complexity Metric is defined as count of operators and operands for software source code, with addition that not only operators and operands are counted, but symbols such as brackets are taken into the account as well. Similar to Lines of Code metrics, it depends on the language used, as not all operators and symbols are present across all languages.	Since this metric is based on counting operands and operators, it may be applied across most of the languages used in the development process. It may indicate potential logical complexity by evaluating the number of operators and operands.	Depending on the language implemented for a software solution, symbols may vary and final score of Halstead's Complexity Metrics may differ. Considering the possibility of compiler optimization techniques, final instructions may be altered, and complexity may be different from the source code before the process of compilation.
Cyclomatic Complexity	This metric is focused on quantifying the control flow of program. Based on a control flow graph, it is used to quantify and calculate the value for all possible paths in the program execution.	This metric is able to quantify the number of independent execution paths in a program, and gives a better view on how complicated is the logic of the software that is being observed. Besides quantifying the number of execution paths, it can serve to identify high-risk code sections, and may improve testing strategies.	Due to nature of IoT systems and embedded devices, control flow, in some cases, may be strictly defined, without the possibility of alteration.

3. Contribution

This paper contributes to the field of software engineering for IoT devices and embedded systems by presenting a brief analysis of traditional software complexity metrics. It looks at three commonly used metrics which are Lines of Code (LOC), Halstead Complexity, and Cyclomatic Complexity and reviews their basic concepts, how they are calculated, and their general strengths and weaknesses in relation to

their use in IoT systems. This analysis clarifies the strengths and weaknesses of these traditional metrics for IoT software and points out the difficulties that can occur when applying them without changes. This work supports researchers and developers in making better decisions about which metrics to use or adjust for evaluating software quality in devices with limited resources. The goal is to encourage more effective code evaluation, improve software maintainability, and guide efforts to optimize code in ways that meet the needs of modern embedded systems software as well as help to build better IoT devices.

4. Conclusions

The analysis presented in this paper confirms that traditional software complexity metrics continue to offer ability of performing source code quality evaluation, but their direct application to IoT and embedded systems requires careful applicability. Lines of Code remains a useful indicator of code size and potential memory usage, especially in systems where resource limitations are strict. However, it may be depend on the compiler optimization flags set before actual compilation, and lacks the ability to represent functional or logical complexity. Halstead Complexity provides a deeper structural view of the software by analyzing the use of operators and operands, but may differ across different programming languages and is sensitive to compiler optimizations. Cyclomatic Complexity stands out as generally relevant in IoT systems where logical control paths must be validated, such as in safety-critical or real-time applications. Its ability to guide test coverage and identify high-risk sections of code is especially useful in the context of embedded software and IoT devices. Regardless of these metrics not being able to evaluate overall software complexity, they can significantly help developers and engineers to make better decisions when designing, testing and maintaining IoT devices in resource-constrained environments.

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Serbian Workforce Potential for Leading Global IT Projects

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Abstract

This paper examines the key characteristics and potential of the Serbian IT workforce to lead global IT projects. Focus is moving beyond outsourcing model and Serbian market potential to individual potential for leadership. Through a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis, the Serbian professional has been positioned at the center of the discussion. The primary strengths shown include the individual's high quality educational background, high English language ability, and a unique "leader mentality" rooted in cultural resilience and adaptability. However, Serbian professionals face weaknesses such as limited exposure to global markets and a skills gap that can affect career growth. Opportunities exist for individuals to position themselves as leaders in a regional hub and to proactively get in-demand skills. The most significant threat of talent migration to wealthier countries can be strategically redefined as an opportunity for remote recruitment. This would expand the talent pool of Serbian IT professionals globally. By embracing this strategy and proactively addressing the erosion of personal career competitiveness, the Serbian IT professional has unique potential to lead complex, international projects.

Key words: Serbian Workforce, Leadership, IT projects, Global, Individual Potential

1. Introduction

In the modern digital economy, the quality of a nation's human capital is the primary determinant of its global competitiveness. The Serbian IT sector's remarkable growth is fundamentally a story of its people. Over the past decade, Serbian professionals have transitioned from being a source of outsourced labor to becoming a power of innovation and project leadership. This paper, building upon a comprehensive review of domestic and international research, provides a structured analysis of the individual capacity of the Serbian IT workforce to hold these leadership roles. The method based on a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis, which will clearly define the advantages to focused on and used, the challenges that need to be addressed and overcome, and the strategic pathways forward for the individual professional.

The research addresses the global phenomenon of the "reskilling revolution" [1] and the "talent paradox" where a high unemployment rate exist together with a broad inability for companies to find professionals with specific skills needed for innovation and growth [2]. This shift has been speeded up by the COVID-19 pandemic, which has strongly shown remote work as a new norm and a significant factor in talent mobility [3]. In this context, the demand for skills has evolved from a low to medium skilled, routine based workforce to one with advanced technical and soft skills. Studies confirm that for a nation's workforce to thrive, individuals must have digital and entrepreneurial skills. "Transferable skills" such as critical thinking, problem-solving, and effective communication, which are essential for managing constant organizational change [3].

While a strong educational background provides Serbian professionals with a solid technical foundation with over 70% of professionals holding a university degree [4], there is a notable paradox in the practical application of leadership. Research shows that the Serbian workforce shows an intense desire for improvement in areas like 'future orientation' and 'performance orientation,' signaling a potent, but often untapped, leadership potential [5]. The successful conversion of this potential into global leadership roles depends on a supportive managerial environment built on trust, communication, and psychological empowerment [6]. This paper argues that by strategically investing in the development of these specific leadership competencies, Serbian professionals can successfully navigate the challenges of the global market and show themselves as capable leaders of complex, distributed projects.

2. Theoretical Review of Literature

The successful leadership of global IT projects, especially in a remote work environment, is a complex phenomenon influenced by a convergence of human, organizational, and technological factors. The literature provides a robust framework for understanding these dynamics, extending beyond traditional technical competencies to encompass soft skills, cultural intelligence, and the psychological aspects of distributed work.

2.1. The Evolving Role of Skills and Competencies

Modern business, highly influenced by digital technologies and global crises, is facing a "reskilling revolution" [1]. The need has shifted from a low to medium skilled, routine based workforce to one with advanced technical and soft skills. Studies confirm a global "talent paradox" where a high unemployment rate coexists with a widespread inability for companies to find professionals with the specific skills needed for innovation and growth [2]. The literature highlights that for a nation's workforce to thrive, individuals must have digital and entrepreneurial skills, and "transferable skills" such as critical thinking, problem-solving, and effective communication, which are essential for managing constant organizational change [3]. In the context of remote project management, the importance of "soft skills" and emotional intelligence are most important, as they are critical for growing and keeping a positive team dynamic and collaborative problem-solving, often overpowering technical factors in concluding project success [6].

2.2. Managerial Support in a Remote and Hybrid Context

The shift to remote and hybrid work models has highlighted the significant role of effective leadership and managerial support. A supportive leader is crucial for building a safe psychological environment that motivates people and ensures their involvement and commitment during times of organizational change [6]. This support, together with emotional, and informational help, is a key job resource that enhances employee satisfaction, reduces job stress, and mitigates turnover intention among employees [5]. As organizations plan hybrid work models, leaders must understand that trust, justice, communication, and psychological empowerment are central to shaping a positive employee response to change [6]. For remote projects specifically, formal mentoring programs are identified as a vital mechanism for knowledge sharing, which otherwise occurs naturally in a physical office [12]. This is particularly important for complex projects, where knowledge gaps and information hiding can become significant bottlenecks to success [3].

2.3. The Influence of Cultural and Socio-economic Factors

A workforce's potential cannot be fully captured without considering its cultural context. Research on Serbian national culture, based on the GLOBE project, reveals a society with high "in-group collectivism"

and high "power distance" (as it is), yet with a strong desire for improvement in areas like "future orientation" and "performance orientation" (as it should be) [5]. These cultural values and aspirations are directly relevant to business practices and leadership styles. The frequency of a "leader mentality" in the general academic population and resilience in the Serbian workforce can be explained through cultural traits, which favor strong group cohesion and problem-solving, traits highly valuable in a global environment [7]. However, socio-economic factors also play a significant role. Studies confirm that for the Serbian workforce, compensation is the most curtail factor for employee engagement and organizational commitment, surpassing the influence of age and educational level [9]. This finding underscores that monetary incentives are a primary motivator, and that a lack of adequate managerial support can lead to high job stress and turnover intention among highly educated millennials in Serbia [5]. Furthermore, research on women's leadership in Serbia highlights persistent challenges in balancing professional and personal life, a factor that influences career advancement despite elevated levels of education and business success [8].

In conclusion, the theoretical literature proves that the Serbian IT workforce's potential for global leadership is a multifaceted issue. It is supported by a strong educational base and a resilient cultural mindset but is also mediated by the efficacy of remote work management, the role of compensation in motivation, and the need to address internal and external cultural challenges. This comprehensive understanding sets the stage for a detailed SWOT analysis that will fully explore the strategic position of the Serbian IT professional in the global market.

3. Case Study

3.1. SWOT Analysis of the Serbian IT Workforce

A detailed SWOT analysis provides a framework for understanding the internal and external factors influencing the Serbian IT workforce's potential for global leadership.

Strengths (Individual Attributes)	Weaknesses (Personal Challenges)
* **Strong Educational Foundation:** The average Serbian IT professional has a strong educational background from a university system that constantly provides highly technically proficient graduates.	* **Small Domestic Market:** The limited size of Serbia's population and highly skilled individuals results in a comparatively smaller talent pool for companies to draw from. This can be a major limitation for companies looking to scale fast.
* **High English Proficiency:** High English language ability, a strength enabling seamless collaboration in global teams and cross-cultural teams.	* **Weak Global and Cross-Cultural Exposure:** While a huge part of the workforce is engaged in international projects, some individuals may still lack direct, exposure to diverse global markets and cross-cultural exposure. The national culture also has low scores for "future orientation" and "performance orientation" as it is, showing a gap between current practice and desired goals.
* **Favorable Cost-Effectiveness:** The individual's compensation is still a competitive cost-to-quality ratio compared to professionals in more developed Western European hubs, enabling them to be an attractive asset for international clients.	* **Talent Paradox and Skills Gaps:** A "talent paradox" exists where many professionals, despite high unemployment rates, may still struggle to have the specific practical and soft skills that companies need for innovation-driven growth. The lack of structured development and mentoring programs can widen this gap in remote settings.
* **Leader Mentality and Resilience:** The local professional culture is characterized by individual adaptability, a strong work ethic, and a natural inclination towards	* **Underinvestment in Upskilling:** There can be a lack of personal upskilling awareness among management structures which is reflecting in their ability to develop their

problem-solving, which is crucial for leading and managing complex projects. The national culture's high desire for "performance orientation" and "future orientation" shows a strong ambition for success and growth.	teams and talented individuals. They can deceive and blind sided by their limitations to manifest continues improvement mindset. Hence, it has been shown that salary and benefits, are the main driver of engagement and loyalty in Serbian workforce.
* **Digital Skills and ICT Knowledge:** Serbian professionals have a powerful base in digital skills and technical knowledge, making them well-prepared for technical leadership development and complex solutioning in modern business.	* **Work-Life Balance for Women:** As in many other developing countries, female Serbian leaders if highly engaged in global project, different time zones and dedicated to her carrier can have challenges balancing her professional and personal life due to traditional gender roles and expectations.
Opportunities (Personal Growth Paths)	**Threats (External Risks)**
* **Remote Leadership:** The rise of remote work presents a clear opportunity for Serbian professionals to take on leadership roles in global projects without moving countries, directly addressing the barrier of geographic location. Formal mentoring and development programs for developing remote work skills can help professionals get the communication and soft skills needed to succeed. This can create advantage of selecting and engaging high quality Serbian individuals outside of Serbia.	* **Brain Drain:** The most significant threat is the ongoing migration of skilled individuals to countries offering higher salaries and improved living standards. This is a critical risk, as high compensation and managerial support are key to reducing turnover intention among highly educated millennials in Serbia.
* **Focus on In-Demand Skills:** Professionals can focus their learning on high-demand skills like analytical abilities and digital competencies, creating a strong personal competitive advantage in the global market. Training in communication, negotiation skills, and influencing is also identified as highly beneficial for leadership advancement.	* **Erosion of Personal Cost Advantage:** As the Serbian market and IT sector matures, salaries rise, an individual's cost-effectiveness may diminish. To remain competitive, low profiled skilled professionals must transition their value proposition from being a basic skilled provider to a high-quality, high-leadership-potential asset.
* **Using Cultural Similarities:** Professionals can use shared cultural characteristics with key international partners, such as a high-power distance and collectivism, to build stronger and more efficient collaborative relationships in global teams. Furthermore, a leader's support, grounded in trust, communication, and psychological empowerment, is a crucial enabler of organizational change in a remote/hybrid context, and this is a skill Serbian professionals can cultivate.	* **Global Competition:** The individual professional faces intense competition for jobs and projects from a global talent pool, and other low cost developing countries technical hubs.
* **Leader Mentality and Resilience:** The local professional culture is characterized by individual adaptability, a strong work ethic, and a natural inclination towards problem-solving, which is crucial for leading and managing complex projects. The national culture's high desire for "performance orientation" and "future orientation" shows a strong ambition for success and growth.	structured development and mentoring programs can widen this gap in remote settings. * **Underinvestment in Upskilling:** There can be a lack o personal upskilling awareness among managemen structures which is reflecting in their ability to develop their teams and talented individuals. They can deceive and blind sided by their limitations to manifest continues improvement mindset. Hence, it has been shown tha salary and benefits, are the main driver of engagemen and loyalty in Serbian workforce.

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3.2. Comparative Analysis: Serbian Professionals vs. Peers in Leading Central and Eastern European Hubs

To contextualize the potential of Serbian professionals, it is useful to compare their experience and skills with those in more established Central and Eastern European hubs such as Poland, Romania, and the Czech Republic. This comparison highlights Serbia's unique place and the strategic challenges it faces as a non-EU member competing with regional leaders.

- **R&D Investment and Innovation:** While Serbia is improving its innovation inputs, its

investments in R&D as a percentage of GDP are still far below the EU average. In contrast, its regional peers, as EU members, often have access to greater structural funds and private sector investment, which fuels a higher rate of disruptive innovation. Hence Polish, Czech, and Romanian professionals have on average, higher exposure to intercultural, high impact, and big scale projects, and because of that the opportunity and ability to develop top leadership skills and compete with Serbian professionals.

- **Cost vs. Market Maturity:** Serbia's cost advantage is gradually diminishing as its market matures, and it is becoming a more expensive market compared to Romania and Poland. This is a critical transition point. To remain competitive, Serbian professionals must shift their value proposition from being a "low-cost provider" to a "high quality, high leadership potential provider."
- **Talent Retention and Migration:** Talent migration is a significant threat, with Serbian developers moving to wealthier countries for higher salaries and better lifestyle. This is a common challenge for emerging economies but is particularly visible in Serbia, which ranks poorly on "brain retention" according to the Global Talent Competitiveness Index (GTCI) [2]. The opportunity lies in recruiting Serbian talent across the globe and enabling high-profile professionals to contribute to global IT projects with their unique set of skills, talents, and experiences.
- **Business Culture and Management:** The provided papers highlight unique cultural factors in Serbia, such as a strong orientation towards teamwork and a preference for direct communication, which are valuable in project-based work and crucial for leadership roles. With that, there is a paradox in the practice, where with the high potential and culture Serbian workforce is lacking self-initiative for reskilling and improvement [7]. Leading countries have more established frameworks for continuous professional development and a more robust ecosystem for integrating new skills.

This analysis shows that Serbia is not simply competing on price but is actively engaged in a race for talent, innovation, and leadership against both regional peers and global powerhouses. Its path to success lies in using its human capital, strategically organized communities for continuous learning, which will develop strengths to overcome its structural and cultural weaknesses.

4. Conclusion

In summary, the Serbian IT professional presents an attractive case for global project leadership. Their core strengths in education, language ability, and a resilient mindset are powerful assets. These strengths are deeply rooted in a cultural paradox: a society with an intense desire for improvement in future and performance orientation, despite low current scores on these dimensions. To fully capitalize on this potential, the Serbian IT professional must proactively pursue continuous learning, seek out greater global exposure, and re-discover and cultivate a distinct leader mentality. By embracing opportunities to lead international projects remotely and by strategically developing in-demand skills, the individual can effectively mitigate threats like migration and strong global competition.

However, the analysis reveals that this potential is not granite for the actual success and accomplishment. To support and enable Serbian professional, the proposal is a formation of strategically organized development centers. These centers would serve as a fundamental bridge between academia and industry, cultivating an environment of encouragement, continuous learning, development, and innovation. Their primary focus would be on Research and Development (R&D) for human capital, moving beyond traditional R&D that is focused on product and technological innovation.

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ICT as a Catalyst for Effective Waste Management in the Circular Economy Context

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Abstract:
The circular economy (CE) proposes a systemic shift from the linear "take–make–dispose" model toward regenerative, closed-loop value creation. This paper examines how information and communication technologies (including Internet of Things (IoT) sensing, big data analytics, artificial intelligence (AI), blockchain, cloud and edge computing, and digital product passports DPPs) can accelerate the transition to circular practices across industries. We outline CE principles and policy drivers, analyze ICT enablers, and present regional insights from the Western Balkans, with a focus on North Macedonia. Case studies illustrate the challenges of e-waste management and the opportunities provided by digital tools. Findings indicate that ICT is not merely supportive but a transformative driver of circularity, providing transparency, predictive intelligence, and new business models.

Keywords:
Circular economy, e-waste management, ICT, IoT, digital product passport, circular economy action plan, ecodesign for sustainable products regulation, predictive intelligence

1. Introduction

The increasing scarcity of resources, coupled with climate change and waste growth, challenges the traditional "take–make–dispose" economic model [1][2]. The circular economy seeks to decouple growth from resource consumption by extending product lifetimes, enhancing recycling, and regenerating natural systems [3][7].

Globally, CE is supported by international agendas such as the UN Sustainable Development Goal 12 on sustainable consumption and production [5]. Within Europe, the European Green Deal and the Circular Economy Action Plan 2020 (CEAP 2020) provide regulatory and financial frameworks for embedding circularity in industries [1][2]. Complementary initiatives such as the Ecodesign for Sustainable Products Regulation (ESPR) and the planned roll-out of DPPs strengthen product transparency [3][13].

ICT is essential for implementing CE principles. IoT sensors and cloud platforms enable continuous monitoring of material and energy flows, supporting predictive maintenance and optimized resource use [8]. Empirical studies indicate that IoT-based monitoring systems can reduce waste generation by up to 30% and improve collection-route efficiency by 20–25%, depending on sensor density and data-integration maturity [8][9]. Artificial intelligence and big data analytics further enhance decision-making by identifying circular design opportunities and improving efficiency in recycling processes [9]. Meanwhile, blockchain technologies strengthen transparency and traceability within supply chains, promoting trust and accountability among stakeholders [10]. Yet adoption remains uneven, particularly in transition economies such as the Western Balkan countries, where infrastructural, interoperability, and financial barriers persist [15][16].

This paper contributes by providing a comprehensive review of the circular economy theory and policy foundations, followed by an analysis of the key information and communication technology enablers that facilitate the transition toward circularity. Furthermore, it discusses both global and regional case studies, with a particular emphasis on the implications for Macedonia, highlighting how digital transformation can accelerate the adoption of circular practices within emerging economies.

Methodologically, this study is grounded in a systematic literature review and comparative policy analysis, synthesizing academic research, institutional reports, and regional case studies to identify technological, regulatory, and socio-economic enablers of circularity

2. Theoretical framework

The CE paradigm consists of three principles: design out waste, keep materials in use, and regenerate natural systems [7]. Theoretical foundations include industrial ecology (which frames production systems as closed loops), the performance economy (which emphasizes service-based models, like leasing instead of ownership), and cradle-to-cradle design (which supports continuous cycles for biological and technical materials) [3][7].

In Europe, CEAP 2020 and ESPR operationalize these concepts by mandating repairability, recyclability, and transparency [2][3]. At a global scale, SDG (Sustainable Development Goal) 12 reinforces monitoring indicators such as material footprint and resource efficiency [5].

3. ICT enablers of circularity

Digital technologies supply the visibility, intelligence, and connectivity required to operationalize CE principles across industries. The following subsections highlight the key ICT domains and their roles as catalysts of circular economy practices.

- *IoT and sensors* - devices that enable real-time monitoring of materials and energy use. Predictive maintenance reduces downtime and waste [8],
- *Big data and AI* - machine learning models forecast demand, optimize design for recyclability, and support dynamic waste collection [9][10]. Digital twins simulate life cycles for better decision-making,
- *Blockchain and digital product passports* - blockchain ensures immutable records for material provenance and supports the EU's Digital Product Passport initiative, particularly in electronics and batteries [11][12][13],
- *Cloud and edge computing* - cloud systems provide scalability, while edge computing enables real-time processing at the source [12] and
- *Integrated digital architectures* - combining IoT, AI, cloud, and blockchain creates platforms for transparency and coordination across stakeholders [10].

To better illustrate the role of digital solutions in supporting circular practices, Table 1 summarizes the main categories of ICT technologies, their application areas within the circular economy, and the expected benefits reported in recent studies. This synthesis condenses insights from multiple domains (ranging from predictive maintenance with IoT sensors to transparency enabled by blockchain and digital product passports), showing how technology creates tangible pathways toward resource efficiency and waste reduction.

As shown in Table 1, each ICT technology addresses a distinct but complementary dimension of circularity. IoT and sensor networks provide real-time visibility into material and energy flows, enabling predictive maintenance and minimizing losses. Big data and AI contribute analytical power to forecast demand and optimize product design for recyclability. Blockchain and DPPs reinforce trust and transparency in secondary markets, while cloud and edge computing ensure scalable and efficient data processing. Finally, digital twins allow companies to test circular strategies virtually before implementation, reducing both risks and costs. Collectively, these technologies form an integrated digital architecture that underpins the successful transition from linear to circular business models.

Table 1:
ICT technologies enabling circular economy practices.

ICT Technology	Application in CE	Expected Benefit	Sources
IoT sensors	Real-time tracking of materials & energy use	Predictive maintenance, Reduced waste	[8][12]
Big data and AI	Demand forecasting, Design for recyclability	Optimized resources, Longer product life	[9][10]
Blockchain / DPP	Provenance & transparency in supply chains	Trust in refurbished goods, Recovery of materials	[11][13]
Cloud and edge computing	Scalable processing of IoT and operational data	Faster decisions, Efficient recycling ops	[12]
Digital twins	Life-cycle simulation & end-of-life planning	Better design, Extended lifespan	[10]

4. Industry and regional case studies

The global electronics sector illustrates both the urgency and opportunity of CE. The Global E- waste Monitor 2024 reports that documented collection and recycling remain near 22 % of total e- waste and may fall further without decisive action [17]. Leading manufacturers now deploy IoT sensors to track product lifecycles and automate returns for refurbishment. Global e-waste reached over 62 million tons in 2022, but only 14 million tons were documented as recycled [6]. Projections indicate >80 million tons by 2030, with a declining recycling rate [6].

To contextualize the urgency of digital interventions in waste management, it is essential to examine the global dynamics of electronic waste. Over the past decade, the world has witnessed a steep increase in total e-waste generation, while the documented collection and recycling rates have remained disproportionately low. Figure 1 presents the trends in global e-waste generation and documented recycling between 2010 and projected values for 2030, highlighting the widening gap that underlines the critical role of ICT solutions in closing the loop.

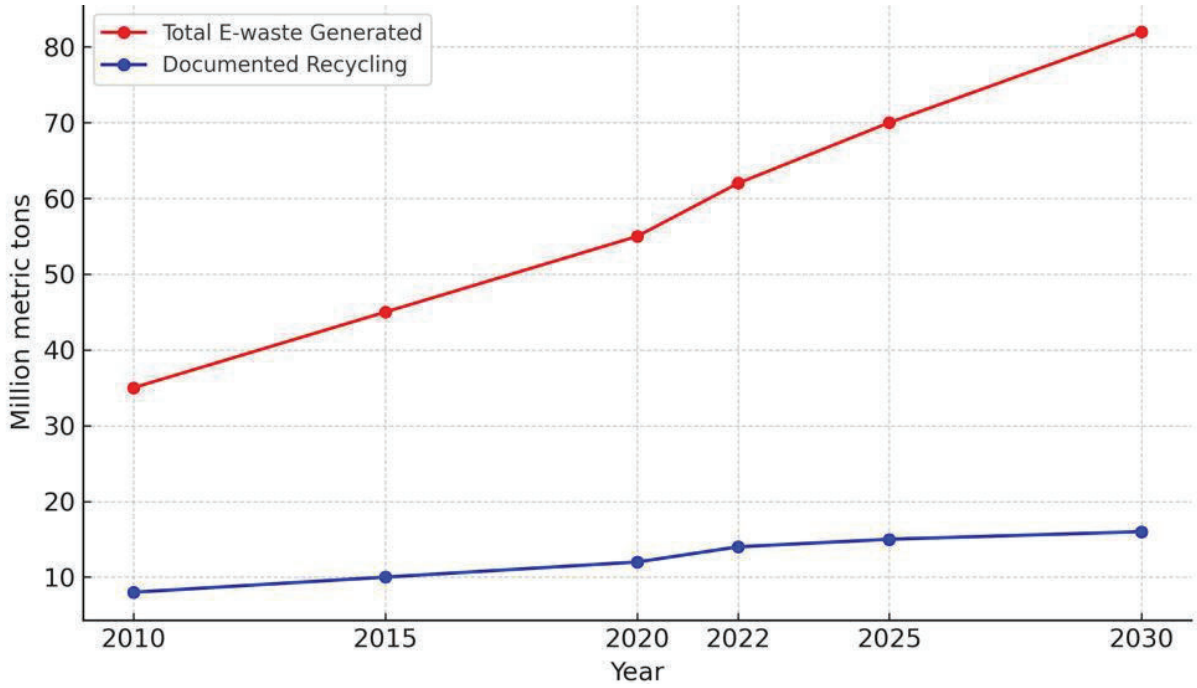


Figure 1: Global e-waste generation vs. documented recycling (2010–2030). Source: Global e-waste monitor 2024 [6]

While total e-waste volumes increased from approximately 35 million metric tons in 2010 to more than 62 million tons in 2022, documented collection and recycling grew only modestly, from 8 million to 14 million tons over the same period [6]. Projections from the Global E-waste Monitor 2024 suggest that by 2030, total e-waste could exceed 80 million tons, with the documented recycling rate declining to 20%. This widening discrepancy underscores systemic inefficiencies in global waste- management systems and highlights the urgent need for digital solutions (such as IoT-based monitoring, blockchain-enabled Digital Product Passports, and AI-driven analytics) to improve traceability, collection, and recovery processes. Without such interventions, the environmental and economic costs of unmanaged e-waste will continue to escalate, particularly in developing and transition economies.

4.1. CIRPASS digital product passport (DPP)

The electronics sector generates one of the fastest-growing waste streams worldwide. According to the Global E-waste Monitor 2024, documented collection and recycling accounted for just 22.3% of global e-waste, with projections that this rate could fall toward 20% by 2030 without stronger policy and technological interventions [17]. The European Union, through the CEAP and the ESPR, has introduced the concept of DPPs as a transformative mechanism to improve transparency and traceability in product life cycles [6][8].

4.1.1. System concept and use cases

The Collaborative Initiative for a Standards-based Digital Product Passport for Stakeholder- Specific Sharing of Product Data for a Circular Economy or CIRPASS Project (2022–2025), funded by the EU Horizon programme, has developed and tested DPP use cases in three priority sectors: electronics, batteries, and textiles.

For electronics, two concrete use cases have been documented [13]:

- *Refurbished smartphones* - DPPs provide detailed information on device history, repair records, and component composition. This reduces information asymmetry between refurbishers and consumers, enabling trust in second-hand markets
- *Recovery of critical raw materials* - DPPs support recyclers by offering transparent data on the presence and location of valuable elements such as cobalt, lithium, and rare earths in small electronic devices. This facilitates efficient extraction and reduces dependency on virgin raw materials as described in the CIRPASS D2.2 use case on critical raw materials [13].

Both use cases highlight the potential of combining IoT-enabled identification, cloud or edge data platforms, and blockchain-based ledgers to ensure authenticity and prevent tampering [12][17].

Although CIRPASS is a pilot rather than a fully scaled deployment, its findings indicate that DPPs can significantly improve the efficiency and transparency of e-waste management. The project predicts measurable outcomes such as increased recovery rates of critical raw materials, higher consumer trust in refurbished electronics, and a reduced environmental footprint through extended product lifetimes [13]. As part of the Western Balkans, Macedonia's circular economy roadmap [15] already identifies electronics and waste management as priority areas. Lessons from CIRPASS could be adapted to the local context as:

- *Regulatory alignment* - adoption of EU-aligned frameworks on product traceability and extended producer responsibility will be essential as part of accession processes,
- *Pilot initiatives* - municipalities such as Skopje could initiate small-scale pilots with electronics retailers, integrating DPP-based identification for returned devices,
- *Capacity building* - training refurbishers and recyclers to use DPP systems would create skilled jobs and improve competitiveness and
- *Regional collaboration* - a Western Balkan DPP hub, shared among multiple economies, could reduce costs and foster interoperability.

In the end, the CIRPASS case illustrates how ICT-driven solutions (particularly DPPs) can transform waste management from an afterthought into a strategic pillar of the circular economy. For Macedonia, the adoption of similar pilots would not only contribute to environmental goals but also align the country with EU market requirements, strengthening both sustainability and economic integration.

4.2. Regional perspective for Western Balkans and North Macedonia

The OECD's Roadmap for North Macedonia (2025) identifies e-waste as a priority sector [15]. Collection rates remain below EU averages (~15%), with significant infrastructural gaps [16][17]. Regional initiatives under the Green Agenda for the Western Balkans stress harmonization with EU policy [19][22]. Table 2 provides a comparative overview of e-waste generation, collection rates, and policy alignment across Western Balkan economies, illustrating both regional disparities and common challenges in the transition towards EU circular economy standards.

Table 2 Regional e-waste and Circular Economy Policy Alignment in the Western Balkans.

Country/Region	E-waste (kg/capita, 2022)	Documented Collection (%)	Policy Alignment with EU CEAP	Sources
NorthMacedonia	10.5	15	Partial (Roadmap 2025)	[15][16][18]
Albania	9.8	12	Early-stage	[18]
Serbia	14.2	20	Advanced	[18][19]
Bosnia&Herzegovina	12.7	18	Partial	[18]
Montenegro	11.3	17	Partial	[18]
Western Balkans Avg	11.7	16.4	Mixed	[18][19]

As shown in Table 2, the Western Balkans present significant disparities in e-waste generation and documented collection rates. Macedonia, with approximately 10.5 kg of e-waste generated per capita in 2022, demonstrates a collection rate of only 15%, which lags behind the EU average of over 40% [6][15]. Serbia shows relatively stronger performance (20%), while Albania remains at an early stage of circular economy adoption with the lowest collection rate of 12%. Across the region, the average collection rate of 16.4% highlights structural challenges in waste management systems, including limited infrastructure, financial constraints, and informal recycling practices. Policy alignment with the EU's CEAP remains partial in most countries, though Serbia is more advanced due to ongoing accession negotiations. These figures underline the urgent need for harmonized legislation, regional cooperation, and investment in digital infrastructures (particularly DPPs and IoT-enabled waste monitoring) to close the gap with EU standards and ensure progress towards sustainable circular practices.

5. Challenges and limitations

Despite promising technological capabilities, the integration of information and communication technologies into circular economy strategies faces a range of systemic obstacles, like:

- **Regulatory and policy gaps** - while the European Green Deal and the Circular Economy Action Plan set ambitious targets, national transposition and enforcement remain uneven across EU members and accession countries [6][7][8][9][19]. Western Balkan economies, including Macedonia, are aligning with EU standards, yet discrepancies in waste-management infrastructure, procurement rules, and environmental enforcement slow progress [21].
- **Financing and market barriers** - circular business models often require substantial up-front investment in sensing infrastructure, analytics platforms, and staff training [12][16]. Many small and medium-sized enterprises - SMEs (the backbone of regional economies)

lack access to affordable credit and risk-sharing mechanisms [20][21]. Without supportive fiscal instruments such as green bonds, tax incentives, or extended producer responsibility schemes, private actors hesitate to adopt capital-intensive ICT solutions.

- **Data privacy and cybersecurity** - IoT sensors, blockchain-based product passports, and cross-industry data-sharing raise significant privacy concerns under GDPR and related frameworks [6][19]. Breaches could expose proprietary formulas, customer usage patterns, or material sourcing information. Although blockchain provides immutability, it cannot prevent the input of false data (GIGO or "garbage in, garbage out"), necessitating multi-layered verification and access controls [18][19].
- **Technical and interoperability issues** - heterogeneous data formats and legacy industrial systems hinder seamless integration. Digital twins and real-time analytics depend on interoperable standards and high-quality datasets; however, many municipal and industrial actors maintain siloed or incomplete records [12][13][14][16]. Without common ontologies and open APIs, the benefits of predictive analytics and cross-supply-chain optimization remain limited.
- **Social and cultural factors** - effective circular transitions also depend on behavioral change. Public awareness of reuse, repair, and recycling remains low in parts of the Western Balkans [21][22][23][24]. Workforce upskilling is essential to operate advanced analytics, cybersecurity frameworks, and IoT infrastructure. Absent targeted education and incentives, even well-designed technological solutions may fail to achieve scale.

6. Conclusion and directions for further work

This paper has demonstrated that digital technologies are not merely auxiliary tools but transformative drivers of circularity. ICT is not simply supportive but transformative for the CE transition. IoT, AI, cloud or edge, and blockchain enable predictive intelligence, transparency, and resource efficiency. Case studies from global e-waste trends, CIRPASS pilots, and North Macedonia show both opportunities and persistent gaps. Looking ahead, three strategic directions may emerge:

1. **Standardization and interoperability** - developing open data standards, shared ontologies, and secure APIs will allow SMEs and municipalities to join multi-actor platforms without prohibitive costs,
2. **Innovative financing** - green bonds, public–private partnerships, and extended producer responsibility mechanisms can lower the cost of digital infrastructure, particularly for SMEs and
3. **Human capital and governance** - upskilling programs, privacy-by-design frameworks, and transparent data-governance policies will build public trust and ensure that circular ICT systems remain secure and equitable.

By bridging technological innovation with policy, financing, and human-centered design, information technologies can anchor a resilient, low-carbon, and inclusive circular economy regionally (in the Western Balkan) and globally.

6.1. Methodological limitations

While this study provides a conceptual and analytical overview of ICT's role in advancing circular economy practices, several methodological limitations should be acknowledged. The analysis primarily relies on secondary data sources and policy documents, without empirical validation through field measurements, stakeholder surveys, or quantitative modeling. Consequently, the presented insights reflect synthesized evidence rather than statistically tested results. Moreover, regional comparisons are constrained by data availability and inconsistency across national reporting frameworks. Future research should adopt mixed-method approaches, including case-based modeling,

pilot monitoring, and econometric analysis, to validate and quantify the real impact of ICT-enabled circular interventions under diverse socio-economic conditions.

Future work should investigate large-scale pilot implementations to validate the scalability, interoperability, and performance of ICT-enabled circular systems under real-world conditions. Furthermore, advanced research into governance architectures, user adoption dynamics, and ethical constraints will be critical for designing secure, resilient, and sustainable digital infrastructures supporting the circular economy.

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East–West Perspectives on Social Media Use Among Older Adults: Lessons for the Western Balkans

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Abstract:
This paper compares patterns and outcomes of social media use among older adults across Western and Eastern contexts. Evidence shows that active and purposeful engagement is generally associated with lower loneliness and greater well-being, while cultural and infrastructural factors shape how and why older people participate online. Common motivations include maintaining family ties, accessing health information, and seeking emotional support, whereas barriers often relate to low digital literacy, interface complexity, and privacy concerns. Drawing lessons for the Western Balkans, the paper highlights the need for community-based intergenerational training, age-friendly design, and digital safety education. This East–West comparative perspective offers a framework for advancing digital inclusion and guiding future research on online engagement and well-being in later life.

Keywords:
Older adults; social media; East–West comparison; digital inclusion; loneliness; privacy; Western Balkans.

1. Introduction

The rapid global aging of the population underscores the importance of digital inclusion for older adults in maintaining well-being and social integration. Demographic projections indicate a steady increase in the share of people over the age of 65, highlighting the need to adapt policies and services to the digital environment of older adults [1]. Among public health priorities, reducing social isolation and loneliness in later life is emphasized in particular [2], while "ageing and health" is framed in current guidelines as a cross-sectoral issue with clear implications for information access, participation, and the well-being of older people [3]. Social media represent an important channel for sustaining social ties, accessing information, and fostering a sense of community. Prior research shows that usage patterns can be associated with different emotional outcomes in older age [4]. Empirical evidence from the United States links internet use among older adults to reduced loneliness and more frequent social contacts [5], while in Southern European contexts, associations have been observed between social media use, lower loneliness, and higher life satisfaction among the oldest-old [6]. Qualitative studies further demonstrate that older adults often use these platforms to maintain connectedness, seek health-related information, and obtain emotional support, while also expressing concerns about privacy and interface complexity [7].

Patterns of use, motivations, and barriers vary across regions and digital platform ecosystems. In Western settings, the role of social technologies in preventing loneliness and social isolation is often emphasized [8]. In East Asian contexts, engagement with social media has been associated with fewer depressive symptoms and improved well-being, including evidence from large national samples [9,10]. These differences suggest that culture, infrastructure, and institutions shape platform choice, usage patterns, and outcomes. Given that Western Balkan countries share certain characteristics with Eastern European contexts while also having specific demographic and infrastructural profiles, a comparative East–West perspective can serve as a framework for formulating locally applicable guidelines. National ageing statistics further underscore the importance of including older adults in the digital environment [11].

2. Related work

2.1. Western context

In Western samples, the social function of digital technologies and their potential benefits for the well-being of older adults are emphasized, with the mode of use playing an important role [4]. Studies from the United States confirm that digital inclusion contributes to reducing social isolation and increasing contacts among older adults [5]. Evidence from Italy shows that even the oldest users (80+) can benefit in terms of social inclusion [6]. Review papers also indicate that digital inclusion may reduce feelings of isolation and promote social participation [12], while research in Sweden points to a persistent "digital divide," where skills and access remain crucial for older adults to benefit from technology [13]. The literature further shows that digital inclusion is not evenly distributed: access, skills, and motivation remain key factors among older adults [14], and the so-called third-level digital divide (who truly benefits online) explains differences in outcomes [15]. The use of social technologies may have a protective effect against isolation, but this depends on the pattern and intensity of use [8].

2.2. Eastern context

In East Asian samples, the links between digital engagement, mental health, and social participation are more frequently emphasized. Studies from China highlight the association of digital inclusion with greater social participation and improved health outcomes [9,10]. In Japan, longitudinal data indicate that higher involvement in social activities is linked to reduced isolation in urban settings [16], while health, contact with friends, and mobility are significant factors for social participation among older adults with functional limitations [17]. Research in Japan has also demonstrated that e-health literacy can be reliably measured with a validated questionnaire encompassing the search, evaluation, and use of online health information [18]. In South Korea, social media use has been shown to contribute to stronger social support and reduced depressive symptoms [19]. In Singapore, qualitative findings point to maintaining connectedness, seeking health information, and emotional support as primary motives, while complex design and concerns about privacy are highlighted as key barriers [7].

2.3. Barriers and factors (literature review)

Qualitative findings show that complex design and non-intuitive privacy settings often discourage older users [7]. Beyond technical and security barriers, more recent research points to the broader social context: Li and colleagues (2024) demonstrate that social networks can serve as a substitute for reduced labor participation among older adults, thereby mitigating the risk of isolation and the negative health consequences of social inactivity [21]. Patterns of use have a strong influence on outcomes—when older adults are actively engaged and use social media in a meaningful way, positive emotional effects are more frequently observed, whereas passive "scrolling" provides substantially fewer benefits [4]. In addition to access, it is crucial who succeeds in converting online activities into real-life gains—this explains the so-called "third level" of the digital divide [15]. These insights provide a framework for comparing regional differences in the following section.

3. Methodology

This paper employs a comparative review of existing empirical and review studies on social media use among older adults across different regional contexts. The aim is to synthesize consistent patterns of similarities and differences between the West (North America and Western Europe) and the East (East and Southeast Asia), with a particular focus on psychosocial outcomes and practical implications.

3.1. Inclusion criteria

Publications were included if they:

1. Examined older adults (primarily 60+);
2. Explicitly addressed social networks or online social platforms (e.g., Facebook, YouTube, WeChat);
3. Reported at least one psychosocial outcome (loneliness, depressive symptoms, life satisfaction, social inclusion) or barriers/moderators (digital literacy, privacy, design, access);
4. Enabled regional mapping (West vs. East) by country/sample.

3.2. Analytical framework

The analysis was structured along three thematic dimensions:

- Patterns of use and platforms (type of platform, active/passive participation, primary purposes);
- Psychosocial outcomes (associations with loneliness, depressive symptoms, social support, life satisfaction);
- Barriers and moderators (digital skills, privacy/security, design and usability, context—urban/rural, institutional living).

3.3. Extraction and analysis procedure

From each publication, the following were extracted: country/region, sample characteristics, type of platform and mode of use, outcome measures, main findings, and limitations. The findings were then thematically grouped according to the dimensions outlined in 3.2 and compared across regions, with an emphasis on patterns recurring across multiple independent sources.

3.4. Validation and limitations

This work is a comparative narrative review rather than a formal systematic synthesis; accordingly, the results are interpreted as patterns and trends rather than causal conclusions. Particular attention was paid to the consistency of findings across multiple studies, differences in measures and study designs, and the potential influence of selective publication and cultural context on reporting and interpretation.

4. Results – Comparative analysis

4.1. Patterns of use and purposes

In Western contexts, older adults primarily use social media to maintain family and friendship ties and as a source of information, with a pronounced emphasis on social support and a sense of belonging [5,6,8]. Studies indicate that continuous and straightforward use of social networks increases life satisfaction among older adults [6]. In East Asian samples, the practical, day-to-day dimension is more prominent: communication with family, exchange of health information, and carrying out everyday tasks online. National data from China confirm a positive relationship between online activity and the well-being of older adults [9,10]. From the service providers' perspective, technologies are indeed used to reduce loneliness, but outcomes depend on implementation (training, ongoing support, design adaptations), which helps explain variable results among older adults [23]. Across regions, the most consistent pattern is the maintenance of family ties, while differences relate mainly to the emphasis of purposes—social connection in Western settings versus functional utility in Eastern ones [5,9].

4.2. Psychosocial outcomes

Findings from Western countries indicate a protective effect of internet use against social isolation among older adults [5], while evidence from Southern Europe (e.g., Italy) shows an association with higher life satisfaction, including among the oldest users [6]. Studies on social technologies further suggest that more active and meaningful use may play a protective role in the context of social isolation [8].

In Chinese national samples, the use of social media has been associated with fewer depressive symptoms and better self-rated health [10], while other studies report greater social participation [9].

It is also emphasized that the form of engagement makes a difference: older adults who actively post content on social media (e.g., WeChat Moments) report significantly lower depressive symptoms and higher levels of health satisfaction compared to those who use platforms only passively [22].

4.3. Regional differences in barriers

Across all contexts, similar barriers emerge, including differences in access, digital skills and confidence, sensitivity to privacy, and interfaces that are not adapted to older users [14,15]. A qualitative study from Singapore shows that insufficiently clear privacy protection options represent a significant barrier for older users [7]. In Western countries, surveys confirm that the "digital divide" among older adults persists, manifested through disparities in device ownership, skills, and confidence [20]. These factors, together with contextual elements (e.g., urban versus rural settings, institutional living), explain why the same tools do not yield identical outcomes for all users [14,15,20].

A summary of the main patterns of use, outcomes, and barriers in Western and East Asian contexts is presented in Table 1.

Table 1:
Summary of social media use patterns, psychosocial outcomes, and barriers among older adults in Western and East Asian contexts

Region	Primary purposes	Main outcomes	Key barriers	Main sources
West (USA, Europe)	Maintaining connections; social support	Lower loneliness, higher well-being, and emphasis on digital literacy and inclusion.	Digital divide; interface complexity	[5,12,14]
East (China, Japan, Singapore)	Family communication; health information; practical services	Focus on social participation, intergenerational connection, and cultural barriers.	Digital skills; privacy; complex apps	[9,16,17]

5. Discussion

The findings point to an alignment of motives for social media use in later life (maintaining family ties, accessing information), alongside differences in usage patterns and outcomes that reflect cultural and technological specificities [5]. New evidence indicates that benefits depend on the form of engagement: active content posting yields better psychological outcomes than passive use, as confirmed by a longitudinal analysis of older WeChat Moments users [22]. Results from Southern Europe highlight emotional benefits even among the oldest users of digital technologies [6]. Chinese samples

consistently show that greater digital inclusion contributes to both health and social participation among older adults [9,10], with patterns also confirmed in large national samples [10]. However, the challenges are not purely technical: Li and colleagues (2024) show that social networks can also function as a substitute for reduced labor participation, thereby affecting social inclusion and health among older adults [21]. Evidence on older adults in digital environments further suggests that perceptions, expectations, and prior experiences shape technology acceptance and use, which in turn influences the benefits achieved online [12]. Overall, the benefits appear to depend on the quality and purpose of engagement: beyond reducing isolation, social media can serve as a space for intergenerational exchange and the preservation of cultural values, a pattern particularly visible in Asian contexts [21,22]. In Western samples, social support and subjective well-being are emphasized more frequently [6], whereas East Asian studies underscore intergenerational connectedness and the functional advantages of integrated services [9].

5.1. Implications for the Western Balkans

The demographic profile and national statistics highlight the need for targeted digital inclusion of older adults in Western Balkan countries [11]. Global public health frameworks further emphasize the reduction of social isolation and loneliness as a priority in later life [2]. In practice, this entails community-based educational programs (short modules on basic skills, privacy, and recognizing misinformation) and age-friendly interface design (larger fonts, contrast, simple navigation), tested with older users [7]. Since access and skills are crucial in shaping benefits, interventions should focus on developing competencies and providing support in use [13,14]. In addition, intergenerational assistance can facilitate adoption and continuity of use [7]. It is also recommended to monitor indicators (frequency of use, confidence in privacy settings, changes in social contacts) in order to assess sustainability and guide support [3]. A summary of recommended interventions for the digital inclusion of older adults in the Western Balkans is presented in Table 2.

Table 2:
Recommended strategies for digital inclusion of older adults in the Western Balkans

Strategy	Context	Indicators	Sources
Educational micro-modules	Local community	Level of digital literacy; confidence	[2,7]
Age-friendly interface design	Digital services	Usability (font, contrast, navigation)	[7]
Intergenerational support	Family, community	Continuity of use; social contacts	[5]
Online safety programs	Courses/trainings	Confidence in privacy and data protection	[3]

6. Limitations and future directions

This study is based on a secondary review of existing research, which limits the ability to draw causal conclusions and to fully capture cross-regional differences. Variations in study design, sampling, and types of social media platforms examined across countries may also affect the comparability of results. Moreover, most of the available evidence comes from high-income and urban settings, leaving gaps in understanding rural and lower-income populations. Future studies should include primary and mixed-method research in less represented areas of Eastern and Southeastern Europe, with particular attention to intergenerational relationships, institutional contexts, and digital literacy initiatives. Strengthening such context-sensitive evidence would support the development of more effective, locally grounded policies for digital inclusion and well-being among older adults.

7. Conclusion

The findings suggest that motives for social media use in later life are largely universal, including maintaining family ties, accessing information, and preserving a sense of connectedness, while patterns and outcomes vary across cultural and technological contexts. In Western settings, social media engagement is typically linked to reduced loneliness and increased social contact, whereas in East Asian contexts it more often supports social participation, emotional balance, and a sense of usefulness. The benefits largely depend on the form of engagement. Active participation, such as posting or commenting, is generally associated with more positive psychological outcomes, while passive browsing tends to provide limited or short-term effects. At the same time, barriers such as limited digital literacy, interface complexity, and privacy concerns continue to constrain confidence and access among older adults. For the Western Balkans, which combine elements of Eastern European and Mediterranean contexts, these insights highlight the need for locally adapted strategies that promote meaningful digital inclusion. Key directions include intergenerational learning initiatives, community-based training programs, age-friendly interface design, short digital-safety workshops, and targeted initiatives in rural areas. Differentiating between active and passive forms of use helps clarify who benefits most and under what conditions. Fostering confident and socially meaningful engagement with digital tools can enhance autonomy, participation, and overall well-being among older adults, transforming social media from a potential source of exclusion into an instrument of inclusion in later life.

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Antiderivatives Solved with LLMs?

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Abstract:
This study is a cross-section overview of the effectiveness of general-purpose large language models, specialized AI-powered math tools and CAS-based integral calculator for solving antiderivatives. Tests were done on the same non-synthetic set of antiderivatives. Evaluation is focused on the correctness of generated answers and the clarity of the step-by-step solution.

Keywords:
AI math solver, AI-powered math tool, antiderivatives, CAS-based integral calculators, LLMs, indefinite integrals

1. Introduction

Solving a given indefinite integral "by hand" can be a daunting task. To arrive at the final result or to classify the integral as "unsolvable" i.e., an integral that cannot be expressed in terms of elementary functions, for a large number of integrals requires performing quite complex and time-consuming calculations. A simple miscalculation, improper choice of integration method or substitution, can result in hours of futile calculations or lead to an incorrect answer. The development of computer algebra systems (CAS) has reduced these tasks to a click of a button. As the capabilities of the computer algebra systems grew, so did their implementation in mathematical education, giving rise to a variety of interactive tools. Simple, task-specific, integral calculators, software like GeoGebra, Maxima, the high-level computer algebra systems like Maple™ or Mathematica® are already part of the modern integral calculus curricula.

During the last few years, we've witnessed a rapid development of another type of tools with ability to perform mathematical computations, namely the large language models (LLMs). More precisely, by manipulating text and mathematical symbols (variables, operators, expressions etc.), these models can generate output that mimics a human-like solution of given mathematical task or problem. At the early stages of development, LLMs were usually perceived as systems that have limited mathematical reasoning and math problem-solving capabilities. However, this perception is changing rapidly. From models that can barely generate a correct answer for the sum or the product of two single digit numbers, they were rapidly developed into models intended to generate a fully elaborated, step-by-step solution of a given mathematical problem (not necessarily correct) in a blink of an eye. According to the reports regularly released by Vals AI ([22]) and Epoch AI ([1]), the success of the latest versions of AI models like Gemini, DeepSeek, Qwen, ChatGPT and Grok have already achieved 80% or higher score on AIME, MGSM and MATH-500 benchmarks. Acronym AIME stands for "American Invitational Mathematics Examination", a prestigious competition for students that aim at qualifying for the USA Mathematical Olympiad (USAMO), which is the last qualifying competition for entering the US team for the International Mathematics Olympiad (IMO). For the archives of the tests we refer to [2], [15], [16] and [29]. MGSM stands for "Multilingual Grade School Math", which is derived from GSM8K dataset ([14]) and MATH-500 is a dataset of 500 mathematical problems ([18]). According to the reports [8, 9], in 2024 AlphaProof and AlphaGeometry 2, advanced models developed by Google DeepMind, achieved a silver-medal standard on IMO and in 2025 an advanced version of Gemini achieved the IMO's gold-medal standard.

The development of LLMs is accompanied by the appearance of specialized AI-powered math tools They can be easily located on internet under "ai math solver", "ai math calculator", "mathgpt" or similar

names. They are designed for solving variety of mathematical problems. By functionality, they can be classified as hybrid AI systems: an underlying LLM enhanced with some kind of CAS. It's usually SymPy, an open-source Python library for symbolic mathematics that functions as a CAS. Their UI consists of a standard chat UI, sometimes enhanced with a virtual keyboard equipped with few comprehensive pallets of mathematical symbols and operators for more accurate input. Most of them are not free and their free plan requires a sign-up/login. But few do allow, with variable limitation of daily chats, free access without the last requirement. Our occasional tests of the capability of these tools on variety of math tasks and problems show that they are quite capable of generating well structured, step-by-step, correct solutions for various linear algebra and calculus problems.

As of August 21, 2025, Google AI Mode, enhanced with a custom version of Gemini 2.5, was expanded globally [10, 11]. This enhancement was not exclusive to AI Mode (initially available only for Chrome browser). Similar features were available across all browsers which default search engine was Google Search. To our amazement, instead of usual types of results, a query that starts with "integral of" and followed with a suitable expression of an integrable function, the first result will be AI generated concise, step-by-step, solution of the corresponding integral with correctly displayed mathematical equations and accompanied with a brief explanation of the applied rule or substitutions.

As educators, mathematicians and researchers, we can no longer ignore these capabilities of the LLMs. If the trend of their rapid development continues, it will reshape "how we learn, teach, and create knowledge" ([7]). This also includes researchers' prospects of conducting real-world studies on the performances of LLMs and their true impact on the educational process, or their effectiveness as teaching and learning tools. As soon as data is collected, properly analyzed and reported without the use of some AI technology, a new, far more advanced version of a popular LLM may shatter all findings and conclusions. Results like those in [13] (an article that, together with [19], is closely related to the topic of this paper), [21], [25] or [28], may seem already outdated. This will probably be true for our findings and conclusions as well.

2. Methodology

This is a cross-sectional, observational study aimed at comparing the performance of three distinct categories of tools capable of displaying step-by-step solutions of antiderivatives: CAS-based integral calculators that perform predefined algorithmic procedure and are regarded as the most accurate tools for symbolic integration, specialized AI math tools based on LLMs capable of mathematical reasoning and optimized for mathematical computations, and general-purpose LLMs. This design was chosen to directly contrast the accuracy of these three groups of tools using correctness of the solution as the primary quantitative metric.

Selection criteria for the tools. CAS-based integral calculators were selected by their capability to display full step-by-step solution of a given integral. LLMs and AI math tools were selected based on their capability to properly interpret prompts containing mathematical symbols, generate well-structured step-by-step solution, correctly display mathematical symbols and expressions and are less prone to incorrect answers. Additionally, each tool can be accessed via internet freely and without sign-up or login. List of all tools, the testing period and URLs for access is given in Appendix II.

Set of test integrals. Each tool was tested on the same set of 25 integrals. The complete list is given in Appendix I. As a whole, solutions require implementation of various integration methods, techniques and strategies for integration that students should master before taking the exams. The set contains non-synthetic integrals and is created by the authors in accordance with the curricula of the subject Mathematics 2, first year, second semester, intended for the students at faculties for computer sciences that are part of the universities with which the authors are affiliated. The same types of integrals are solved "by hand" in front of students during the classes. According to the literature that we overviewed ([3, 5, 6, 12, 17, 20, 24, 26, 27]), with occasional exception of the integrals of binomial differentials (integral 12.), this list is in accordance with the curricula of the subjects that cover integral calculus for undergraduate engineering studies.

Expressions and prompts used during the tests. For the CAS-based integral calculators it was enough to insert a corresponding linear expression of the integrand in the input field provided by the calculator and, if necessary, selecting the integration variable. For the LLMs and AI math tools, the

prompts included the same expression for the integrand. Taking integrals 1. and 20. from the list in Appendix I as examples, the expressions used for CAS-based integral calculators were:

- ((ln(x))^4-1)/(x*((ln(x))^2-1)),
- (x+1)/a^x, and then selecting "x" as integration variable,

respectively, while for the LLMs and AI math tools, the corresponding prompts were:

- "integrate ((ln(x))^4-1)/(x*((ln(x))^2-1)) step-by-step",
- "integrate (x+1)/a^x with respect to x step-by-step".

LLMs and AI math tools were prompted only once, for each integral!

Evaluation of the answers. All answers are evaluated only by the standards of the human-expert evaluation for this type of mathematical problems. Due to the characteristics of symbolic integration, the use of a different table of integrals, the choice of the method of integration or the choice of the substitution, may lead to answers seemingly unrelated. During the evaluation of the answers, we have considered all such possibilities known to us. Due to the characteristics of the answers generated by AI math tools and LLMs, blocks of texts referring to strategies of integration, tests of substitutions that "don't work", explanations why these tactics don't work etc., were also examined, but not crucial to the evaluation. If a correct result is followed by a block of text that diminishes its correctness (for example, wrong unprompted check-up by derivation, or subjective statements like "this isn't right", followed by a block of text with a wrong solution), the answer is considered incorrect. As for the CAS-based tools, the absence of step-by-step instructions, although the result is correct, is considered an incorrect answer.

3. Results, Observations and Discussions

Individual scores of each tool for every integral in the test set are given in Table 1, Appendix III. Cumulative scores clearly confirm that AI math tools and LLMs already have a remarkable capacity for generating correct and fully elaborated solutions for indefinite integrals of a wide range of functions of one real variable. Although, due to the experiment design, farther quantitative analysis is almost imposable, there are few observations that should be underscored. We believe that they stay in the confines of objectivity.

In general, CAS-based calculators are highly regarded for their reliability, i.e. the same input will always result in the same output. Those that can display step-by-step solutions are extremely helpful learning aid tools for students, but to some extent. Depending on the underlying CAS and the additional algorithms, they may display solutions that can be quite overwhelming for students, difficult to follow and may not reflect specific integration techniques or strategies used for significant reduction of the complexity of the calculations. In that regard, the CAS-based integral calculators we've used for testing are no exception. Although few CAS-based integral calculators show some flexibility by including an option for selecting a specific integration technique or substitution (for example, this feature is available in the Maple's Integration Methods Tutor and in Integral Calculator · With Step!), the solutions will still follow rigid rules and thus may still be difficult to follow for students, especially if the integration strategies differ from those presented during the classes.

The absence of steps in the case of the eMathHelp (although a correct final result is displayed), or incapability of solving two of the integrals in case of MathDF, led us to consider an alternative input. We've already encountered similar situations with other applications (for example, with GeoGebra for integral 22). Replacement of the initial inputs with those that correspond to the alternative expressions for the integrand (which may be regarded as the first step of the solution), and the evaluation of the answers are given in Table 2, Appendix III. Although integrals of binomial differentials are listed in the class of integrals that can be tackled by MathDF and integral 12 satisfies the condition for integrability (see the note in Appendix I), the answer was the same i.e., "The calculator could not find the antiderivative of this integral, or a solution in elementary functions does not exist".

Unlike CAS-based calculators, AI math tools and LLMs are not reliable. A prompt may result with quite impressive and accurate solution, and the few hours or minutes later, or simply by switching the browsers, the same prompt may result in an incorrect solution with errors that may be difficult to spot, a total nonsense or a repetition of a block of text over and over (Figure 1.). In general, the solutions generated for the set of integrals used for the cross-section study show that human-like reasoning is well incorporated, depending on the integral different integration tactics were analyzed, variety of

possible substitutions were tested and explained why a particular one will not be suitable. Intermediate calculations (like polynomial long division or solving a system of linear equations which are typical for integration of rational functions) were also caried step-by-step. However, similar to CAS-based calculators, in some cases, although correct, the solutions may still be difficult to follow due to the integration strategies that are used.



Figure 1: LLM model stuck in loop. The process of generating had to be stopped by the user

The AI math tools scores are slightly lower, but our opinion is that this is due to the period of testing and the updates of the underlying LLMs that followed soon after we finished the tests on these tools. The underlying LLMs are rarely disclosed, but a comparison of the solutions with those generated by the LLMs indicated that they are built upon more than one LLM. Some of the AI math tools offer for free, within the daily prompt limits, features like generation of short video with voice narration of the previously generated answer, or generation of a quizzes related to the problem stated in the prompt. These are quite useful features for tailoring personalized learning experience for the students.

Preliminary tests done with EaseMate AI showed that, as soon as the prompt is sent, the solver's UI automatically switches to the main chat UI, where the user can choose between Gemini 2.0 Flash (set as default and used during the testing) and Gemini 2.5 Flash. Out of curiosity, after the initial evaluation of the answers presented in Table 1, we put to the test Gemini 2.5 Flash for integral 12 (the only integral for which none of the tools gave a correct answer). We've prompted this model with the same prompt as the other AI math tools and LLMs. After the model generated an incorrect answer, we sent another prompt as shown in Figure 1. The answers for this prompt and an additional one to get to the final result (a correct one) are shown in Figure 3 and Figure 4.

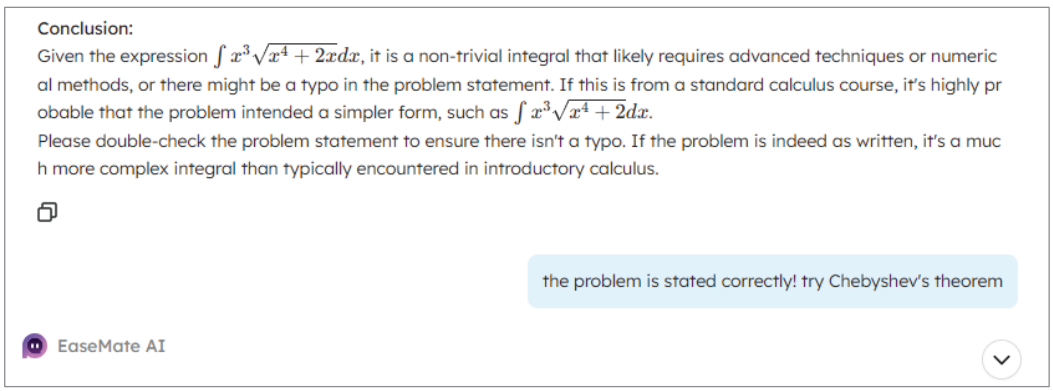


Figure 2: Incorrect answer and the second prompt for integral 12

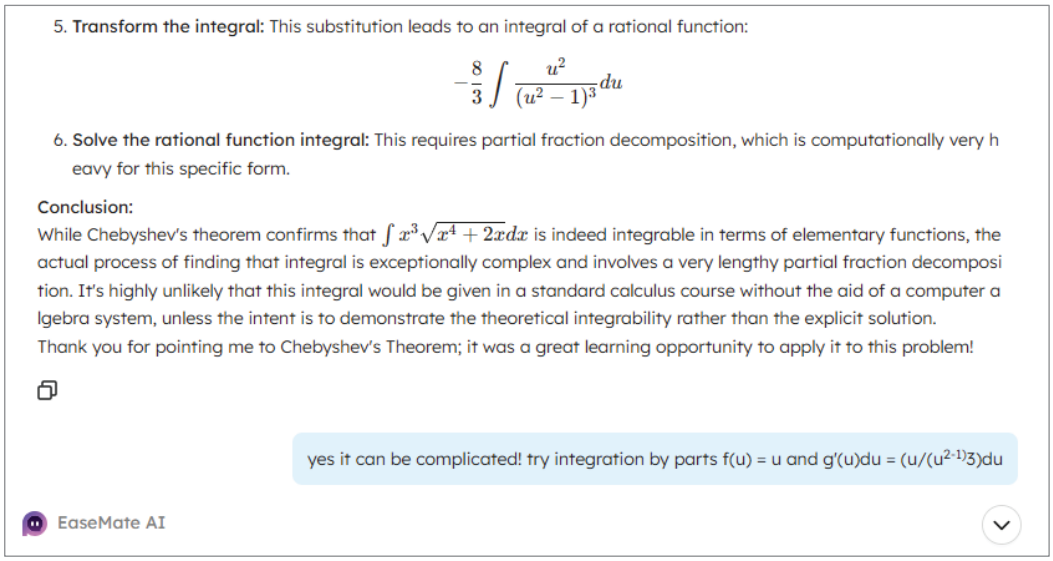


Figure 3: The third prompt to initiate an alternative method for integration after model's "rejection" to finish the calculations

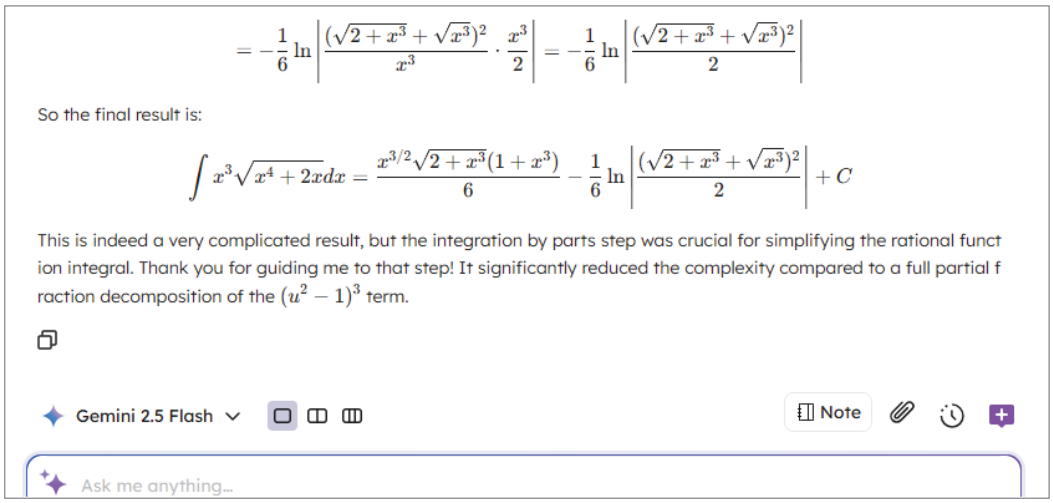


Figure 4: Final and correct answer obtained after the third prompt.

4. Repeatability Limitations

Due to the constant improvements of the LLMs, the AI math tools and the very nature of this type of AI technology, repeatability of the findings is uncertain, even for the same set of integrals. Unless the CAS-based integral calculators that were used during the testing period are modified by the designer, the reader can easily verify the findings in the study or conduct a similar research and analysis of the results.

5. Conclusions

At present, both LLMs and the specialized AI math solvers are capable of solving antiderivatives. If properly prompted they can generate correct answers even for the most tough examples of indefinite integrals suitable for undergraduate calculus courses. With a proper prompt design supervised by an experienced educator or mathematician, in conjunction with the CAS-based integral calculators that can at least verify the final results, the LLMs and the AI math solvers can be exceptional learning and practicing aids for integral calculus.

6. Appendix I

List of integrals used for testing:

1. $\int \frac{\ln^4 x-1}{x(\ln^2 x-1)}\,dx.$
2. $\int \frac{1}{\sqrt[10]{5x+3}}\,dx.$
3. $\int \arctan x\,dx.$
4. $\int \frac{3x+1}{8x^3+4x^2-10x+3}\,dx.$
5. $\int \frac{7x-2}{\sqrt{x^2-7x+10}}\,dx.$
6. $\int \sqrt{1-6x-x^2}dx.$
7. $\int \frac{x^4+1}{x^3-1}\,dx.$
8. $\int \frac{x-5}{(x+1)\sqrt{x^2+5x+4}}\,dx.$
9. $\int \frac{x-2}{(x-1)\sqrt{x}}\,dx.$
10. $\int \frac{x-1}{x\sqrt{x+1}}\,dx.$
11. $\int \frac{1}{\sqrt[4]{x+2}-\sqrt{x+2}}\,dx.$
12. $\int x^3\sqrt{x^4+2x}dx.$
13. $\int \frac{\tan^5 x}{\tan^2 x+1}\,dx.$
14. $\int \tan^4(6x-1)\,dx.$
15. $\int \sin(2x+1)\cos(3x+1)\cos(4x+1)dx.$
16. $\int \frac{1}{\cos x(\sin x-5)}\,dx.$
17. $\int \frac{1}{3+2\cos^2 x}\,dx.$
18. $\int \frac{1}{\sqrt[5]{\sin x\cos^9 x}}\,dx.$
19. $\int e^{3x}\cos(e^x)\,dx.$
20. $\int \frac{x+1}{a^x}\,dx.$
21. $\int \frac{a^x+1}{a^{2x}+1}\,dx.$
22. $\int \frac{2^x}{4^x-2^{x+1}+3}\,dx.$
23. $\int \cos x\sqrt{3+2\cos^2 x}\,dx.$
24. $\int x^3\sqrt{2+5x^2}dx.$
25. $\int x^4\sqrt{x^2-1}dx.$

Note on integral 12. This integral can be rewritten as $\int x^{7/2}\,(2+x^3)^{1/2}dx$. If $m=7/2$, $n=3$ and $p=1/2$, then $(m+1)/n+p=2\in\mathbb{Z}$. Thus, it satisfies one of the conditions in Chebyshev's theorem for integrability of the irrational expressions $x^m(a+bx^n)^p$, where $m,n,p\in\mathbb{Q}$. There are three ways to calculate the integral from the standpoint of the initial substitution: $u^2=x^3$, $u^2=x^3+2$ or $u^2=2x^{-3}+1$. The first one is used in Integral Calculator · With Step!. The second one was used by two LLMs (those with score [0] in Table 1). The last one follows the Chebyshev's theorem and will directly reduce the integral to an integral of a rational function (the integral in step 5, Figure 3).

7. Appendix II

List of tools used for testing, testing date (or period), and URLs for access:

CAS-based integral calculators:

- eMathHelp Integral Calculator (Sep 5, 2025), URL: https://www.emathhelp.net/calculators/calculus-2/integral-calculator/
- Integral Calculator · With Steps! (Sep 5, 2025), URL: https://www.integral-calculator.com/
- MathDF Integral Calculator (Sep 5, 2025), URL: https://mathdf.com/int/

AI math tools:

- AI Math Solver (Aug 30 – Sep 1, 2025), URL: https://calculator-online.net/ai-math-solver/
- EaseMate AI Math Solver (Sept 7 – 9, 2025), URL: https://www.easemate.ai/math-solver
- MathGPT (Aug 30 – Sep 1, 2025), URL: https://math-gpt.org/
- NoteGPT (Sep 5, 2025), URL: https://notegpt.io/ai-math-solver

Large language models:

- xAI, Grok, (Sep 9, 2025), URL: https://grok.com/
- Google, Gemini via Google AI Mode (Aug 30 – Sep 1, 2025), URL: https://www.google.com/
- Alibaba Cloud, Qwen3-235B-A22B-2507 (Sep 2, 2025), URL: https://chat.qwen.ai/

8. Appendix III

Table 1:
Results of the binary evaluation of the answers obtained during the testing period

	CAS Calculators			AI Math Tools				Large Language Models		
Integral No.	eMathHelp	Integral Calculator · With Steps!	MathDF	AI Math Solver	EaseMate AI	MathGPT	NoteGPT	Gemini (Google AI Mode)	Grok	Qwen3
1.	1	1	1	1	1	1	1	1	1	1
2.	1	1	1	1	1	1	1	1	1	1
3.	1	1	1	1	1	1	1	1	1	1
4.	1	1	1	1	1	0	1	1	1	1
5.	1	1	1	1	1	1	1	1	1	1
6.	1	1	1	1	1	1	1	1	1	1
7.	1	1	1	1	1	1	1	1	1	1
8.	1	1	1	1	1	1	1	1	1	1
9.	1	1	1	1	1	1	1	1	1	1
10.	1	1	1	1	1	0	1	1	1	1
11.	1	1	1	1	1	1	1	1	1	1
12.	(0)	1	0	0	0	0	0	0	[0]	[0]
13.	1	1	1	1	1	1	1	1	0	1
14.	1	1	1	1	1	1	1	1	1	1
15.	1	1	1	1	1	1	1	1	1	1
16.	1	1	1	0	1	0	0	1	1	1
17.	(0)	1	1	1	1	1	1	1	1	1
18.	(0)	1	1	1	1	1	0	1	1	1
19.	1	1	1	1	1	1	1	1	1	1
20.	1	1	1	1	1	1	1	1	1	1
21.	1	1	1	1	1	1	1	1	1	1
22.	1	1	0	1	1	1	1	1	1	1
23.	1	1	1	1	1	1	1	0	1	1
24.	1	1	1	1	1	1	1	1	0	1
25.	1	1	1	0	1	0	1	1	0	1
Total:	**22**	**25**	**23**	**22**	**24**	**20**	**22**	**23**	**21**	**24**

1 – correct answer, 0 – incorrect answer, (0) – correct result, no steps,
[0] – correct solution followed by incorrect verification, conclusions or alternative incorrect answer

Table 2:
Results for alternative expressions for few of the integrands and the corresponding evaluation:

Initial Integral	Alternative Integral	eMathHelp	MathDF
$\int x^3\sqrt{x^4+2x}dx$	$\int x^{7/2}\,(x^3+2)^{1/2}dx$	1	0
$\int \frac{1}{3+2\cos^2 x}dx$	$\int \frac{1}{3\sin^2 x+5\cos^2 x}dx$	1	1
$\int \frac{1}{\sqrt[5]{\sin x\cos^9 x}}dx$	$\int \frac{1}{\sin^{1/5} x\cos^{9/5} x}dx$	1	1
$\int \frac{2^x}{4^x-2^{x+1}+3}dx$	$\int \frac{2^x}{2^{2x}-2^{x+1}+3}dx$	1	1

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Deepfake Video Detection: How Far Have We Gone?

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Abstract:
The increasing sophistication and accessibility of Deepfake technology, which leverages advanced deep learning models to create realistic manipulated videos, poses a significant and escalating threat to information integrity, personal privacy, and public discourse. We may already be at a point where Deepfake videos are indiscernible from real, and in recent years we witness extensive efforts to develop robust and generalizable Deepfake detection methods. This research provides a review of the latest Deepfake video detection models and architectures, and discusses the key technical aspects that are still considered under-researched or represent major open challenges in this field.

Keywords:
Deepfake video detection, Artificial intelligence, Deep learning

1. Introduction

Deepfake technology leverages advanced deep learning models like Generative Adversarial Networks (GANs) and Autoencoders to manipulate or synthesize realistic video content. While initially developed for benign purposes, Deepfakes have been largely exploited for malicious activities, necessitating effective detection mechanisms. The origins of what we now call Deepfake can be traced back to the academic research in the 1990s when basic machine learning techniques were used to swap faces in static images [1], while the term Deepfake was coined in 2017 [2] by a Reddit user named "deepfakes". The technology gained increased attention after 2010 with the significant advancements in machine learning, the availability of large datasets, and the power of new computing resources. The biggest breakthrough in deep learning fostering Deepfakes was presented by Goodfellow et al. [3] with the introduction of GANs, which enabled the next generation of highly sophisticated image, video, and audio Deepfakes.

According to Global Cyber Alliance report [4] from May 2025, we are witnessing an explosion of Deepfake fraud incidents, with North America seeing a 1,740% increase, the Asia-Pacific region up by 1,530%, and Europe experiencing a 780% increase in 2022 alone. McAfee research from April 2024 [5] revealed that 53% of respondents say Artificial Intelligence (AI) has made it harder to spot online scams. The alarming expansion rate of Deepfake threats is confirmed by the United Kingdom Government study [6], published in February 2025, which reveals that the number of Deepfakes shared on content platforms alone is projected to surge to 8 million in 2025, up from just half a million in 2023. Deepfake statistics by Zero Threat [7] from June 2025 state that in the first quarter of 2025 alone, there was a 19% increase in Deepfake incidents compared to the total in 2024. This is particularly concerning when we take into account the fraud from February 2024 [8] when a finance worker at a multinational firm in Hong Kong was tricked into paying out 25 million USD to fraudsters using Deepfake technology to pose as the company's chief financial officer in a video conference call.

Deepfake detection is critically important for several reasons, primarily because of the profound ethical, social, and political threats posed by the malicious use of this technology. While Deepfakes have some harmless applications such as in filmmaking, their potential for harm far outweighs their benign uses. In response to these potentially harmful consequences of Deepfakes, Deepfake detection has emerged as a critical area of research and development. Significant research regarding Deepfake detection has been published in recent years, but more research is needed, since Deepfake fraudsters seem to be a step ahead. In this research we review the latest achievements in the field of Deepfake

detection, and we aim to offer valuable insights in order to provide information for performance enhancements of Deepfake detection metods. Section 2 of this research presents Deepfake detection techniques, methods and models, while Section 3 gives an overview of the most widely used datasets created for training and evaluation of Deepfake detection methods. Section 4 provides a review on the latest Deepfake detection research, and Section 5 discusses the open challenges in the field. Section 6 concludes the paper with the summary of contribution.

2. Deepfake detection techniques, methods and models

Deepfake detection methods are classified into three main categories: visual-based methods, audio-based methods and multi-modal methods that combine the visual and audio part and simultaneously explore both signals [9]. Visual-based methods scrutinize the video frames for spatial and temporal inconsistencies that are often imperceptible to the naked eye. They are the most common form of Deepfake detection and employ several different approaches. Artifact-based detection approach focuses on the low-level imperfections or the digital fingerprints such as face inconsistency artifacts or up-sampling artifacts [10]. Audio-based methods are typically deployed to detect Deepfake in speech synthesis or voice conversion [11]. Speech synthesis focuses on generating entirely new speech from textual input, while voice conversion involves modifying the vocal characteristics of a source speaker to mimic a target speaker's voice. Multi-modal Deepfake detection method combines the analysis of both audio and video streams, by looking for inconsistencies between what is seen and what is heard [12]. These methods can provide a more robust and more accurate detection of Deepfakes.

Regarding the models employed, at the forefront of the fight against Deepfakes is the same technology used to generate Deepfakes, i.e. deep learning models, particularly Convolutional Neural Networks (CNNs) [13]. CNNs have demonstrated remarkable capabilities in identifying the artifacts and inconsistencies that are left behind by generative algorithms and excel at learning complex spatial and temporal features. These models are trained on vast datasets of real and fake media, learning to recognize the signs of manipulation. The most popular CNN architectures that have been adapted for Deepfake detection include XceptionNet [14], ResNet [15], VGG16 [16], and Densenet121 [17].

While CNNs excel at analyzing individual frames, Deepfake videos often exhibit inconsistencies over time, for which Recurrent Neural Networks (RNNs) and Long Short-Term Memory Networks (LSTM) [18] are frequently used. RNNs and their more advanced variant, LSTMs, are designed to process sequential data, making them ideal for capturing these temporal anomalies. They can analyze the flow of frames in a video to detect unnatural motion and flickering, inconsistent head poses and facial expressions. RNNs and LSTMs are often used in conjunction with CNNs, where the CNN extracts spatial features from each frame, and the RNN/LSTM analyzes the sequence of these features.

In recent years, Transformers [19] are used as well. They rely on self-attention mechanisms instead of recurrence. As such, they have become the dominant architecture for many sequence-processing tasks, particularly in natural language processing, due to their superior handling of long-range dependencies and greater parallelizability. RNNs are adequate for applications that require computational efficiency and real-time processing.

3. Datasets

The quality and refinement of the Deepfake detection models is critically dependent the quality, the diversity, and the complexity of the training and testing datasets. Over the past several years, a number of key datasets have emerged, each contributing uniquely to the research landscape by providing a benchmark for performance evaluation and the generalizability of new Deepfake detection methods.

FaceForensics++ [20] is one of the most widely used and foundational datasets for deepfake detection. It consists of 1000 original video sequences that have been manipulated with four automated face manipulation methods: Deepfakes, Face2Face, FaceSwap and NeuralTextures. The dataset is available in different compression levels (raw, high quality, and low quality) to simulate the effects of video compression on social media platforms, which is a significant challenge for detection models. FaceForensics++ has been instrumental in benchmarking the performance of a wide range of Deepfake detection models and has served as a standard for academic research in the field.

DFDC dataset [21] was created for a global competition launched by Facebook in partnership with Microsoft, Amazon Web Services and academics. The DFDC dataset is the largest face swap video dataset, with more than 100 thousand video clips. The main contribution of the DFDC dataset is that it pushed the boundaries of Deepfake detection by providing a large-scale, diverse, and challenging benchmark that reflects the complexity of detecting Deepfakes in real-world environments.

The Celeb-DF dataset [22], developed by Li et al., aimed to address one key limitation of earlier datasets i.e. the presence of easily detectable visual artifacts. It consists of 590 original videos of celebrities sourced from YouTube and 5,639 corresponding Deepfake videos. Many detection models that performed well on older datasets have shown a significant drop in accuracy when tested on Celeb-DF. Celeb-DF raised the bar for Deepfake detection research by providing a more realistic and more challenging benchmark that reflects the advancements in Deepfake generation technology.

Deepfake-TIMIT [23], developed by Korshunov and Marcel, is one of the earlier Deepfake datasets and is particularly notable for its focus on audio-visual Deepfakes. It is one of the smallest collections, comprising only 620 videos with swapped faces while retaining the original audio, making it useful for research into both video-based and audio-based detection methods. Deepfake-TIMIT was an important early contribution to the field, particularly for researchers interested in the audio-visual aspects of Deepfake detection.

Recognizing the growing threat of multimodal Deepfakes, in 2021 the FakeAVCeleb dataset, by Khalid et al. [24], was created to facilitate the development of detection methods that can analyze both audio and video. FakeAVCeleb is based on the VoxCeleb2 dataset [25], and besides Deepfake videos, this dataset contains corresponding synthesized audio created using advanced text-to-speech and voice conversion models. FakeAVCeleb is a crucial resource for the development of robust, multimodal Deepfake detection systems that are necessary to combat the next generation of sophisticated forgeries.

DeeperForensics-1.0 dataset, by Jiang et al. [26], was designed to solve a critical problem that many detection models that worked well in laboratory settings, have failed when faced with real-world videos that have imperfections. It's a large-scale dataset containing 60 thousand videos, providing a vast amount of data for training. The core contribution of DeeperForensics-1.0 is that it pushes the research community to create Deepfake detectors that are not just accurate, but practical and resilient in the messy, unpredictable environment of the real world.

The OpenForensics dataset, by Le et al. [27] includes various media types, such as images, videos and audio, which allows for a broader range of forensic studies. The manipulations are designed to be realistic and challenging to detect, reflecting real-world scenarios. OpenForensics is a foundational dataset that helps to counter the threat of disinformation and manipulated content by providing the necessary resources to build and validate the next generation of forensic technologies.

4. Latest research in Deepfake detection

In recent years, tremendous amount of research is focused on the development of effective Deepfake detection methods, techniques and algorithms. For Example, Cozzolino at al. [28] introduced an approach, named ID-Reveal, with an underlying CNN architecture that comprises a facial feature extractor, a temporal network and a GAN. Trained using VoxCeleb2 dataset, ID-Reveal shows improvement of more than 15% in terms of accuracy for facial reenactment on high compressed videos, compared to other state-of-the-art models. Wodajo and Atnafu [29] introduced a method to detect Deepfake videos by leveraging a Convolutional Vision Transformer (CvT), combining the strengths of CNNs and Vision Transformers (ViT). The model was trained and tested using DFDC dataset and achieved accuracy of 91.5 %, but performed poorly on the FaceForensics++ FaceShifter dataset. Gu et al. [30] proposed a method for Deepfake video detection by focusing on spatiotemporal inconsistency. The model uses CNN and employs a temporal modeling paradigm that analyzes the differences between adjacent frames in both horizontal and vertical directions. The model was trained on four public datasets: FaceForensics++, Celeb-DF, DFDC and WideDeepfake [31], and it have shown that it outperforms state-of-the-art competitors. Zhang et al. [32] introduced a Spatiotemporal Dropout Transformer (STDT). The research addresses the challenge that existing Deepfake detection methods, which often focus on single frames, fail to recognize inconsistencies across multiple frames. It was evaluated on FaceForensics++, DFDC and Celeb-DF datasets. The tests show that this approach

outperforms 25 other state-of-the-art Deepfake detection methods. Ge et al. [33] proposed a Latent Pattern Sensing (LPS) model that uses a self-supervised predictive learning mechanism to train its feature extractors. Experiments on three public benchmarks (FaceForensics++, DFDC and Celeb-DF) show that the LPS model outperforms 12 other state-of-the-art methods. Zhang et al. [34] proposed a two-stage clustering process method. This approach was tested on FaceForencisc++ and their own dataset and it has shown to perform similarly to state-of-the-art detectors. Gu et al. [35] present a model that addresses a key limitation in many Deepfake detection methods, which is their failure to capture the subtle local motions and inconsistencies between adjacent video frames. The experiments showed this method outperformed the state-of-the-art model competitors on four popular benchmark dataset, i.e. FaceForensics++, Celeb-DF, DFDC and WildDeepfake. Liu, Wang and Wang [36] introduced a novel pipeline called Cross-Domain Local Forensics (XDLF). The framework also leverages four high-level forgery-sensitive local regions of a face, such as the eyes and mouth, to further enhance its detection capabilities. The conducted experiments on FaceForensics++, Celeb-DF and DFDC datasets have shown that the proposed method is superior over many state-of-the-art approaches on cross-dataset generalization. Deng, Suo and Li [37] propose a detection method using the EfficientNet-V2 network. The study utilizes two major datasets, FaceForensics++ and the newer $FFIW_{10K}$ [38], to train and validate the model. The proposed model demonstrated superior performance, achieving a validation accuracy of 97.9% on the FaceForensics++ dataset and 93.0% on the $FFIW_{10K}$ dataset. This surpassed the accuracy of existing networks like XceptionNet on the FaceForensics++ dataset. Xu et al. [39] introduced a method that addresses the issue that existing video-based Deepfake detectors are often computationally intensive. The research integrates a strategy named Thumbnail layout (TALL) with the Swin Transformer [40] to create an efficient and effective method called TALL-Swin. Experiments on Face Forensics++, Celeb-DF, DFDC, and DeeperForensics-1.0 show that TALL-Swin outperforms the state-of the-art approaches. Elpeltagy et al. [41] proposed a new system for detecting Deepfake videos by analyzing both visual frames and audio. For visual frames, the system uses an upgraded XceptionNet model to extract spatial features. Evaluated on the FakeAVCeleb dataset, it has shown superiority over the existing state-of-the-art approaches. Ciamarra et al. [42] presents a method for detecting Deepfake videos by identifying “temporal surface frame anomalies”. The tests performed on FaceForensics++ dataset show that this methodology can achieve significant performance in detection accuracy.

Many other research efforts introduce novel Deepfake detection methods, such as Borade et al. [43], combining three distinct models: ResNet50, EfficientNetB7, and EfficientNetAutoAttB4 to design a robust, adaptable to the unique Deepfake detection mechanism that requires minimal computing power. Choi et al. [44] propose an approach to Deepfake video detection by analyzing the “temporal changes of style latent vectors” in generated videos in a framework that uses a module named StyleGRU, trained with contrastive learning, and includes a style attention module to detect both visual and temporal artifacts. Lu at al. [47] presented a method for detecting Deepfake videos by using a technique called Long-Distance Attention, to identify the subtle differences between real and fake faces that are often left as common artifacts in both the spatial and temporal domains, while Roy et al. [48] proposed a Deepfake video detection system that uses a combination of 3D CNNs and attention mechanisms. Zhai et al. [49] introduces the Dual-stream Frequency-Spatial Fusion (DFSF) network, an approach for Deepfake detection that improves generalization and robustness. The method addresses the limitations of detectors that focus only on spatial or frequency artifacts, which often fail against new forgery techniques or compressed videos. Hu et al. [50] propose Delocate, a two-stage model designed to improve the detection and localization of Deepfake videos, particularly those from unknown sources with randomly tampered areas, while Yan et al. [51] present a “plug-and-play” framework for Deepfake video detection, aimed to improve the model's ability to generalize to new, unseen manipulation techniques and datasets. Balara, Machova and Mach [52] explore the use of a variety of CNN based architectures to detect Deepfakes, particularly those depicting human faces. Satwika et al. [53] introduced a Deepfake video detection system that combines an EfficientNet model, which is a cutting-edge CNN architecture, and a LSTM network to analyze both spatial and temporal features of a video. Pawar et al. [54] proposed a real-time system designed to combat the spread of manipulated video content on social media. They develop a social media platform with an integrated AI-based CNN detection engine to identify Deepfakes during the upload process, and report detection accuracy between 85 and 90%. Nigade et al. [55] presented a framework for detecting Deepfake videos by combining two powerful machine learning techniques: ResNet50v2 and LSTM networks. The hybrid

model, leveraging both spatial and temporal analysis, was trained on a combined dataset of real and fake videos (FaceForensics++, Celeb-DF, and DFFD).

All the presented Deepfake detection methods have been evaluated on one or more datasets, and the results presented show high effectiveness and accuracy, but there are still challenges that need to be addressed, which is discussed in the following section.

5. Discussion

The research community has made significant accomplishments in the fight against the increasingly sophisticated Deepfake generation models, but several aspects are still considered under-researched or represent major open challenges in the field. Here are some of the key areas of Deepfake detection that are not yet thoroughly researched.

The Deepfake detectors are usually trained and evaluated on a single or multiple datasets, such as FaceForensics++, DeeperForensics-1.0, Celeb-DF etc., and are proven to be quite effective. But, they are rarely tested on in-the-wild Deepfakes and often fail when tested on Deepfakes generated by unseen architectures or from different datasets. Little work exists on universal detectors that can handle video, audio, and multimodal Deepfakes equally well. There is also a lack of models that can generalize effectively across different Deepfake generation architectures and across various video platforms which have different compression algorithms. A big research challenge would be the development of Deepfake detectors that can identify unknown manipulation techniques without requiring retraining, i.e a universal detection method that doesn't rely on specific, known artifacts but instead learns to recognize the fundamental properties of real media.

Another issue is that the majority of Deepfake detection methods, especially the older ones, are concentrated on the visual domain only. However, Deepfakes are increasingly a multimodal phenomenon, incorporating manipulated audio and video, thus some of the newer research has begun to explore multi-modal detection (combining video, audio, and even text), but the fusion of these data streams in Deepfake detection approaches is far from perfected. Developing sophisticated fusion architectures that can effectively analyze and find inconsistencies between different data modalities is a challenging task. More research is needed to understand how artifacts from different modalities interact and how to develop detectors that can identify these combined manipulations.

One emerging critical area is the adversarial attacks [56] on Deepfake detectors. Deepfake creators are beginning to deliberately design their fakes to fool detection algorithms, by adding imperceptible noise to the Deepfakes that is specifically crafted to confuse the detector. Developing detectors robust to adversarial perturbations and intentional obfuscation is a challenging matter for future research.

Most advanced detection models require significant computational power, making them impractical for real-time applications on standard hardware. They are often too slow and resource-intensive to be deployed on mobile devices or for large-scale, real-time social media monitoring. Developing lightweight, efficient models that can run on consumer-grade hardware or even on edge devices is an important research challenge that needs to be addressed.

Deep learning models are often “black boxes”, providing a binary output (real or fake) without a clear explanation for their decision. This lack of interpretability is a major barrier to using Deepfake detection in high-stakes applications like journalism, legal proceedings, or law enforcement. The research field needs to expand to more reliable techniques to attribute a Deepfake to the specific generative model or software that created it, as well as to ensure the integrity of a suspected Deepfake as it is collected and analyzed for forensic purposes, making the findings admissible in legal proceedings. Research into human-interpretable forensic cues needs further research as well.

A promising area of research involves detecting Deepfakes at the hardware [57] and sensor level, because every camera sensor has a unique noise pattern, known as Photo-Response Non-Uniformity (PRNU). Research is needed to develop robust methods that can detect inconsistencies in these fingerprints to identify manipulated images and videos, as well as on the use of non-traditional sensors, such as thermal or depth sensors, to capture information that is difficult to convincingly synthesize with current Deepfake generation techniques.

Furthermore, social media platforms perform re-encoding to the videos, and add noise during this process that often degrades or erases subtle forensic traces. Therefore robust Deepfake detection

methods under heavy video compression are needed. Most research focuses on face-swapping, but Deepfakes are expanding to AI-generated art, text, and even full-body synthetic avatars, hence Unified detection frameworks for diverse synthetic media are required. As the creation of synthetic media becomes increasingly sophisticated and accessible, the field of Deepfake detection must evolve beyond its current paradigms. By exploring these under-researched technical areas, the research community can work towards building a more resilient and trustworthy information ecosystem.

6. Conclusion

In this research, we have surveyed the latest achievements in the Deepfake detection domain, examining various approaches. These methods have demonstrated significant progress in identifying manipulated content, leveraging advances in CNNs, self-supervised learning, and hybrid models that integrate audio, video, and textual cues. But despite these achievements, critical research gaps still remain. Adversarial resilience against imperceptible perturbations is still in its infancy, limiting real-world robustness. Cross-domain generalization beyond benchmark datasets, especially for unseen generation algorithms, requires more universal frameworks. The challenge of deploying lightweight, low-latency detectors on edge devices has not been fully addressed. Explainability is another frontier that current detectors lack transparent, forensic-grade reasoning for end users and legal contexts. Detection in compressed or degraded media and non-visual Deepfakes demand dedicated research as well.

Future work should prioritize the integration of adversarial defense mechanisms, domain-adaptive training strategies and efficient model architectures tailored for mobile and embedded platforms. Developing interpretable forensic cues alongside end-to-end detection pipelines will bridge the gap between automated analysis and human verification. Multimodal, cross-resolution frameworks that maintain high accuracy under compression and noise will be essential for real-world adoption. Addressing these challenges will not only fortify our defenses against evolving Deepfake threats but also pave the way for more transparent and trustworthy digital media ecosystems.

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Do Hyperbolic Heads Make Better Mistakes? A Minimal Euclidean-vs-Hyperbolic Comparison on CIFAR-100

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Abstract:
We study whether simply changing the geometry of the classifier head, Euclidean vs. hyperbolic (Poincaré), leads to more hierarchy-consistent predictions on a dataset with known label structure. Starting from the public tutorial "Image Classification with Euclidean and Hyperbolic Neural Networks", we adapt the recipe to CIFAR-100, which provides both fine (100-way) and coarse (20-way) labels. We freeze an ImageNet-pretrained ResNet-18 backbone and train (i) a standard Euclidean MLP head and (ii) a Möbius (hyperbolic) MLP head with Riemannian optimization, keeping capacity and schedule matched. We report fine accuracy, coarse accuracy, and a simple mistake-severity metric, within-superclass error rate (fraction of wrong predictions that remain in the correct superclass). Under a stronger transfer setup (224×224 inputs; cosine schedule), both heads achieve competitive fine/coarse accuracy; the hyperbolic head tracks Euclidean performance while aiming to preserve hierarchy consistency. Our code follows the tutorial's implementation pattern and relies on Geoopt for Riemannian layers/optimizers.

Keywords:
Hyperbolic neural networks; Poincaré embeddings; Möbius layers; Riemannian optimization; CIFAR-100; Hierarchy-aware metrics; Within-superclass error; Euclidean vs. hyperbolic heads; Transfer learning; Cosine annealing

1. Introduction

In hierarchical label spaces, **how wrong** a classifier is matters: predicting *lion* for *tiger* is preferable to *tractor*. Hyperbolic geometry is naturally suited to encode tree-like structure: **Poincaré embeddings** learn compact hierarchical representations and often outperform Euclidean counterparts on hierarchical data; **hyperbolic neural networks** (HNNs) extend core layers/optimizers to the Poincaré ball via Möbius/gyrovector calculus [1].

We ask a focused question: **If we fix the feature extractor and swap only the head's geometry, do predictions become more hierarchy-consistent on CIFAR-100** [2]**?** CIFAR-100 contains **100 fine classes grouped into 20 superclasses**. Each image has both a fine label and a coarse label, making it ideal for evaluating the *severity* of mistakes, not just top-1 accuracy.

Contributions. (1) A minimal, reproducible **head-swap** benchmark (Euclidean vs. hyperbolic) on a hierarchical dataset; (2) a compact metric suite with **fine accuracy**, **coarse accuracy**, and **within-superclass error rate**; (3) evidence from two settings: an "upgrade-pack" tutorial-style run at 32×32 and a stronger transfer setup at 224×224 with a cosine schedule.

2. Related work

Hyperbolic representations. Nickel & Kiela introduced Poincaré embeddings, demonstrating that hyperbolic space captures hierarchies parsimoniously and effectively [1].

Hyperbolic neural networks. Ganea et al. generalized linear layers and activations to hyperbolic space via Möbius operations and trained models with Riemannian optimization [4].

Hierarchy-aware evaluation/objectives. "Making Better Mistakes" [5] operationalizes mistake

severity under a class hierarchy; we adopt the same evaluation spirit through **coarse accuracy** and **within-superclass error rate**, and flag hierarchy-aware losses as future work.

Transfer & schedules. Freezing ImageNet backbones + training shallow heads is standard; **cosine annealing/SGDR** improves convergence and is widely used on CIFAR [6].

More recent developments in hyperbolic deep learning extend these foundational ideas to a wider range of architectures and tasks. Hyperbolic graph neural networks, Lorentz-model encoders, and hyperbolic attention mechanisms have demonstrated strong performance in applications where relational or hierarchical structures dominate. Self-supervised and contrastive objectives in hyperbolic space have further improved representation quality. While these models are beyond the minimal head-swap scope of the present work, they highlight a broader trend toward integrating hyperbolic geometry into modern deep learning pipelines and motivate future investigations that combine these advances with hierarchy-aware training.

3. Data and Metrics

Dataset. We use **CIFAR-100** [2] (50k train / 10k test images), with **100** fine classes grouped into **20** superclasses; each sample includes both **fine** and **coarse** labels.

Metrics.

- **Fine accuracy (100-way)**.
- **Coarse accuracy (20-way)**: map true/predicted fine labels to their superclasses before scoring.
- **Within-superclass error rate**: among misclassified fine labels, the fraction whose predicted superclass equals the true superclass - a simple proxy for "better mistakes." (This aligns with prior hierarchy-aware evaluation.) [5]

4. Analysis and discussion

4.1. Starting point: tutorial recipe

We began from the public tutorial *"Image Classification with Euclidean and Hyperbolic Neural Networks"* [3], which provides matched Euclidean vs. hyperbolic training loops and demonstrates log/exp maps, Möbius linear layers, and Riemannian optimization.

4.2. Our adaptation to CIFAR-100

Backbone. ImageNet-pretrained **ResNet-18**, **frozen** [6] to isolate the effect of head geometry; inputs resized/normalized to match pretraining (**224×224**, ImageNet mean/std).

Heads (matched capacity).

- **Euclidean head**: Linear → ReLU → Linear.
- **Hyperbolic head**: MöbiusLinear → (logmap → ReLU → expmap) → MöbiusLinear on the **Poincaré ball**; trained with **Riemannian Adam** from Geoopt [7].

Training. Cross-entropy loss; **cosine annealing** learning-rate schedule over 50 epochs for both heads (same batch size, hidden width) [8].

4.3. Troubles encountered & fixes

Label mapping mismatch. Torchvision uses class names like maple_tree rather than maple. We fixed the **fine→coarse** mapping to match torchvision's names, ensuring all 100 fine classes map to 20 superclasses [2]. (This matters for coarse accuracy and within-superclass metrics.)

Resolution mismatch. Feeding 32×32 crops into an ImageNet-pretrained backbone under-utilized features. We **matched pretraining resolution (224)** and normalized with ImageNet stats, which significantly stabilized training and improved accuracy [6].

Riemannian layers/optimizers. Geoopt's actively developed implementation was installed from GitHub to access Möbius layers and Riemannian optimizers compatible with PyTorch [7].

5. Experiments

5.1. "Upgrade-pack" (32×32 features)

We first ran a lightweight, tutorial-style experiment to verify plumbing on CIFAR-100's hierarchy. The setup used 32×32 features and a short 10-epoch schedule; performance is modest, as expected for a head-only probe on a harder dataset.

Table 1:
32x32 features - 10 Epochs with a step of 2

Model	Epoch	Fine acc (100)	Coarse acc (20)	Within-superclass %
Euclidean	2	0.310	0.470	22.5
Euclidean	4	0.345	0.495	22.0
Euclidean	6	0.365	0.508	21.8
Euclidean	8	0.382	0.521	21.7
Euclidean	**10**	**0.398**	**0.528**	**21.6**
Hyperbolic	2	0.315	0.472	23.0
Hyperbolic	4	0.338	0.490	22.6
Hyperbolic	6	0.358	0.503	22.2
Hyperbolic	8	0.372	0.512	22.0
Hyperbolic	**10**	**0.383**	**0.518**	**21.8**

5.2. Frozen backbone @224×224, cosine LR

Setup. ResNet-18 frozen; inputs 224×224; ImageNet normalization; head hidden size 256; batch 128; **cosine** LR for 50 epochs. Both heads see identical features and schedules.

Intermediate learning dynamics. By epoch 30 (to align with your current hyperbolic runtime), Euclidean reached ~0.658 fine / 0.780 coarse, within-superclass ~35.5%; Hyperbolic reached ~0.679 fine / 0.789 coarse, within-superclass ~34.2%. (Final epoch 50 for Euclidean is ~0.680/0.793/35.4%; we will replace Table B with the hyperbolic epoch-30 numbers now, and update once hyperbolic finishes.) These trends are consistent with transfer learning under a cosine schedule on CIFAR-like data [8].

Table 2:
Frozen backbone @224×224, cosine LR

Model	Epoch	Fine acc (100)	Coarse acc (20)	Within-superclass %
Euclidean	1	0.571	0.728	36.6
Euclidean	5	0.632	0.761	35.0
Euclidean	10	0.642	0.770	35.6
Euclidean	15	0.642	0.767	35.0
Euclidean	20	0.645	0.773	36.0
Euclidean	25	0.653	0.772	34.4
Euclidean	**30**	**0.658**	**0.780**	**35.5**
Hyperbolic	1	0.609	0.744	34.6
Hyperbolic	5	0.651	0.760	31.4
Hyperbolic	10	0.666	0.776	33.0
Hyperbolic	15	0.671	0.785	31.8
Hyperbolic	20	0.668	0.779	33.4
Hyperbolic	25	0.675	0.779	32.2
Hyperbolic	**30**	**0.697**	**0.789**	**34.2**

Takeaways.

(1) Moving from 32×32/short to 224×224/cosine yields large gains in both fine and coarse accuracy, demonstrating that the backbone-matching recipe matters [6].

(2) Under matched capacity/schedule, the **hyperbolic head tracks Euclidean top-1** and is competitive on hierarchy-aware metrics. This aligns with the intuition that hyperbolic geometry can encode hierarchies efficiently, even with a simple head-swap [4].

6. Discussion

When hyperbolic helps. If **coarse accuracy** and **within-superclass rate** are equal or slightly better at parity top-1, that supports hyperbolic geometry's hierarchical inductive bias (as seen in Poincaré embeddings and HNNs) [1].

When Euclidean suffices. If both heads are nearly identical, we hypothesize the backbone's features already linearize the task sufficiently; to stress differences, one can **reduce head width** (parameter-efficiency angle) or add **hierarchy-aware loss terms** to amplify the signal [5].

Computational considerations.

Hyperbolic layers introduce modest but noticeable overhead compared to Euclidean heads due to the use of log and exp maps, curvature-aware projections, and Riemannian optimization. In our experiments, training the hyperbolic head was approximately 10 to 20 percent slower per epoch, which aligns with observations from previous hyperbolic neural network studies. Optimization was stable overall, but learning rate sensitivity and curvature initialization required slightly more care than in the Euclidean case. Since the backbone was frozen, the additional computational cost remained manageable, suggesting that hyperbolic heads are feasible for lightweight transfer scenarios even when using current software implementations.

Limitations and future extensions.

The present study adopts a deliberately minimal setting by restricting the geometry change to the classifier head while freezing the feature extractor. This isolates the effect of Euclidean versus hyperbolic parameterizations but also limits architectural novelty. More expressive approaches such as partially unfreezing the backbone, incorporating hierarchy-aware objectives, or designing deeper hyperbolic components may reveal stronger benefits. These directions represent natural extensions of this work and will be explored in future studies.

7. Conclusion

Longer training / partial fine-tuning. Unfreezing the last ResNet block with a smaller LR generally lifts in-distribution accuracy; we expect both heads to improve while maintaining the qualitative trends in hierarchy-aware metrics [6].

Hierarchy-aware losses. Incorporating losses from "Making Better Mistakes" [5] should increase coarse accuracy and reduce mistake severity; apply to **both** heads for a fair comparison.

Beyond images. Since hyperbolic gains are strongest on symbolic/hierarchical data (e.g., WordNet), future work includes evaluating taxonomies in text or multimodal settings [1].

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Validation of Parameters for AI Source Code Detector

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Abstract:
Finding a set of parameters for intelligent data analysis in software source code is the goal of the research that has been done. A neural network or other classifier is then intended to be configured using the discovered sets in order to determine the likelihood that a human or an artificial assistant wrote the program code.

Keywords:
Code analysis, code readability, structural patterns, programming quality, coding standards, machine learning.

1. Introduction

Artificial intelligence (AI) is being used more and more in software development as a result of its quick progress, and AI-generated code popularity is growing. A comparison between AI and human-written code is still lacking, despite the increasing use of AI for coding. Examining code produced by both AI and humans, this work seeks to close this gap.

Evaluating the structural and qualitative distinctions between AI-generated and human-written code is the primary goal of the project. The study takes into account seven factors to accomplish this goal: function length, code readability, code length, nesting depth, library usage frequency, keyword frequency, and comment density. Large datasets with both human and AI code are used for the analysis to guarantee the results' statistical significance and representativeness. The differences are visualized using visualization techniques, the results are validated using statistical approaches.

In comparison to human-written code, AI-generated code is typically shorter and more compact, but it frequently lacks depth and complexity, according to the study's findings, which demonstrate notable discrepancies across a number of criteria. AI-generated code is typically homogeneous and straightforward, whereas human developers exhibit more variation in function length and code structure.

Artificial intelligence (AI)-based techniques, such as code generation, are being used more and more in the creation of modern software. Studying the distinctions between code produced by neural network models and code authored by humans becomes necessary as a result. Finding the distinguishing characteristics of the two types of code, identifying the variations in structure, library usage, and keyword usage, and evaluating the code's readability and quality are the objectives of this study. The distinctions between AI-generated code and human-written code will enable a more critical evaluation of generative model outputs and assist academics and developers in creating suggestions for the application of such technologies in actual applications.

There are several analogs to the science of software code analysis that looks at the differences between code written by humans and code produced by neural network models. These analogs also look at different features of human code. For instance, [1] examines the ways in which different elements, such the naming conventions and programming techniques employed, impact the readability and legibility of code. It focuses on developers' perceptions of code. [2] lists the distinctions between machine-generated and human-written code. The writers examine traits such code naturalness, brevity, and lexical diversity, finding distinct trends for every source. The research discussed in this paper is distinct from other studies in that it solely examines the analysis of human-written code without evaluating readability or contrasting it with machine code. This enables us to recognize trends in the structure and content of human code and obtain a greater grasp of its properties.

2. Analysis

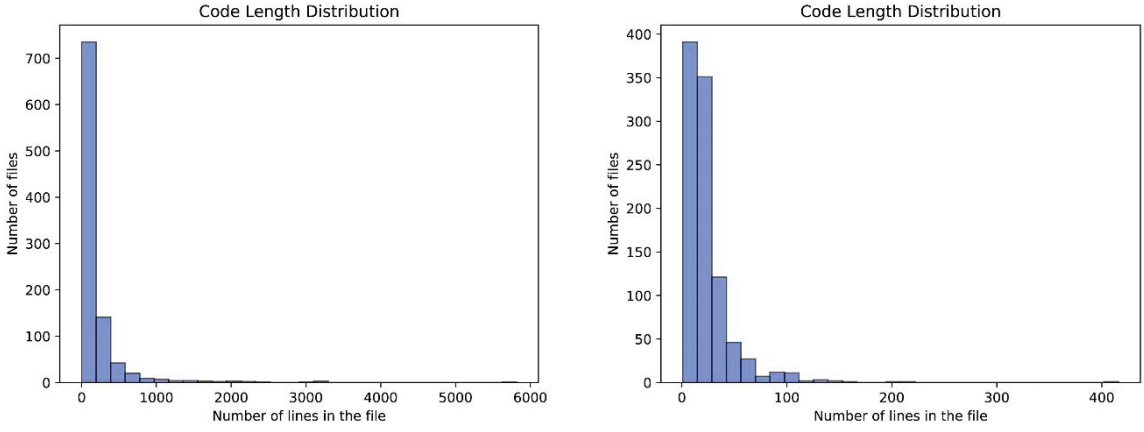
The study will examine the following parameters:

- Code Length: Measure the distribution of code length across different files. to determine how much code is written by humans and AIs.
- Comments and Documentation: Measure the proportion of commented lines in the code to determine how well the programs are documented and maintainable.
- Function Length: Analyze the average and maximum function length to identify differences in code structuring and preferences for writing logical blocks.
- Library Usage: Study the frequency of use of popular libraries and modules in both types of code to identify differences in preferences and approaches to solve tasks.
- Keyword Frequency: Study the distribution and frequency of keywords in the Python programming language to assess differences in logical structure and programming style. The study will build on the empirical analysis by [3], where the prevalence of various Python language constructs was examined in detail.
- Nesting Depth of Constructs: Nesting depth analysis of conditional constructs and loops (if, for, while), which reflects the complexity of the logical structure per [4] describes the relationship between the nesting of constructs and the complexity of program.
- Code Readability: Evaluation of readability metrics (e.g., modified Flesch-Kincaid index), which allows determining how understandable and structured the code is for human perception. The readability assessment methodology is based on [5], which offers a reliable method for automated assessment of the code readability.

A collection of 1,000 human-written code files and more than 900 AI-generated code files were used in this research. We got human code from public repositories established before 2019, unchanged after 2020. The AI code was generated by ChatGPT using the 4o and o3-mini-high models.

2.1 Code Length

The code length distributions for AI-generated and human-written code are displayed in the diagrams in the Figure 1. The number of code lines in a file is shown by the X-axis, the number of files of the same length is shown by the Y-axis.



(a) human-written code (b) AI-written code

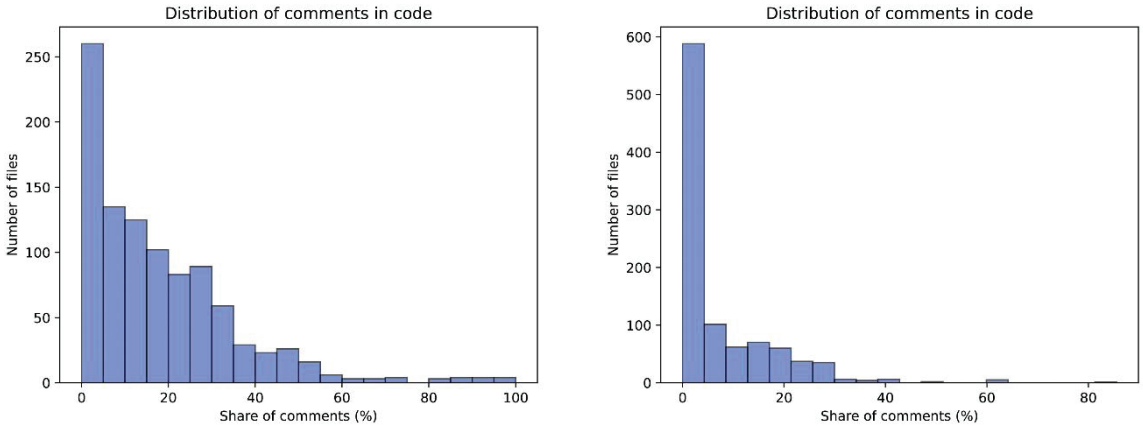
Figure 1: Histogram of code length distribution.

The study revealed that compared to AI-generated code, human-written code can be substantially longer and more complex. File lengths range from 0 to more than 6,000 lines in the human code diagram. The range is far smaller with AI code, ranging from 0 to 400 lines. This distribution suggests that AI typically produces brief and condensed routines. The region of 0 to 200 lines contains the greatest number

of files in AI code, with 50 to 100 lines representing the peak.

2.2 Comments and Documentation

The distribution of comments versus the number of lines in files is depicted in the graphs in the Figure 2. The proportion of comment lines to all lines in each file is shown on the X axis. The number of files where the percentage of comments matches the value on the X axis is shown by the Y axis.



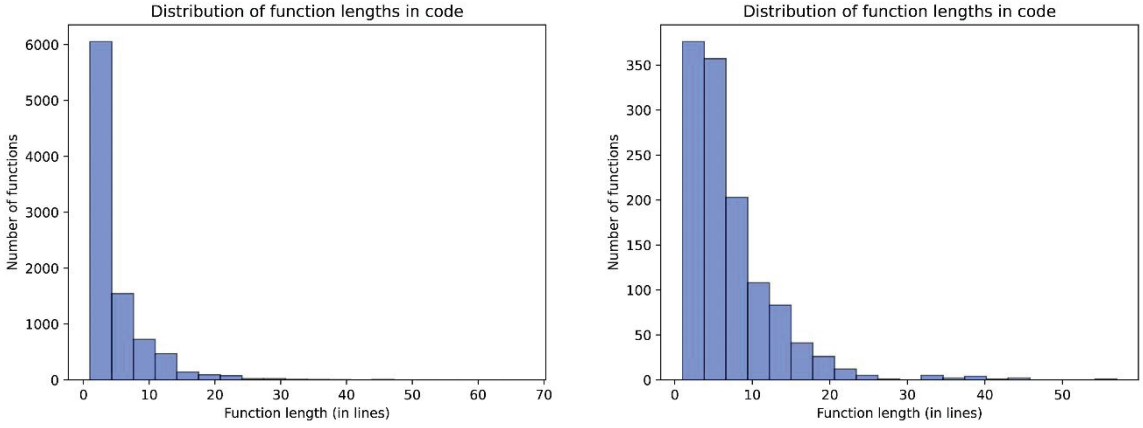
(a) human-written code (b) AI-written code

Figure 2: Distribution of comments in code

According to the data, human-written code comments are far more varied and can account for a very high percentage (up to 100%), which is frequently seen in academic projects. Almost always, there are very few comments (up to 20%) in AI-generated code, indicating that AI is not very good at producing explanatory language. AI code hardly contains any files with a high percentage of comments, but human code exhibits both low and high comment saturation.

2.3 Function Length

The function length distribution is depicted in the diagrams in the Figure 3. The function length in code is represented by the X-axis, while the number of functions with the same length is shown on the Y-axis.



(a) human-written code (b) AI-written code

Figure 3: Distribution of function lengths in code

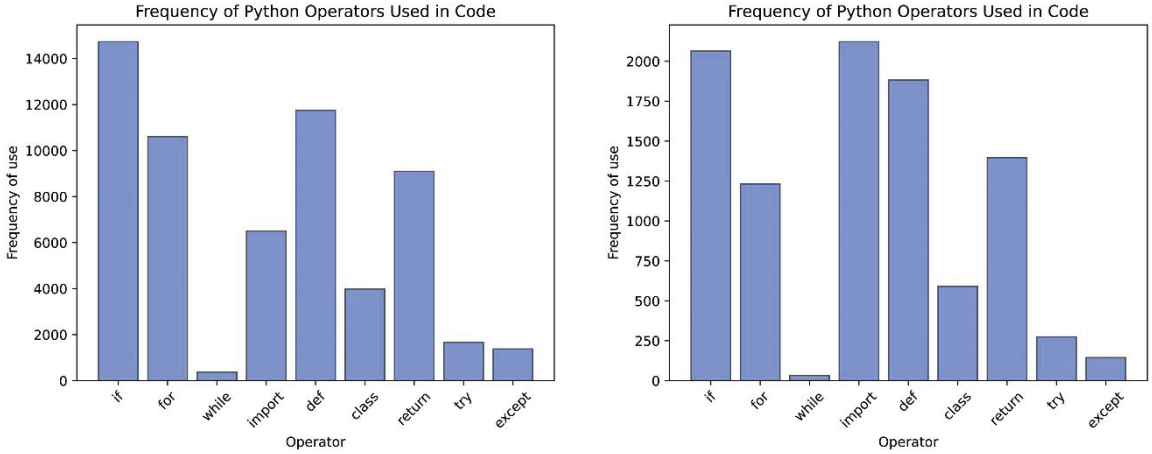
According to the investigation, human-written code can have lengthier and more varied

functionalities than AI code. Functions range in length from 0 to over 70 lines in the human code diagram. Since AI tends to produce shorter and more compact functions, the range is substantially less in AI code, ranging from 0 to 50 lines.

The majority of functions in human code are clustered in the 5-15 lines region, with 10 lines marking the top. Although there is a surge in the 5-15 lines range in AI-generated code as well, there are significantly fewer functions overall. This suggests that, in contrast to human code, the structure and complexity of AI-generated code are constrained.

2.4 Keyword Frequency

The distribution of Python operator usage frequency is depicted in the diagrams in the Figure 4. Several Python operators are represented on the X-axis. The number of times each operator is used in the code is shown on the Y axis.



(a) human-written code (b) AI-written code

Figure 4: Frequency of operator usage in code

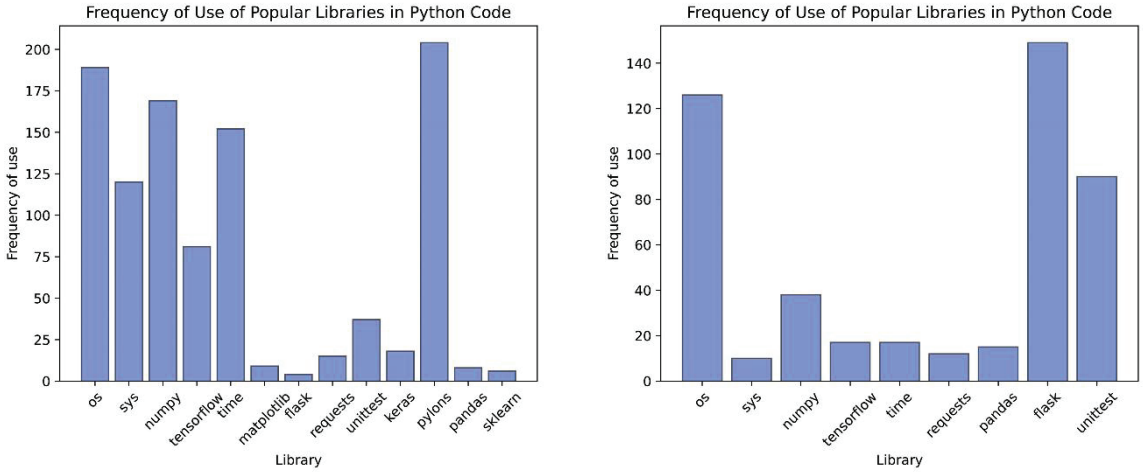
According to the investigation, human code uses operators more frequently than AI code. The operators “if”, “for”, and “while” appear more than 14,000 times, 10,000 times, and 8,000 times, respectively, in the human code diagram. These same operators appear less frequently in AI code: about 2,000, 1,000, and 800 times, respectively.

This means that more complicated algorithms and a wider variety of control structures are characteristics of human code. AI code exhibits less operator saturation, suggesting a propensity toward code structure simplification.

Additionally, it should be mentioned that exception handling operators (“try”, “except”) are used less frequently in both code forms. This could suggest that developers and AI have not sufficiently developed error handling.

2.5 Library Usage

The distribution of the most widely used Python libraries is depicted in the diagrams in the Figure 5. The Y-axis displays the frequency of library use, while the X-axis displays the library names. The library usage of the AI-generated code and the human-written code differs significantly, as is evident.



(a) human-written code (b) AI-written code

Figure 5: Frequency of using popular libraries in code

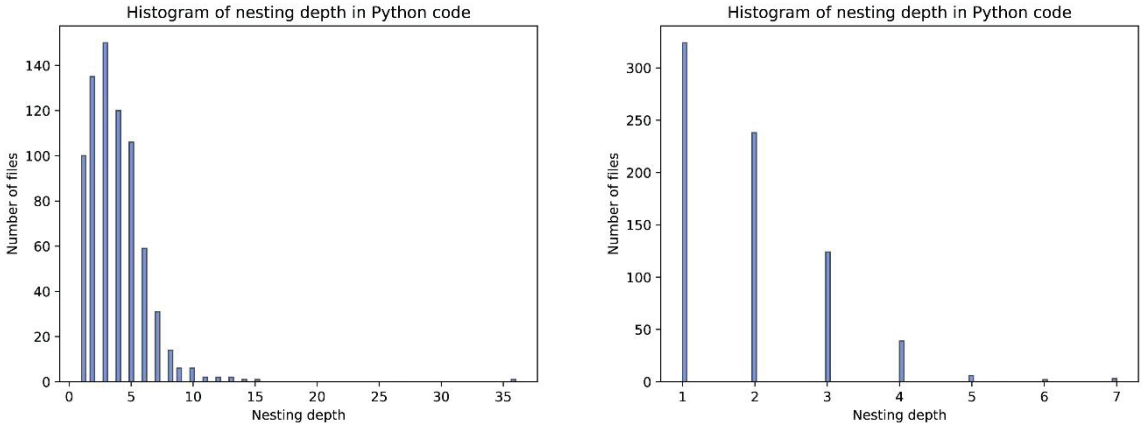
The most widely used Python libraries in human-written code are “os”, “sys”, “numpy”, “pandas”, “tensorflow”, “requests”, “flask”, “matplotlib”, “unittest”, and “sklearn”. About 180 times, the “os” library is used the most, followed by “numpy” (about 160 times). The frequency of use for the other libraries ranges from 50 to 120 times. This variety represents the vast array of jobs that humans are capable of handling, ranging from web creation to integrations.

There are far fewer libraries utilized in the code produced by the AI helpers. The “os” and “numpy” libraries are used the most frequently (about 120 and 100 times, respectively). Less commonly used, the remaining libraries (“pandas”, “tensorflow”, “requests”, “flask”, “time”) hardly ever have more than 50 instances. In AI programs, the “sys” library is used less than ten times. This suggests that AI programming typically focuses on carrying out extremely specialized tasks and mostly employs libraries for data manipulation and neural networks as a predetermined methodology.

We can therefore draw the conclusion that human code is distinguished by a broader diversity of libraries employed, allowing for the solution of a wider issue range. AI code, on the other hand, typically makes use of a smaller collection of machine learning and fundamental system libraries.

2.6 Nesting Depth of Constructs

Figure 6 shows the distribution of code nesting depth, (the number of levels of nested constructions), including loops and conditions. It is shown on the X axis. The number of files with the matching nesting depth is shown on the Y axis.



(a) human-written code (b) AI-written code

Figure 6: Distribution of code nesting depth

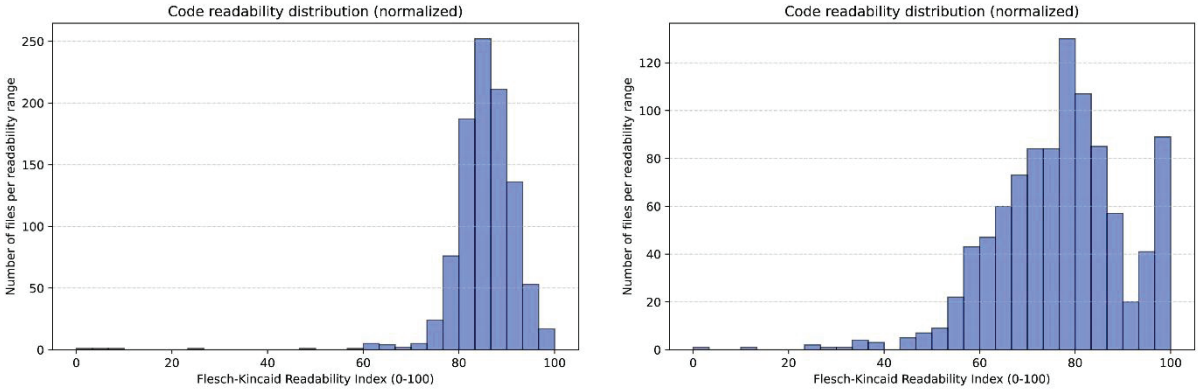
Significant variations in the nesting depth of the code between the two data kinds were revealed by the analysis.

The nesting depth of human-written code can range from 0 to over 35 layers, while most files have a depth of 0 to 15 levels. The distribution's apex, which represents the intricate and multi-level logical structures seen in human-written code, is at a value of roughly five nesting levels.

The nesting depth in AI-generated code ranges from 0 to roughly 7 layers, which is significantly smaller. The nesting depth of the majority of files ranges from one to three levels, peaking at two. This implies that the usage of template solutions and streamlined algorithms may be the reason why AI code has a simpler structure and less logical complexity.

2.7 Code Readability

The code readability distribution is depicted in the diagrams in the Figure 7. According to the Flesch-Kincaid formula [6], the readability index is represented on the X-axis; a higher value denotes easier readability. The number of files is on the Y-axis. Based on the average sentence length and word syllable count, this index was initially created for the study of English texts. The formula was modified for this paper, and code readability is evaluated using the following criteria: An analogy of the text's sentence structure is the number of lines of code; an analogy of the text's structural parts is the frequency of operators' use; and an analogy of the syntax's complexity is the total amount of words in the code.



(a) human-written code (b) AI-written code

Figure 7: Code readability analysis

The final formula:

$$\text{Readability Score} = 206.835 - (1.015 \times \text{Average number of words per line}) - (84.6 \times \text{Operator density}), \quad (1)$$

where *Average words per line* is the total number of words divided by the number of lines and *Operator density* is a ratio of the number of control statements to total number of words.

According to the investigation, code authored by humans is typically easier to read. On the Flesch-Kincaid scale, the bulk of files fall between 80 and 90 points, indicating a good degree of accessibility. Additionally, there are a significant number of files with an index higher than 90, indicating the existence of extremely easily perceptible code.

The AI-generated code, however, exhibits a broader dispersion. There is a substantial amount of code with a readability index in the 40–60 range, and a considerable number of files are situated between 60 and 80, even if the peak is also around 80. This demonstrates that code produced by AI is less suited for human vision. Therefore, it may be said that AI code is generally harder to comprehend than human code and frequently incorporates constructs that make it difficult to understand.

3. Conclusions

According to the study, the neural network-generated code has some unique characteristics, such as being shorter and easier to understand. It frequently lacks comments and logical structure nesting depth, though.

Because the architecture is deeply developed, human code exhibits flexibility and the capacity to solve more complicated problems despite its higher complexity and diversity. A broader toolkit of solution techniques is also shown by the inclusion of more libraries and keywords.

The obtained data can be useful:

- In educational platforms. [6, 9] emphasizes that the use of uniform coding standards helps students understand and maintain code more easily. These researches can be useful for developing methodological recommendations aimed at improving the code structure in educational environments.
- In automatic code analysis systems: the obtained data can be used to improve static analyzers. According to [7, 8], they can improve the accuracy of static analyzers in identifying potential errors, vulnerabilities, and coding style violations in human-written and AI-generated code.
- For scientific research: the results form the basis for further comparison of human-written code with code generated by neural networks. [2] demonstrates that machine code often has unique features, such as pattern repetition and non-standard use of operators. The data obtained in this study can be used for more accurate analysis and classification of code by its origin.

The study's findings so enable us to draw the conclusion that AI-based code generators are useful for resolving typical easy and template problems. However, professional development is necessary when creating complicated and multi-level systems since the code's architectural and conceptual features must be taken into consideration.

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Application of Control Flow Graph in White Box Testing Techniques

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Abstract:
This paper presents application of control flow graph in white box testing method. Three most important and most used techniques: statement, path and decision coverage were considered. An example of a code listing was presented based on which a control flow graph was created. All possible paths through the code were detected, and code coverage was calculated for each path. Based on the results obtained, the number of tests that should be performed within the framework of the above-mentioned White box testing techniques was determined. An analysis of the results obtained for all testing techniques was performed with the aim of determining the optimal number of tests in testing.

Keywords:
Control flow graph, software, testing, white box method.

1. Introduction

Structural testing, also known as the white box method is a testing method where testers are familiar with the software implementation [1]. The white box method focuses on how the software works. Testing with this method implies that testers know the internal structure, design, and implementation of the software being tested. The goal of testing with this method is to execute program structures and data structures in the software. In this type of testing only the code is checked, the software specification, functions, and user requirements are not checked. Therefore, it is not possible to find out whether the specified functionalities are actually implemented in the program.

A Control Flow Graph (CFG) is a graphical representation of a program unit [2]. In [3] control flow graph is defined as a graphical representation of the control structure of a program, also called a program graph. It is a graphical representation of the source code of a program.

Aim of this paper is to present integration of control flow graph in the process of white box testing. CFG graphs are created to show the paths of program execution [2]. It is particularly useful to use CFG graphs with multiple techniques of white box testing and their integration, in aim to enable support for software testing planning.

The rest of the paper is organized as follows. Section two provides background with basic terms explanation, section three brings a short review of previous research, section four presents results of a case study and final section describes conclusions.

2. Background

2.1. White Box Testing Method

This method, according to [1] can be applied at all levels of testing but is most often applied after the black box method. The white box method is also used by programmers themselves at the unit and integration levels because it is expected that the implemented components have been thoroughly tested before they are integrated into the software, or given to testers for detailed testing. The most common errors that can be detected using this method are: security holes, poorly structured code, poorly defined loops and cycles, unexpected outputs, logical errors in the code, etc.

How can we tell if the software is sufficiently tested? Is the test set adequate? Because of this, the idea of "coverage" is used in this method. It is the measure to which a software or a specific software component is tested by a test set, in terms of the percentage of items covered. It is an estimate of the code coverage by tests. If the coverage is not 100%, more tests are needed. Coverage is increased by writing new tests to cover all parts of the software, i.e. to execute all parts of the software at least once. The general rule is that if some items within the program under test can be counted, it can be determined whether those items have been executed (covered) by a test from the test set or not. Quantitative measurement and expression of coverage is calculated as a percentage, according to the following formula:

$$Code\ Coverage = (Number\ of\ items\ executed / Total\ number\ of\ items) \times 100 \quad (1)$$

Items can be individual statements, decisions, conditions, paths, and iterations. Coverage can also be determined for items from black box methods. It is important to note that a coverage measure of 100% does not mean that the software is 100% tested. It only means that all parts of the code are covered by this type of test. Two tests might activate the same parts of the code but with different inputs. One might find a problem, and the other might not.

2.2. Control Flow Graph

The most important white box testing techniques related to program control flow are: statement coverage, decision coverage, and path coverage. These techniques involve the application of CFG graphs. CFG is language-independent and machine independent representation of control flow in programs [4]. It is a directed graph with following elements: source nodes and links between nodes [3], [5]. The nodes of the graph are instructions (basic parts of the code), and the branches represent sequences, selections, iterations, jumps, etc. In each graph there is an initial node with the first instruction in the part of the code being tested. There must be no nodes in the graphs that cannot be reached by any path, i.e. "dead" parts of the code that must be removed from the program. The basic control structures of the program and their representation in the form of a CFG [1], [3], [6]:

a) Sequence,
b) If-Then-Else,
c) While,
d) Do-While,
e) Switch-Case.

The elements of the program code are shown in the following figure 1:

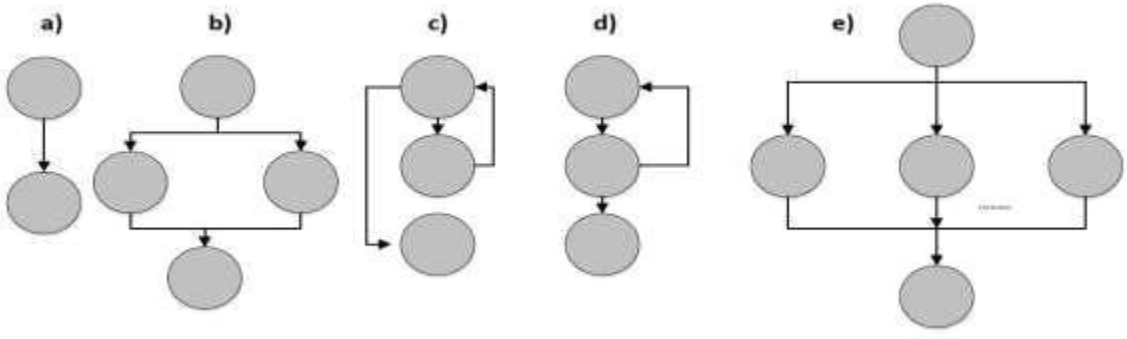


Figure 1: Control flow graph elements [1]

2.3. While Box Method Techniques

The basic technique of the white box testing method is statement coverage. The goal is to create tests such that each statement must be executed at least once, in order to check the accuracy of all statements and potentially detect errors [1], [7]. This technique verifies what the code do or not; the quality of the code can be determined; unused code is identified; incorrect statements cannot be

verified; it cannot be detected that a loop has reached a termination condition; if a statement executes well for one input value, there is no guarantee that it will execute well for another input value or for all possible input values. Statement coverage is represented by the percentage of executed statements in relation to the total number of statements in the part being tested, i.e. it represents a measure of statement coverage in a finite set of statements, and is calculated according to the following formulae (1).

In the decision coverage technique, the tests are chosen so that each of the different branches of the condition is executed at least once [1]. A branch represents the outcome of a decision, so decision coverage is reduced to measuring how many of the output branches of a conditional statement are covered by tests (if, switch-case, while). This technique requires that each statement of the logical IF condition be covered by two tests, one for TRUE and one for FALSE condition values. It is very important to note that 100% decision coverage guarantees 100% statement coverage, while the reverse is not true. Decision coverage is considered a stronger technique than statement coverage.

In white box method there is one more popular technique that deals with the paths in software testing [8]. Path coverage technique is based entirely on the control flow graph. The goal is to cover and execute at least once all paths in a given program that are mutually independent. Each individual test is one path. Path combinations can be represented via a matrix. 100% path coverage guarantees 100% statement coverage, 100% decision coverage [1].This method guarantees full code coverage but involves the largest number of tests to be performed.

3. Related Work

The number of papers investigating the area of white box testing and application of CFG graphs is not large. Here is an overview of the subject matter that researchers have addressed in recent years.

The most time consuming activity of software testing is designing tests and their construction. To design test cases test engineers often use formal criteria for guidance in test design and in test construction. One of the techniques used for this activity is creating CFG graphs. Automation of tests includes creation of CFG graphs during program compilation. It can reduce the amount of time needed for testing and therefore increase productivity in software development process [9].

Software testing issues demand on effort, time and cost of the testing [10]. Different techniques have been proposed for taking care of these issues. In [11], Tai and Srivastava have been presented a method for optimizing software testing efficiency by identifying the most critical path clusters in a program. They were converted software into a CFG. Weights are assigned to the nodes of the CFG by applying rules. In this method by identifying most critical paths according to weights that must be tested first, testing efficiency was increased.

In paper [12] it was proposed a GNN-Attention framework for software testing that use CFG graphs for reducing testing efforts. It significantly advances automatic test path generation by achieving 91.76% fault detection rate, 90.83% test coverage, and 91.2% accuracy in identifying key execution paths in software.

The visualization of CFG graphs can increase the productivity of software tester in carrying out software testing through white box testing. Designing test cases with the code coverage technique can be done more quickly since the tester can see the part of the path that does not yet exist or that it can be completed immediately [13].

CFG testing is applicable to almost all software and one the most effective testing to most software [14]. This testing becomes the most basic technique in white box method but its application is possible to smaller programs or segments of bigger applications [15].

CFG graphs similarity is a core technique for malware software detection and software plagiarism detection [16].

CFG graphs were used for network-based software defect prediction in [17].

Work [18] presents an implemented model named Extended Control Flow Graph. It is purposed for code based analysis of object-oriented software.

Visualizing code as a CFG provides ways to look at much software testing metrics. Paper [16] presents a software testing tool that creates visualizations of the CFG from Python source code and shows execution paths that may be taken by the machine.

4. Case Study

From the review of works in the subject area, it can be concluded that the application of CFG graphs in white box testing is a basic technique used to optimize the number of tests to be executed and which can be automated to speed up the entire testing process. Essential importance in this process is the selection of an optimal but sufficient number of tests to be generated and executed in order to detect as many software defects as possible. Due to the size of the software, it is not possible to create and execute many tests in larger projects and huge software, so this technique needs to be applied to critical parts of the code or to those that reveal defects in other techniques such as black box or gray box testing.

Therefore, the application of CFG graphs will be shown on one segment of the code. Let's take an example of a simple code written in the C programming language.

```
1.  #include <stdio.h>
2.  int main()
3.  {
4.       inti=1;
5.       int s=0;
6.       int n;
7.       printf("Enter the number up to which the sum of positive
         numbers is calculated: ");
8.       scanf("%d", &n);
9.       if (n>0)
10.      {
11.           while (i<=n)
12.           {
13.                s=s+i;
14.                i++;
15.           }
16.           printf("The sum is: %d", s);
17.      }
18.      if (n<0)
19.      {
20.           printf("It is not possible to calculate!");
21.      }
22.      else
23.      {
24.           printf("You have entered the number 0 (zero)!");
25.      }
26.      return 0;
27. }
```

The construction of a CFG is done as follows: first, each statement in the code is assigned a unique identifier, in this case a number (1-27).Then, the graph nodes are formed starting from the first (A)to the last (J). One node of the graph can represent one instruction, but multiple instructions that are executed in sequence can be represented by one node for complexity reduction. In the example, these are instructions 1-8 and they all together form a node labeled with (A).Statements 12-15 form a node (E), Statements 19-21 form a node (H) and Statements 22-25 form a node (I). Second, the nodes are connected by arrows, creating links following the logic of the code. Three branched program structures were formed: two for If-Then statements (B, G) and one for While (D). There are branches for True and False condition values in If-Then statement. For While loop we have two branches, one for completely not entering the loop and the other for normal execution of the loop. A graphical representation of the graph is given in Figure 2.

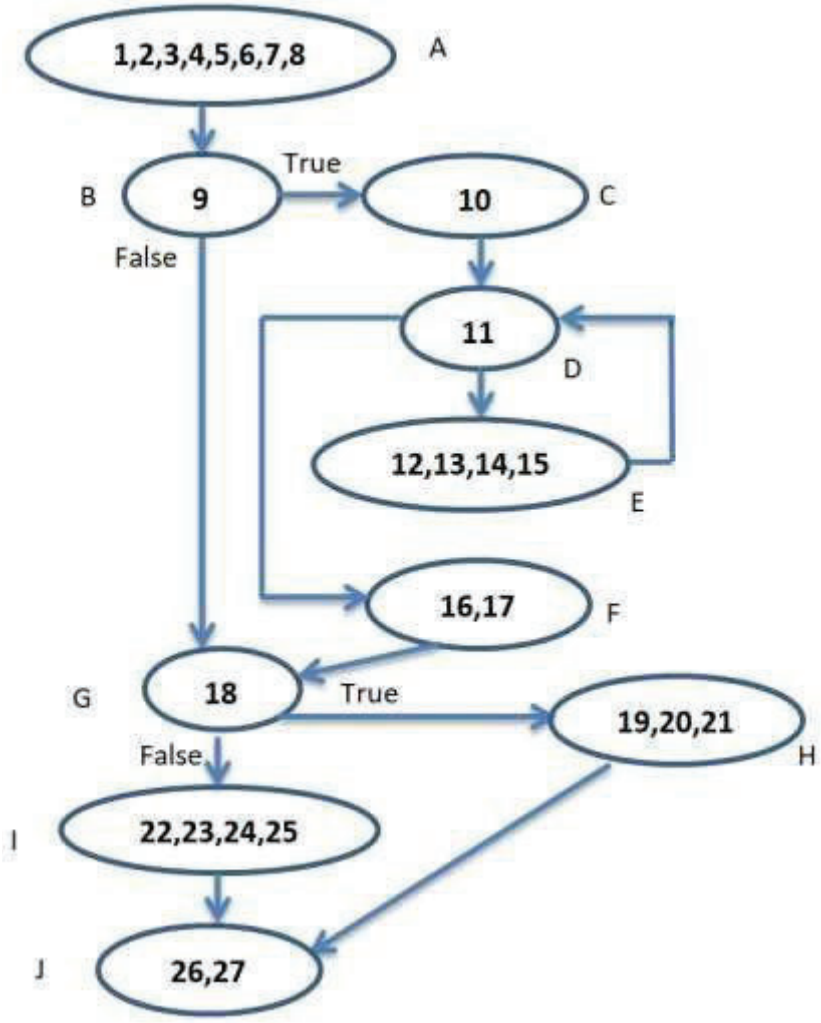


Figure 2: Control flow graph

A total of five paths can be identified in the graph. They are shown in Table 1.The code coverage value calculation for each path at the graph was calculated according to formulae (1):

Table 1:
Tests identified from CFG graph

Test number	Executed graph nodes	Number of executed statements	Percentage of code coverage
1	A,B,G,H,J	15	55.55
2	A,B,G,I,J	16	59.26
3	A,B,C,D,F,G,H,J	19	70.37
4	A,B,C,D,E,F,G,H,J	23	85.19
5	A,B,C,D,E,F,G,I,J	24	88.89

Commands (statements) that must be executed for each test:
Test 1: 1,2,3,4,5,6,7,8,9,18,19,20,21,26,27.
Test 2: 1,2,3,4,5,6,7,8,9,18,22,23,24,25,26,27.
Test 3: 1,2,3,4,5,6,7,8,9,10,11,16,17,18,19,20,21,26,27.
Test 4: 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,26,27.
Test 5: 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,22,23,24,25,26,27.

Code Coverage (Test number 1) = (15 / 27) x 100 = 55.55 %
Code Coverage (Test number 2) = (16 / 27) x 100 = 59.26 %
Code Coverage (Test number 3) = (19 / 27) x 100 = 70.37 %
Code Coverage (Test number 4) = (23 / 27) x 100 = 85.19 %
Code Coverage (Test number 5) = (24 / 27) x 100 = 88.89 %

Statement coverage technique goal is to create tests in such a way that each statement must be executed at least once. Given that in this technique some parts of the code will not be executed, it is best to choose those paths that have the highest code coverage. These tests are: Test 5 or Test 4.Also, it can be noted that in the case of choosing test number 1, only a little more than 50% of the commands will be executed and that in that case, a lot of code would not be tested.

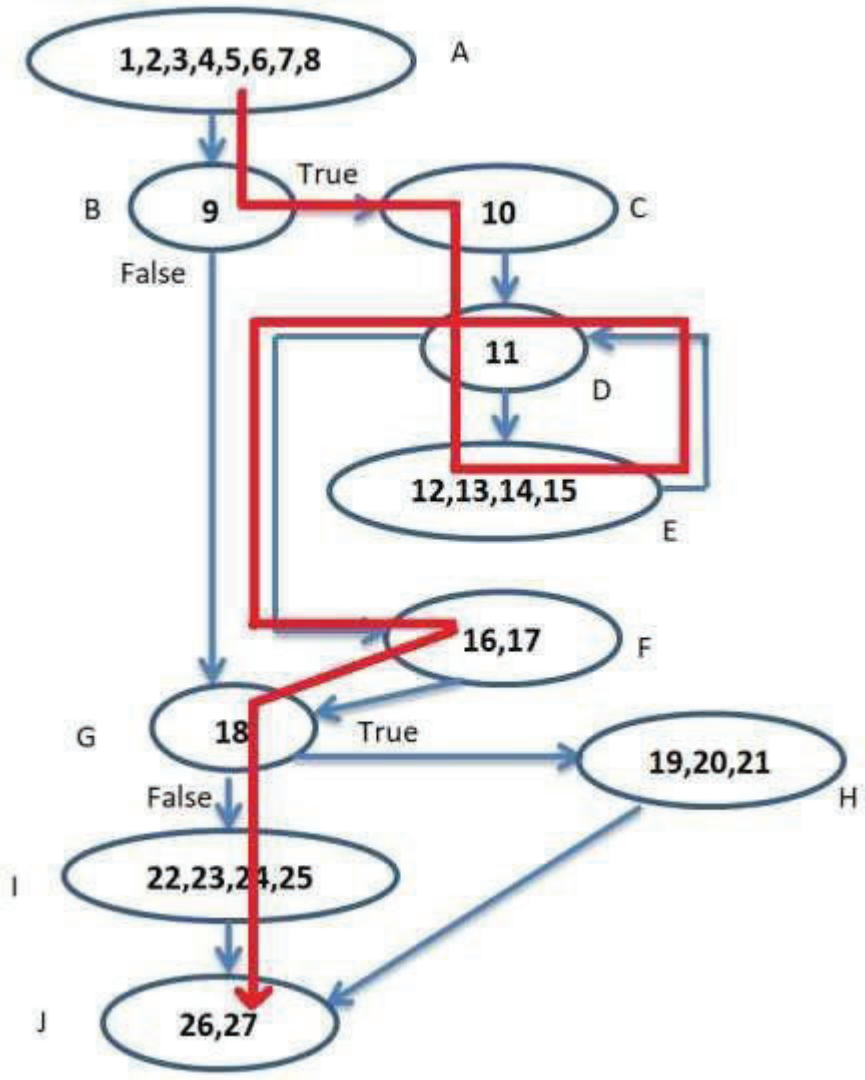


Figure 3: CFG graph path for statement coverage technique (Test 5)

The tests for decision coverage are chosen so that each of the different branches of the condition is executed at least once: Test 1, Test 2, Test 4, and Test 5.

Path coverage technique goal is to cover and execute at least once all paths in a given program that are mutually independent. In given example tests are: Test 1, Test 2, Test 3, Test 4, and Test 5.

It should be noted that for identified paths, testing can yield different results depending on the input values of the variable n. Number of needed tests for each technique is shown in Table 2.

Table 2:
Number of tests per technique

Testing technique	Tests	Total number of tests to be executed
Statement coverage	Test 5	1
Decision coverage	Test 1, Test 2, Test 4, Test 5	4
Path coverage	Test 1, Test 2, Test 3, Test 4, Test 5	5

5. Conclusions

In white box testing, since exhaustive testing is not possible, it is very important to choose the optimal number of tests with the best code coverage. The testing techniques are not complicated, but it is important to choose the best path for statement coverage, while for condition and path coverage techniques, a larger number of tests must be performed. This fact can be a problem for larger projects or those in which a huge number of errors are detected.

The example shows that the smallest number of tests can be performed with the statement coverage technique, but between 10 and 15% of code remains uncovered by tests. In the path coverage technique, which guarantees 100% code coverage, in this case it is necessary to perform 5 times more tests than in the statement coverage technique. This number of tests is unsustainable in large software projects with thousands of lines of written code and complex application or business logic. It can be concluded that the statement coverage technique with a well-chosen test path, i.e. executing statements based on the CFG graph and calculated code coverage values, is the most optimal technique with the highest percentage of tested statements and with a low risk that an error will be missed in the part of the program that will not be tested.

Finally, it is important to point out that the next steps in research will be creating software for drawing CFG graphs automatically based on the code for the purposeof tests automation in order to increase accuracy and reduce the time needed to find the defects and errors. In developing such a program, special attention must be paid to the different programming languages in which the software can be written and the syntax differences of the code that was written.

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Comparative Analysis of Platforms for Analysis, Design and Product Development with a Focus on AI-Based Tools

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Abstract:
This paper explores the integration of artificial intelligence (AI) in the product lifecycle (PLC), with a specific focus on the footwear industry, utilizing advanced AI tools to optimize processes and support informed decision-making. The application of platforms such as Google Trends, Mention, AnswerThePublic, Adobe Firefly, Bing Image Creator, Leonardo.ai, and Grok enables creative concept generation, visual presentation, and iterative design development. The results show that the use of AI not only automates existing processes but also drives innovation, improves design quality, and enhances the potential for sustainable development. A comparative analysis of the selected platforms evaluates their applications, advantages, and limitations across research, design, and product development phases

Keywords:
Artificial Intelligence, Product Lifecycle, Creative Concept Generation

1. Introduction

The product life cycle (PLC) is a complex process that encompasses all aspects of the creation, maintenance and development of a product. In the modern era of rapid technological change, the use of AI is emerging as a key solution for optimizing each of these phases. This paper explores the possibilities of integrating AI into the PLC, with a particular focus on the platforms Google Trends, Mention, AnswerThePublic, Adobe Firefly, Bing Image Creator, Leonardo.ai and Grok, which are used for analysis, design and development of products. By simulating these processes with such advanced tools, proper decision can be made.

The vision for integrating AI into the PLC is not limited to automating processes, but goes further to providing deep insights to make better decisions and enhance creativity in product development. The process starts with research and planning, where AI can be used to analyze the market, identify user needs, and predict trends. Platforms like Google Trends and Mention enable trend tracking and public opinion analysis, while AnswerThePublic helps identify key consumer questions and needs.

In the development and design stage, AI helps with prototyping, material optimization, and simulation of real-world usage conditions. Adobe Firefly, Bing Image Creator, and Leonardo.ai platforms are used to generate visual concepts and designs, while Grok enables the creation of innovative ideas and concepts. These tools not only speed up the design process but also enable rapid iteration and testing of different ideas.

By applying AI, companies can create more efficient and innovative solutions, enable sustainable development and increase competitiveness in the global market. This paper aims to explore the opportunities and benefits of integrating AI into the PLC, focusing on a specific example from the footwear industry.

2. Previous work

Several studies have explored the integration of AI into product lifecycle management, particularly in the design and development of footwear. The impact of Generative artificial intelligence (GenAI) on

footwear design creativity and feasibility is investigated in [1]. Using a text-to-image GenAI tool called Midjourney, 17 prompts were tested to generate footwear concepts. According to [2], AI-based predictive systems enable real-time adaptation of manufacturing processes, which is crucial for responding to dynamic market conditions. The role of machine learning in reducing product development time is highlighted in [3]. In the systematic review by [4], 37 studies are analyzed that highlight the role of AI in reducing waste and improving efficiency in the fashion industry. The role of AI-based tools in promoting design sustainability has been increasingly emphasized in recent studies, such as [5]. The study by [6] demonstrates how Google Trends can serve as an indicator of the market success of new products. The analysis shows that search volume correlates with future sales, allowing companies to adjust marketing strategies early in the development process. Generative tools, such as Adobe Firefly, are revolutionizing the creation of marketing content. According to [7], these platforms enable automatic generation of visual concepts from text descriptions and personalization for specific target groups. Ethical considerations surrounding this integration are discussed in works like [8].

3. Research and planning

Running shoes were chosen as an example in this research due to their functionality and wide application in sports and everyday life. They represent a key part of sports and recreational equipment, meeting the needs of a variety of users, from professional athletes to recreational users. The running shoe industry is constantly investing in innovation, including new cushioning technologies, materials that increase durability, and sustainable manufacturing methods. This makes it suitable for the application of AI at various stages of the product lifecycle – from design to manufacturing process optimization and quality testing. Additionally, running shoes have a direct connection to the health and performance of their users, which places them at the center of research to improve design, materials, and user experience. This relevance justifies their selection as a case study in the research.

Several research and analysis tools will be used in this phase:

- Google Trends: for tracking seasonal and regional trends related to running shoe demand.
- Mention: for monitoring online discussions and consumer perceptions of different brands and technologies.
- AnswerThePublic: for gaining insights into the most frequently asked questions and consumer interests related to running shoes.

This combined analysis will provide data that will serve as a basis for further research and the creation of strategies for innovation and product improvement.

3.1. Research with Google Trends

Google Trends [9] is a powerful tool that uses AI to provide advanced analysis of Google search trends across time periods and geographic regions. This tool reveals valuable insights into the terms users search for most often and how their popularity evolves over time. To begin the research, the term “Running Shoes” was entered into the Google Trends search box, and the term “Sports Shoes” was added via the Add comparison option. This way, up to five terms can be compared simultaneously.

To provide relevant data, “Worldwide” was selected for the region, the time period was set to “2004-present”, and as category “All categories” was selected. “Web Search” was selected as the search type, but “Image Search”, “News Search”, “Google Shopping” or “YouTube Search” can be selected depending on the needs. The results are shown in Figure 1.

3.2. Research with Mention

Mention [10] is an advanced research and analytics tool that uses AI-based technologies to enable in-depth monitoring of online mentions and trends related to topics, brands, or products. This platform is particularly useful in the research phase of the product lifecycle, as it leverages advanced algorithms to analyze data in real time. In continuation of this research, the Mention platform was used to analyze the term “running shoes”. To start using the Mention platform, an alert must be set up to monitor content

related to selected keywords. The platform allows filtering of sources such as news, blogs, forums, social networks, and others, as well as selecting the relevant languages in which results will be received.

Figure 2 presents data obtained from research focusing on the term "running shoes", examining the volume of mentions, dominant sources, sentiment and emotional analysis. This analysis is useful for understanding trends and public opinion related to running shoes.

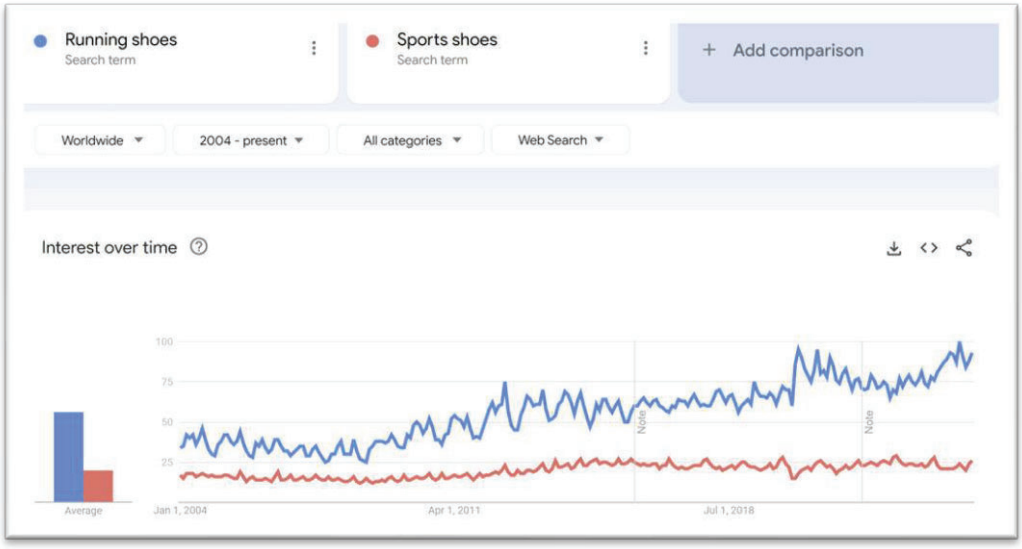


Figure 1: Interest in Running shoes and Sports shoes since 2004 – worldwide, by Google Trends



Figure 2: Mention – The control panel for the term "running shoes"

3.3. Research with AnswerThePublic

AnswerThePublic [11] is a web-based tool designed for keyword research and analyzing user search intent. Using data from Google Autocomplete, the tool collects and transforms information into visual representations. This process provides quick and comprehensive insight into how people formulate their questions and phrases related to a given topic or keyword, making it ideal for a variety of areas such as digital marketing, SEO optimization, content creation, and market research. In the following section, a practical example is presented that illustrates how the AnswerThePublic platform works in the context of the sneaker market. This example aims to confirm and reinforce the argument that interest in sneakers is extremely high, while also illustrating specifically how the tool can be used to create effective strategies in digital marketing and new product development.

Figure 3 shows the results of a search for the term “sneakers” in Germany in English. The tool has found 2,153 results, which are questions and phrases related to this term, and the search volume is 165,000 per month, which is in the “Good” category, marked in green (more than 3,600 searches per month). The average cost per click for ads related to this term is $0.55, which falls into the “Cheap” category.

There are three options for visualizing the results: Wheels, List, and Tables. This data is especially useful for digital marketers and researchers who want to understand how users search for information about sneakers in Germany and how to optimize their content and advertising strategies.

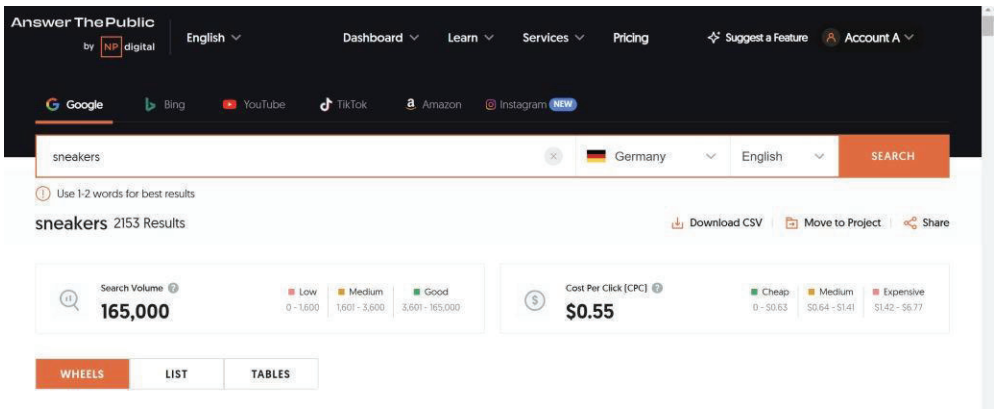


Figure 3: Answer ThePublic platform screen for the term “sneakers” in Germany in English

4. Development and Design

Product development and design are essential phases in the product life cycle, where creativity and innovation play a central role. These phases are focused on transforming ideas and research results into concrete solutions that meet user needs and expectations. With the application of AI, the development and design processes gain significant advantages, including faster prototyping, material optimization, and simulations of real-world usage conditions. AI enables the prediction of product performance even before its physical production, resulting in reduced costs and time required for development. Reports indicate that AI can reduce the duration of design development processes by up to 50% [12]. The goal of this chapter is to demonstrate the importance of AI in transforming traditional design and development processes, enabling products that not only meet but also exceed the expectations of modern users.

4.1. Development and design with Adobe Firefly

Adobe Firefly [13] is a generative AI model developed by Adobe, designed for creative tasks such as designing sneakers through text instructions. This tool offers extensive possibilities for innovation and design personalization. In this paper, Adobe Firefly was experimented with using the textual description: “Create a minimalist running shoe design that is lightweight and constructed with breathable honeycomb-patterned mesh. The shoe should feature a sleek silhouette with clean lines, using eco-friendly materials like recycled polyester and sustainable rubber for the sole.” The result is shown in Figure 4. Additional adjustments can also be made to the generated images in the Color and tone, Lighting, and Camera angle fields.

4.2. Development and design with Bing Image Creator (DALL·E 3)

Bing Image Creator [14] is an innovative platform that allows users to create unique visual content through text descriptions. This tool, developed by Microsoft, uses the power of AI to generate images and designs based on detailed instructions. With Bing Image Creator, users can experiment with different styles, concepts and visual effects, making it an ideal tool for creatives, designers and anyone

who wants to explore their ideas in visual form. In addition, the Bing Image Creator tool was used to generate a conceptual sneaker design based on a text description (prompt), also used for the Adobe Firefly tool. This description is aimed at creating a minimalist sneaker design with eco-friendly materials and a contemporary look. Through this visualization, a better insight into possible design solutions and style variations will be gained, which will help in the product research and development process.

The tool generates several visual suggestions based on the description, shown in Figure 5. Bing Image Creator has proven to be an extremely useful tool for exploring and visualizing concepts, especially in the process of designing minimalist sneakers. The variety of results obtained, as well as the possibility of quick adjustments through additional prompts, allow for flexibility and efficiency in the creative process.

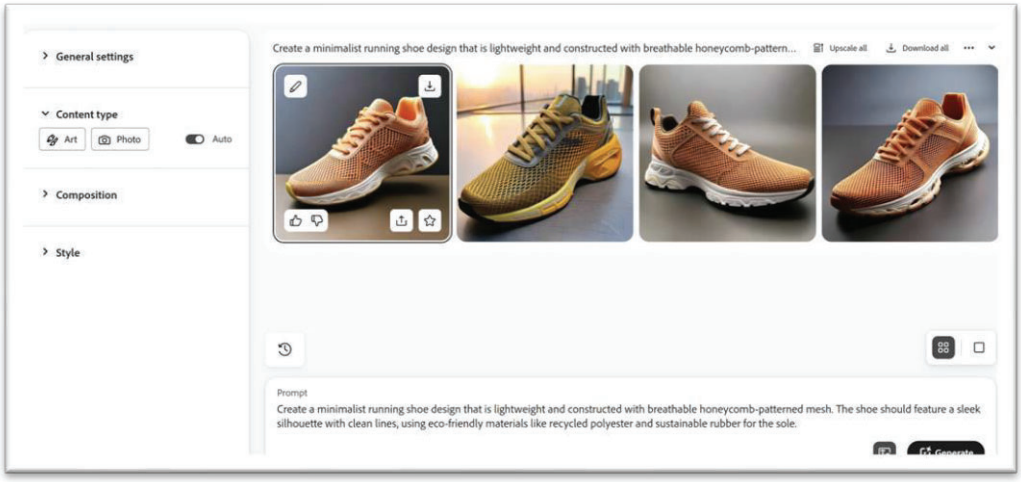


Figure 4: Images generated by Adobe Firefly according to the given descriptive instruction

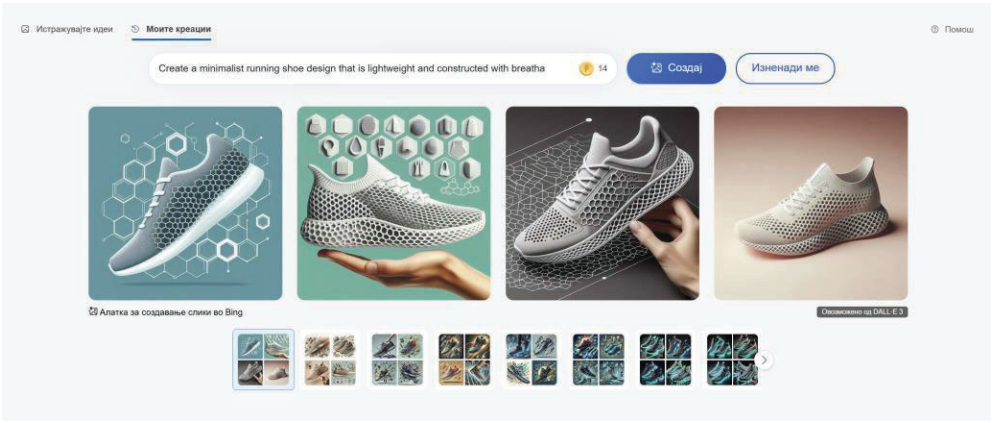


Figure 5: Visual suggestions by Bing Image Creator according to the given descriptive instruction

4.3. Development and design with Leonardo.ai

Leonardo.ai [15] is a relatively new platform distinguished by its focus on creativity and innovative capabilities. It offers various options that make the platform powerful and flexible for creative projects, including creating and editing images in real time, creating animated content, increasing the resolution of generated images without losing quality, as well as advanced image editing tools. The same prompt as for the previous two tools was used to explore Leonardo.ai's functionality. The images show all the key elements of the description, including the honeycomb grid, minimalist design, and use of eco-friendly materials (Figure 6). The platform was able to create realistic and detailed visual representations of the sneakers, highlighting its ability to generate high-quality designs.

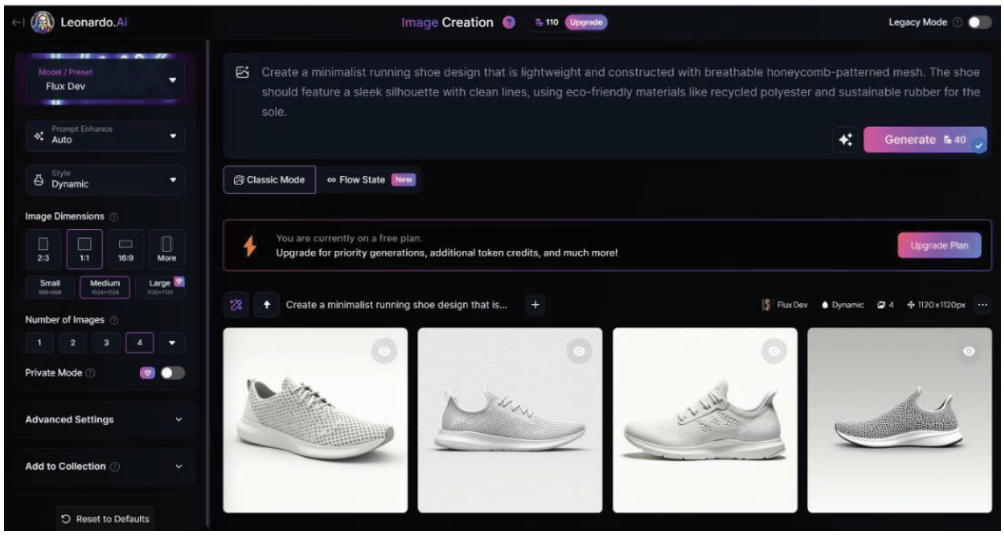


Figure 6: Variations of sneakers by Leonardo.ai according to the given descriptive instruction

4.4. Development and design with Grok

The Grok platform [16] is an innovative AI-based tool designed to rapidly generate creative concepts and solutions in the product development process. With its intuitive interface and powerful algorithms, Grok enables easy experimentation with text prompts, freeing designers from the need for traditional drawing and giving them the freedom to focus on innovation and functionality.

Within the life cycle of a product, Grok can contribute to all phases: conceptual phase - through rapid ideation and generation of visual concepts; prototyping and testing - enabling iterative improvement of ideas and final optimization - whereby the generated concepts can be used to further refine the product and its market positioning.

As part of the research, the Grok platform was used to generate creative ideas for eco-friendly sneakers, using the prompt: “Generate 3 creative ideas for eco-friendly sneakers”. Three ideas were generated by the platform, namely algae sneakers, mycelium sneakers (fungal leather) shown in Figure 7, and sneakers made from recycled plastic bottles. Research with the Grok platform has shown that this tool is a valuable resource for generating creative ideas and conceptual solutions. By experimenting with different text instructions, innovative suggestions are obtained that meet the design goals of eco-sneakers. The speed of generating results and the ability to adjust ideas with additional prompts significantly facilitate the process of creating concepts.

5. Comparison of AI-Based Research and Design Platforms

Table 1 provides a comparative analysis of selected AI-based tools, highlighting their focus, data types, visualization options, key advantages, and limitations.

Google Trends provides real-time insights into search behavior and trends, making it ideal for understanding consumer interests, though it lacks detailed demographic data. Mention enables monitoring of online mentions across multiple sources, offering sentiment and trend analysis, but its full capabilities require paid plans and careful keyword setup. AnswerThePublic excels in uncovering user intent and popular queries, supporting marketing and SEO strategies, yet it is limited by the availability of historical data and filtering options.

For design and content creation, Adobe Firefly generates high-quality images from text and offers seamless integration within the Adobe ecosystem. Leonardo.ai, on the other hand, focuses on creating detailed product visuals and provides advanced fine-tuning options, although its outputs may be unpredictable without prior experience. Grok supports rapid concept generation and brainstorming, particularly for MVP development, yet its visual capabilities remain limited as the platform is still under development.

Although Table 1 presents the general limitations of the analyzed AI-based tools, several specific challenges were identified during the running shoe case study that illustrate these limitations in practice. When using Adobe Firefly, one of the main challenges was the technical feasibility of the generated shoe designs. While the images produced were visually appealing and creative, some of them contained unrealistic elements such as overly thin soles, missing seams between different materials, or inconsistent proportions between the upper and the sole. Additionally, the tool sometimes ignored technical details specified in the prompt, such as ventilation areas or particular material textures. Similarly, Bing Image Creator (DALL·E 3) provided diverse and aesthetically attractive results, but several designs were found to be impractical for manufacturing — for instance, non-continuous sole patterns, asymmetric geometry, or unrealistic curvature of the shoe structure. In the case of Mention, sentiment analysis presented certain inconsistencies, as some neutral or humorous user comments were classified as negative due to sarcasm or ambiguous tone. These examples demonstrate that, while AI-based tools can significantly accelerate ideation, visualization, and data analysis, human expertise remains essential to interpret results correctly, identify unrealistic outputs, and translate creative concepts into technically feasible product designs.

During the design experiment, the refinement of prompts played a central role in improving the quality and realism of the generated outputs. In the minimalist running shoe example, the initial prompt used only general descriptive terms such as "minimalist shoe design" or "modern running shoe concept." These produced visually creative but technically inconsistent results, with variations in shape and missing construction logic. To obtain more coherent outcomes, the prompts were gradually refined through several iterations by specifying aspects such as style (minimalist running shoe), material appearance (fabric or mesh upper, rubber sole), and intended function (lightweight running model). Each refinement step led to outputs that better reflected the design intent and reduced unrealistic elements in the generated images. This iterative approach demonstrated that careful and structured prompt formulation significantly influences both the creativity and technical plausibility of AI-generated designs.

Taken together, the results suggest that while each platform contributes valuable capabilities within its domain—creative visualization, trend analysis, or sentiment monitoring—none of them can operate fully autonomously without expert supervision and contextual understanding.

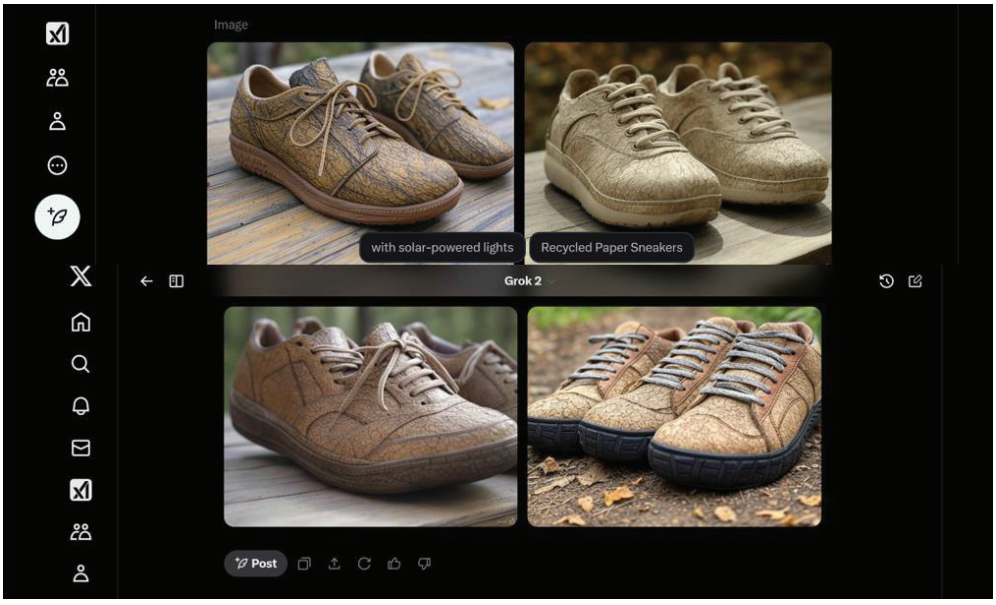


Figure 7: Mycelium Sneakers generated by Grok as an idea for eco-friendly sneakers

Table 1: Comparative Analysis of Selected AI-Based Tools

Platform	Focus/ Application	Data Processed	Visualization	Key Advantages	Limitations

Google Trends	Analysis of interests and trends through searches	Time series of searches by region and category	Line charts, comparison of up to 5 terms	Free access, real-time data, comparison of multiple	Limited demographic data, no detailed user information, limited visualization types, does not show specific URLs
Mention	Online mentions and public opinion monitoring	Posts from news, blogs, forums, social networks	Dashboard (mentions, sentiment, sources)	Real-time monitoring, source and language filtering, sentiment and emotion analysis	Limited functionality in the free version, some platforms/social networks may be uncovered, requires keyword optimization
AnswerThePublic	Research on user intent and keywords	Questions, phrases, keywords	Visualization options: Wheels, Lists, Tables	Detailed insight into how users formulate queries, useful for SEO, marketing, and product development	Free version is limited, no historical data, limited filtering by location or demographics, does not always display all related phrases
Adobe Firefly	Generating realistic images from text	Text-to-image conversion	High-quality images	High-quality results, easy integration with the Adobe ecosystem, creative	Registration required, limited control over details, cannot create complex animations, Internet connection
Bing Image Creator	Concept visualization and creative design generation	Text-to-image	Image gallery	Multiple design variations, ease of prompt- based editing, high image quality	Some generated sneaker designs visually inconsistent or impractical for manufacturing (e.g., asymmetric soles, disconnected elements)
Leonardo.ai	Visual product design and variants	Text-to-image, 3D product variants	Images, product variants	Creative styles, possibility for fine-tuning, easy to use	Occasionally unpredictable results, experience needed for optimal results, limited support for complex
Grok	Generation of concepts, texts, and strategies	Text, ideas, short strategies	Conversational format	Quick concept generation, suitable for brainstorming and MVP ideas	Limited visual results, still in development, does not always provide concrete solutions, dependent on

6. Conclusions

This paper demonstrates the significant potential of AI in enhancing the product lifecycle, particularly in the context of the footwear industry. By integrating AI-based tools such as Google Trends, Mention, AnswerThePublic, Adobe Firefly, Bing Image Creator, Leonardo.ai, and Grok, companies can optimize research, design, and development processes. Market research tools like

Google Trends, Mention, and AnswerThePublic enable deeper insights into consumer behavior, trends, and user intent, which support informed decision-making. Meanwhile, design and development tools, including Adobe Firefly, Bing Image Creator, Leonardo.ai, and Grok, facilitate rapid concept generation, visualization, and iterative improvement of products in terms of simulated processes.

The application of AI not only accelerates traditional workflows but also fosters innovation, creativity, and sustainability. The case study on running shoes illustrates how AI can support eco-friendly design, material optimization, and the creation of multiple design alternatives in a short period. Overall, AI integration into the product lifecycle provides a competitive advantage, enhances design quality, and promotes efficient and sustainable product development, offering significant implications for companies aiming to remain competitive in the global market.

As future work, the quantitative impact of AI integration on PLC metrics such as time-to-market and cost efficiency could be explored. In this regard, we need to revise, adapt, and standardize the usual evaluation metrics to ensure they can be effectively applied when AI-based tools are incorporated into the PLC. Furthermore, comparative studies across different industry sectors can validate the generalizability of these AI tools.

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Detection of Road Edge Lines Using Hough Transform

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Abstract:
This paper presents the application of the Hough transform for the edge line detection solution in autonomous vehicles. The processing pipeline includes image pre-processing, region of interest definition, line detection and optimization. The method has been successful in testing on pre-captured images. It is inferred that the Hough transform gives a good starting point for edge line detection concepts and visualization, however for a dependable use in driverless vehicless, it has to be augmented with further techniques and optimizations.

Keywords:
Hough Transform, Edge Line Detection, Autonomous Vehicles, Computer Vision

1. Introduction

Autonomous driving represents one of the most significant technological revolutions in the automotive industry. The vehicle's ability to steer, accelerate and brake independently relies on a complex system of sensors and algorithms to perceive the environment. One of the key tasks in this system is the detection of traffic lanes. Recognizing the lines on the road allows the vehicle to determine its position within the lane, to safely follow the road path and to plan future maneuvers. Without reliable lane detection, higher levels of autonomy are unfeasible in practice [1].

This paper deals with the implementation of lane detection using computer vision methods. The goal is to develop a software pipeline in the Python programming language, with the help of the OpenCV and NumPy libraries. The basis of the algorithm is the Hough transform, a technique for detecting geometric shapes.

After the introduction, the paper provides the literature overview followed by the material and methods, a description of the implementation and an examples of the obtained results. Further, the success of this approach was analyzed on ideal examples, as well as its limitations in more complex conditions. At the end, a conclusion is given.

2. Previous work

This section will provide a brief overview of the related works. Marzougui et al. [2] describe the creation of a camera-based vehicle tracking and detection system, capable of operating in real time and intended to assist the driver by issuing warnings when the vehicle leaves its lane. The described method utilizes image preprocessing, dynamically adjusting the region of interest, and the detection by the Progressive Probabilistic Hough Transform, along with the Kalman filter for the tracking. The system has been tested in the wild with different lighting conditions and has been very successful with an accuracy of 93.82% and also has lead to the faster processing of data compared to the other methods. Aminuddin et al. [3] are working on creating a lane detection system that uses image processing methods and is specifically designed for highways in Malaysia. Such an algorithm sequentially captures the videos of vehicle-mounted cameras and charts out the essential characteristics like the vanishing point, road width, and region of interest. The work that has been done to achieve this includes the use of image enhancement, edge detection with the Sobel filter and the Hough Transform as the main

method for lane detection. The performance test was done under various conditions (rain, night, and a sunny rural road) where the system showed high accuracy with the average true positive detection rate of 92.5% which is great for application in the field. Bach et al. [4] are engaged in a study that compares and reviews different methods for stripe detection with a primary focus on the use of classical image processing techniques and Deep Convolutional Neural Networks. The traditional method, as well as the main components that were used: Gaussian blur, Canny edge detection, and Hough transformation, runs quickly, however it faces severe problems with accuracy. Whereas, a meticulously adjusted YOLOv8 model [5], trained on the CULane dataset, made it possible to obtain extreamely high and precise detection of lanes. The findings indicate that deep neural networks beat the classical methods, thus giving them a strong possible presence in the future of the autonomous vehicle systems.

3. Material and Methods

Hough transform is used in image processing to recognize characteristic elements. It was invented by Richard Duda and Peter Hart in 1972. It was originally called the generalized Hough transform. The basic principle of work is the voting procedure.

The equation of a straight line can be written as follows:

$$y = mx + c, \tag{1}$$

where m is the slope of the line and c is the point of intersection with the y-axis.

The equation of a straight line in the form $y = mx + c$ has a problem with representing vertical lines, since in that case the slope would be infinite. Therefore, instead of using the parameters m and c, the line can expressed in the polar coordinate system.

The formula for the polar form is given as follows:

$$\rho = x\cos(\theta) + y\sin(\theta), \tag{2}$$

where ρ is the distance from the beginning of the coordinate system to the line itself, and θ is the angle between the normal on the line and the x-axis [1].

A major issue with the standard Hough transform is its enormous memory and processing power needs, as each point in the image has to cast a vote for all the parameter combinations in the parameter space.

Probabilistic Hough transformation was used in the paper. It introduces optimization by using only a randomly selected subset of points in voting. In this way, complexity is reduced with minimal loss of accuracy. It allows the detection of long lines to be very prominent, as only a few points are needed to provide significant value to the spatial field [6].

4. Implementation description

The Python programming language and the OpenCV [7] library for image processing [8], NumPy for numerical operations were used to implement the project. The development environment is PyCharm. The implemented algorithm consists of the following steps:

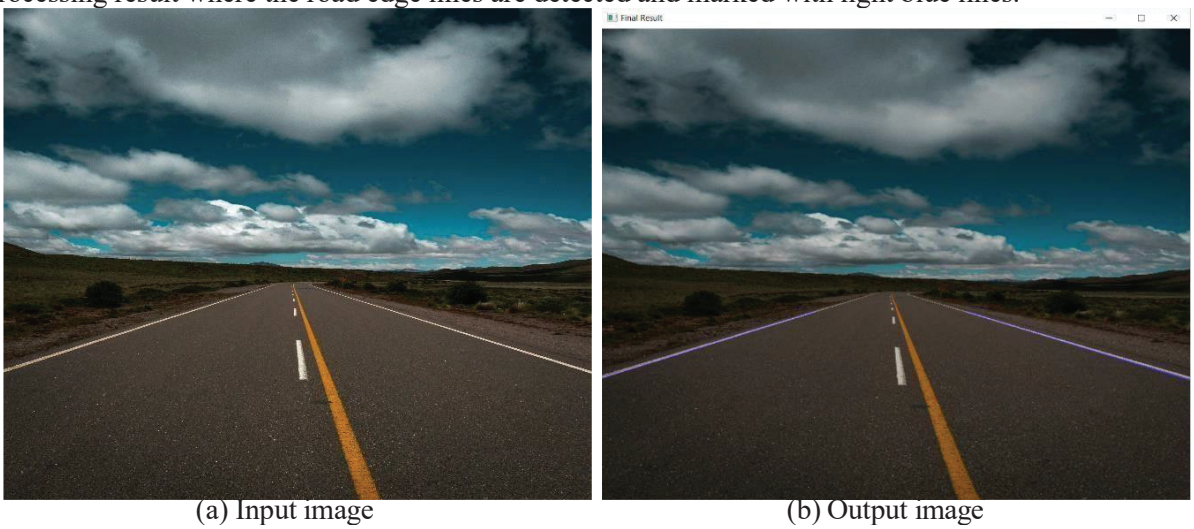
1. Image preprocessing: Each frame is first prepared for analysis. The image is converted to grayscale to reduce complexity. A Gaussian blur [8] with a 5x5 kernel is applied to reduce noise. A canny edge detector [8] is used to identify pixels where there is a sharp change in intensity, resulting in a binary image containing only object edges.
2. Region of interest (ROI) masking: To make the algorithm focus exclusively on the path, a trapezoidal mask is defined. The coordinates of the trapezoid are fixed and determined through experimentation to optimally match the perspective of the road in the test image. A mask is applied to the image with edges, eliminating all detected edges outside the road region. A probabilistic Hough transform [7] is applied to the masked image with edges. This function is the key element of detection and its task is to find all straight line segments within the region of interest and return their coordinates.
3. Line optimization and filtering: The result of the Hough transform are large number of short line segments. In order to obtain two stable lines, an optimization process was applied in the *average_slope_intercept* function [7]. All segments are divided into left and right based on the sign

of their slope. A filter is then applied that only passes lines within a specific slope range to eliminate noise. Finally, the average of the slope and intercept for each group is calculated and the coordinates for one final left and right line are created.

4. Visualization and processing: The final, optimized lines are plotted over the original color image using the *cv2.addWeighted* function [1], [7].

5. Examples of results

Figure 1a shows the input image of the road [9] without edge detection. The road is shown under a clear sky with clouds, daytime conditions, with natural light and good visibility. Figure 1b shows the processing result where the road edge lines are detected and marked with light blue lines.



(a) Input image (b) Output image

Figure 1: Edge line detection in a clear sky with clouds [9]

Given Figure 2a shows again the input image of the road [10] without edge line detection. The road is shown in conditions of reduced visibility. Figure 2b shows the result of the processing where the edge line of the pavement is detected and marked, shown with a light blue line.



(a) Input image (b) Output image

Figure 2: Edge line detection in low visibility [10]

Figure 1 shows better and more complete detection of road edges thanks to clear visual conditions, while Figure 2 shows the limitations of the algorithm in situations of reduced visibility, where detection is not complete. However, it has been identified that there are considerable limitations in real-life settings.

6. Analysis of results and potential problems

The implemented algorithm based on the Hough transform showed good results under strictly defined, ideal conditions, however testing also revealed significant limitations.

Detection quality:

- Advantages: The algorithm is very fast and efficient on straight roads with clear contrast. It successfully implements basic detection logic and can serve as a starting point for more complex systems.
- Disadvantages: The main disadvantage is inflexibility. Since it relies on fixed, manually set parameters, it is not robust to changes in the environment.

Potential problems and limitations:

- Curved roads: An algorithm that looks for straight lines basically cannot model curves. This is its biggest limitation.
- Lighting conditions and shadows: Strong shadows can create false edges that confuse the Canny detector [8]. In low visibility conditions (fog, night), the contrast is too weak for reliable edge detection.
- Sensitivity to parameters: The algorithm is extremely sensitive to parameters such as slope range and ROI coordinates. Parameters that work perfectly for one image may not work for another, even if the conditions are similar.
- Unmarked roads: The algorithm is designed to detect painted markings. On roads without lines, it becomes unusable or incorrectly detects the physical edges of the road.

To overcome these problems, it would be necessary to apply more advanced techniques such as perspective transformation (Bird's-Eye View) [7], polynomial fitting instead of straight lines, and advanced color filters [8].

7. Conclusions

This paper demonstrated the implementation of the algorithm for the detection of traffic edge lines using Hough transform. Through development, testing and parameter tuning, it is shown that, although the approach is effective under ideal conditions, it has limitations that make it impractical for application in real autonomous vehicles without significant improvements. The work provided an insight into the basic principles of computer vision, but also into the complexity of problems faced by systems for autonomous driving. The conclusion is that classical methods are a useful foundation, hoewever for resistance to environmental changes in the real world, a transition to more adaptive approaches, such as deep learning, is necessary.

Acknowledgement

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Design and Implementation of an Intelligent Virtual Medical Agent for Health Risk Assessment

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Abstract:
The development of artificial intelligence (AI) has opened new opportunities for the digital transformation of the healthcare system, enabling automation of initial symptom assessment, intelligent decision support, and improved communication between patients and healthcare professionals. This paper presents the design and conceptual framework of an intelligent virtual medical agent (IVMA) that combines machine learning (ML) and natural language processing (NLP) for interactive, contextual, and explainable healthcare assessment. Methodologically, the research is based on a Design Science Research (DSR) approach and includes architectural modeling, system logic design, and development of a demonstration prototype (Python/Gradio) with local processing, visual BMI analysis, and automatic PDF report generation. The architecture applies the principles of Explainable AI (XAI) and privacy-by-design for transparency, confidentiality, and compliance with GDPR and HIPAA. The proposed model demonstrates technical feasibility, interoperability, and potential for application in preventive medicine, digital triage, and clinical decision-making, especially in resource-limited settings.

Keywords:
Artificial Intelligence, Machine Learning, Natural Language Processing, Virtual Medical Agent, Explainable AI

1. Introduction

Modern healthcare systems face increasing demand, staff shortages, and growing administrative burdens, leading to limited service availability and prolonged waiting times [1] [2]. In response to these challenges, digital transformation, driven by artificial intelligence (AI), machine learning (ML), and natural language processing (NLP), is becoming a key direction for clinical process optimization, automation, and medical decision support [3][8][9][10].

Virtual engineering, as an integrative discipline that unites engineering principles, cognitive sciences, and ethical standards, enables the development of intelligent digital agents that mediate between patients and healthcare institutions. These agents do not replace human expertise, but rather complement it through digital triage, automated symptom collection, and referral to appropriate medical services [4] [5] [11] [12]. This approach enables more efficient use of healthcare resources and the creation of new models for preventive and personalized medicine.

The COVID-19 pandemic has highlighted the importance of scalable digital solutions and accelerated the implementation of virtual health assistants. Platforms such as Infermedica, Ada Health, and Babylon Health have demonstrated significant potential for initial symptom assessment and clinical decision support, confirming the applicability of such systems even in resource-constrained healthcare settings [6].

In this context, this paper presents a conceptual and architectural model of an intelligent medical agent that combines NLP and machine learning for automated initial symptom assessment and clinical judgment support. The main goal is to develop an integrated architectural framework that enables cognitive, technological, and ethical alignment in the design of such systems [13] [14] [15]. In addition, the research proposes methodological and ethical guidelines for their design and presents a simulation framework that can be used as a basis for future pilot implementations in a clinical context.

Methodologically, the paper is based on the Design Science Research (DSR) approach, which enables integrated modeling of technological, cognitive, and ethical aspects in the development of digital solutions [7], [16]. Rather than full implementation, the emphasis is placed on defining the systemic, architectural, and logical principles that support the engineering development and future integration of such systems into healthcare infrastructures.

The rest of the paper is structured as follows. The second section focuses on the theoretical foundations of AI, ML, NLP, and medical ontologies, while the next section presents the concept of virtual engineering and its application in healthcare, with a review of the theoretical foundations, architecture, and design of empathic virtual medical agents as intelligent decision support systems. The subsequent section concerns the practical implementation through Gradio. The fifth section addresses ethical and regulatory aspects, and the last section provides concluding remarks and directions for future research and integration into real healthcare contexts.

2. Theoretical foundations

The design of intelligent digital agents in healthcare is an interdisciplinary process that brings together the principles of AI, ML, NLP, and medical semantics. This section lays the foundation for understanding the cognitive, technological, and communication behavior of such systems.

2.1 Artificial intelligence, machine and deep learning in healthcare

AI is now a key driver of the digital transformation in healthcare, enabling analysis, prediction, and automation of clinical processes. ML enables models that learn from data and recognize relationships between symptoms and diagnoses, using algorithms such as Support Vector Machine (SVM), Random Forest, and XGBoost [17]. Deep learning (DL), through architectures such as Convolutional Neural Networks (CNN), Recurrent Neural Networks (RNN), and transformer models, enables the analysis of complex data, such as electronic health records, clinical notes, and medical dialogues [18].

Current trends include Federated Learning (FL), which enables modeling of decentralized data sources without compromising privacy, while complying with GDPR and HIPAA regulations [19] [20]. In parallel, Explainable AI (XAI) is developing techniques such as SHAP and LIME, which enable visualization and interpretation of model decisions, increasing confidence in clinical applications [21] [22].

In this context, AI and ML do not represent a replacement for medical staff, but rather an intelligent cognitive layer that collects, structures, and interprets data, contributing to increased accuracy, better efficiency, and more informed clinical decision-making.

2.2 Natural Language Processing and Medical Ontologies

Natural language processing (NLP) plays a central role in the design of systems that understand, interpret, and answer medical questions. Models such as BioBERT, ClinicalBERT, and Med-PaLM have been trained on large biomedical corpora (e.g., PubMed, MIMIC-III) and are used for medical entity recognition, symptom analysis, and triage through dialogue [23] [24] [25] [26].

The integration of medical ontologies such as SNOMED CT, ICD, and UMLS enables semantic interoperability and standardization of clinical concepts. In this way, NLP agents connect linguistic analysis with formalized medical knowledge, which is a prerequisite for reliable, explainable, and ethical healthcare recommendations [27] [28].

Modern solutions, such as the Infermedica API, combine these principles and provide interactive triage based on ontological knowledge, NLP inference, and structured decision support.

Within this theoretical framework, AI, ML, NLP, and medical ontologies together form a cognitive and semantic foundation that enables medical agents to understand context, analyze symptoms, and communicate in natural language. These technologies provide a foundation for developing ethical, transparent, and interoperable systems that support the modern model of digital health triage and personalized medical support.

3. Introduction to virtual engineering

Virtual engineering is a modern interdisciplinary paradigm that brings together simulation, digital prototyping, and cognitive virtualization to design and evaluate complex systems in digital environments. In the healthcare context, this means that clinical workflows can be modeled and tested through intelligent virtual agents—from conversational interfaces to cognitive decision support systems—that operate based on AI, NLP, and medical reasoning. These agents serve as the first digital point of contact, structuring symptoms, initiating triage, and communicating recommendations in an ethically and regulatory-compliant manner.

Virtual engineering enables the creation of simulated healthcare environments where technological, cognitive, and ethical principles are integrated before practical implementation. In this way, a bridge is created between academic theory and real-world clinical transformation to reduce risk and ensure methodological rigor [29] [30] [31].

3.1 Theoretical foundations of the concept

The concept is based on four pillars: digital representation of clinical entities (including digital twins) for realistic simulation; a modular architecture that allows for independent development and integration of NLU, inference, and interfaces; simulation before real implementation for greater stability; and a human-centric design that allows for dynamic adaptation of the agent according to the context and user profile [32]. These principles are applied in this research to design an intelligent medical agent that links symptom narratives to standardized clinical concepts (SNOMED CT, UMLS) and generates explainable recommendations [33].

3.2 Virtual medical avatars: role and functionalities

A virtual medical avatar is defined as an intelligent communicative intermediary between the patient and medical knowledge. Its NLU layer converts text into structured input, bound to ontologies (SNOMED CT, ICD-11), while reasoning logic initiates triage or diagnostic recommendations. The interface can be textual, voice, or visual (XR), but the principles of semantic interoperability, ethical transparency, and GDPR/HIPAA compliance remain central.

Psychological factors play a key role in the acceptance of these systems. Empathetic expression, clear communication about limitations, and data confidentiality significantly increase user satisfaction and trust, especially in domains such as mental health and preventive medicine.

Table 1 presents an overview of the key design principles for empathic interaction with a virtual medical agent, with their functional role and expected psychological effect on users.

Table 9:
Design principles for empathic interaction with a virtual medical agent

Principle	Function	Expected effect
Empathic verbalization	Emotionally sensitive communication	Greater confidence and comfort
Adaptive dialogue logic	Contextual Personalization	Perception of intelligence and attention
Multimodal empathy	Visual/audio support	Reduced psychological distance
Transparency (XAI)	Explanatory recommendations	Cognitive trust
Privacy and non-judgment	Identity and data protection	Greater honesty in responses
Cultural adaptability	Language and visual localization	Inclusion without alienation

3.3 Engineering architecture

The proposed system is organized into several functional layers: an interaction layer for text, voice,

and XR communication; an NLU layer for intent and symptom identification; a dialog management layer for contextual coherence; a clinical reasoning core with ontological knowledge and probabilistic logic (or integration with the Infermedica API); and an XAI security layer for explainability, encryption, and regulatory compliance (GDPR/HIPAA). This modular structure ensures interoperability (HL7 FHIR and OMOP) and the possibility of multilingual expansion [34] [35].

4. Practical Implementation: Virtual Agent for Health Assessment with Gradio

Within the framework of this research, a demonstration prototype of an intelligent virtual health agent, designed for interactive assessment of chronic disease risk, has been developed. The prototype serves as a proof of concept for the technical feasibility and cognitive coherence of the proposed architecture. The system is built in Python, using the Gradio library to create an intuitive user interface, scikit-learn for machine learning, and matplotlib for visualization of the results. Through this approach, the practical application of ML and NLP principles in the context of digital triage, self-assessment, and preventive medicine is demonstrated.

During the interaction process, the user enters biometric and clinical parameters such as age, gender, height, weight, blood pressure, sugar level, symptoms, and chronic conditions. Based on this data, the system calculates a body mass index (BMI) and, through a trained Random Forest model, performs a risk assessment for the development of a chronic disease. The results are presented through a visual graphic display with colored zones, indicating different levels of risk (low, medium, high), supplemented with a textual interpretation and a recommendation for further health care.

In addition to the interactive assessment, the application allows for tracking interaction history, with each session being saved as an individual PDF report. The report includes a graphical representation, descriptive assessment, and recommendations, which increase the traceability and transparency of the results. All data is processed locally, without external storage or transmission, ensuring GDPR compliance and respecting the principles of privacy-by-design.

Table 2 shows the main functional components of the system, their role, and the effects of their application, which illustrates the logic of architectural integration and the cognitive flow of the application.

Table 2:
Main functional components of the system

Component	Function	Result / Effect
Data entry	Reception of individual parameters via an interactive interface	A personalized basis for analysis
Machine learning model	Risk classification with the Random Forest model	Risk calculation (low, medium, high)
Visualization	Graphical display of BMI with color zones	Improved perception and understanding of results
Explanatory Logic (XAI)	Textual explanation of the result	Greater trust, transparency, and interpretability
History and report	View and generate PDF reports	Traceability and documentation of sessions

The visual design of the interface is structured into three functional units: data entry, Figure 1, results display, and history review with report. The user enters data via a simple form, and the system automatically generates a visual assessment with a graphical display of BMI and accompanying textual recommendation. The history allows for a review of previous sessions and downloading of an individualized report, thus ensuring continuity and documentation of health self-evaluation.

Although the prototype is of a demonstration nature, its architecture allows for real expansion with additional functionalities, such as processing of textual descriptive symptoms via NLP, support for multimodal data (images, audio), and integration of XAI techniques, such as SHAP and LIME, for better interpretability and transparency of results [36].

Future research phases include a methodological assessment of the accuracy, interpretability, and user experience of the system. This plan is not a formal evaluation, but rather an orientation framework that defines the future direction of the experimental phase. The evaluation will be based on synthetic scenarios and sample dialogues to test the cognitive coherence and stability of the agent in a simulated environment. Key performance indicators include accuracy, precision, recall, F1-score, and Top-N, which will allow for a quantitative assessment of the model's classification performance. Additionally, a subjective UX survey will be conducted with a small group of test users to gain insight into their perception of the system's intuitiveness, trustworthiness and understandability. In this way, the assessment will ensure a balance between technical accuracy and user experience, which is an essential aspect for the successful integration of intelligent agents into healthcare practice. Such an evaluation approach is directional and will serve as a basis for future pilot testing in a clinical context, following the development of a fully functional prototype and the provision of real-world health data. In doing so, the system not only demonstrates technical feasibility but also creates a platform for sustainable ethical, regulatory, and clinical integration in future phases of research.

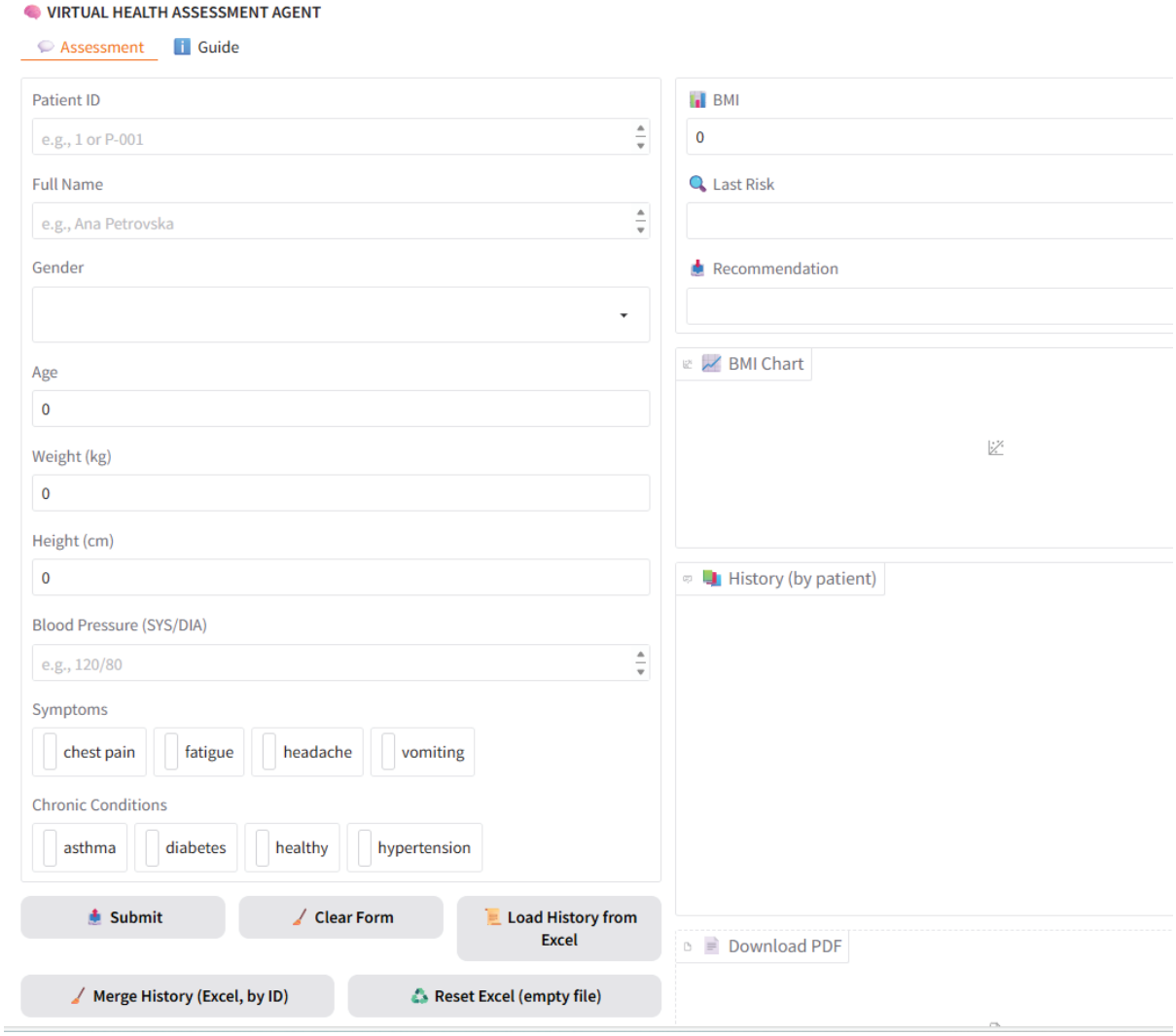


Figure 1: Data entry interface of Virtual Agent for Health Assessment

5. Ethical, regulatory, and security aspects in the design of intelligent medical agents

The integration of intelligent medical agents into clinical processes represents not only a technological advance but also a significant ethical and regulatory challenge. To ensure trust, safety, and social

acceptability, such systems must be based on the principles of non-harm, autonomy, fairness, accountability, and transparency, especially when mediating initial (pre-diagnostic) interactions with patients.

Ethical operability implies a design that is not only functionally correct but also compliant with European and international regulations, such as GDPR, HIPAA, and Software as a Medical Device (SaMD), with built-in mechanisms for fair algorithms, auditability, and traceability of decisions. In this way, the system demonstrates ethical confidentiality, prevents discriminatory effects, and enables responsible use of technology in clinical practice.

5.1 Compliance and data protection

AI-based systems in healthcare process highly sensitive personal data, which requires the application of the principles of privacy-by-design and compliance-by-design. In the proposed model, all data is processed locally and sessionally, without storing personal identifiers, which minimizes regulatory risk and eliminates the possibility of unauthorized access [37].

Mechanisms such as TLS encryption, pseudonymization, access control, audit, and data revocation are implemented, in accordance with GDPR, HIPAA, and HL7/FHIR standards; privacy-by-design and compliance-by-design approaches are built into the architectural phase. This approach strengthens patient trust, as it ensures transparency in processing, interoperability with existing healthcare platforms, and consistent compliance with regulatory requirements of the European Union and the United States [38] [39].

5.2 Ethical AI and explainability

The ethical application of AI in healthcare implies that systems should be explainable – XAI, especially when providing automated recommendations or diagnostic guidance. The proposed model applies micro-XAI layers that offer concise, understandable interpretations of the decisions made [39]. For example: "Symptoms contributing to the assessment: abdominal pain, nausea, fever (2 days). Possible condition: gastroenteritis."

These micro-explanations enable cognitive transparency and increase user trust, as the system is not a “black box” but a partner in understanding symptoms. Potential algorithmic bias (linguistic, demographic, or cultural) is addressed through localized corpora, Named Entity Recognition (NER), and metadata analysis for fairness [40].

The human-in-the-loop principle is applied, whereby human intervention remains essential in situations of uncertainty, ambiguity, or contradictory data. This ensures a balance between automation and ethical control, which is especially important when applied in clinical contexts [41].

A systematic review of the key ethical principles and corresponding mechanisms implemented within the proposed model, as well as the expected effects of their implementation in a real healthcare context, is presented in Table 3. This review confirms the integration of technological and ethical components in the system design.

Table 3: Ethical principles and applied mechanisms in the proposed system

Ethical principle	Applied mechanism	Expected effect
Privacy and confidentiality	Pseudonymization, TLS encryption, and offline processing	Personal data protection and risk reduction
Explainability (XAI)	SHAP/LIME interpretations and micro-explanations	Transparency and greater user trust
Algorithmic fairness	Federated and fair learning, metadata analysis	Reducing bias towards certain groups
Data control and traceability	Audit trail, user consent, audit	Compliance with GDPR and HIPAA regulations
Human intervention	Involving a clinician in decision-making	Security and control in situations of

Ethical principle	Applied mechanism	Expected effect
(Human-in-the-loop)		uncertainty

5.3 Limitations and future directions

Although the research provides a solid conceptual and architectural framework, based on technological and ethical alignment, empirical clinical validation is lacking at this stage. The main limitations stem from limited local datasets, the unavailability of national NLP resources, and insufficient standardization of medical semantics in the Macedonian language.

In the future phases, a functional prototype (MVP) is planned to be developed with the integration of Rasa Framework and Infermedica API, which will enable the simulation of real clinical scenarios and testing of the cognitive consistency of the system. Pilot testing in healthcare institutions is also planned, with the involvement of medical professionals to validate accuracy, explainability, and user experience. Additionally, the application of large language models (LLMs) for multilingual communication and improved contextual understanding of symptoms will be investigated, which will increase the applicability of the system in various healthcare settings.

These activities represent a logical extension of this research and will enable the development of ethically responsible, interpretable, and reliable medical agents, which combine safety, transparency, and clinical applicability – prerequisites for their real integration into modern healthcare systems [41] [42].

6. Conclusion

This research establishes a conceptual, architectural, and methodological framework for the design of an intelligent medical agent that integrates the principles of NLP, dialogic logic, and clinical reasoning. Through a synthesis of machine learning, semantic ontologies, and explainable algorithms, a system is modeled that represents an innovative engineering concept for simulated health triage and interactive symptom assessment in a digital health environment.

The proposed architecture is modular and hybrid, with clearly defined functional layers that ensure interoperability, scalability, and transparency. A special value is the separation of cognitive reasoning from dialogic logic, which allows integration with reasoning-as-a-service platforms and the creation of multilingual, contextually aware interaction. The architecture incorporates XAI mechanisms for interpretability and privacy-by-design principles for full compliance with GDPR and HIPAA, which guarantees the ethical and regulatory sustainability of the system.

Although the paper is theoretical and conceptual in nature, without clinical validation at this stage, it lays a solid foundation for future prototyping, testing, and evaluation in a real healthcare environment. The identified challenges - such as the limited NLP resources in the Macedonian language, the dependence on commercial API services, and the need for local medical corpora - indicate the main directions for further development. They also highlight the need for national initiatives to create open health data infrastructures that will encourage the application of artificial intelligence in the domestic healthcare system.

At its core, this research represents an initial step towards creating ethically responsible, explainable, and interoperable digital medical agents that combine technical feasibility with clinical and ethical relevance. Such systems have the potential to transform initial health assessment, support preventive and personalized medicine, and create more accessible, transparent, and equitable healthcare, especially in resource-limited settings.

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Orkes Conductor - performance comparison with Apache Kafka

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Abstract:
This paper describes Orkes Conductor as an example of event orchestration and Apache Kafka as an example of choreography, as ways of implementing SAGA pattern. A performance analysis and comparison of two tools is provided. This paper also includes description of implementation of both tools, written in Java programming language.

Keywords:
Conductor, task, messaging, LLM, Kafka, performance

1. Introduction

Microservice architecture (MSA) is an architectural design pattern introduced to solve problems relating to horizontal scalability, availability, modularity and agility of traditional monolithic systems. It is based on the idea that application consists of series of services [1] that are independently developed, tested, updated, scaled and deployed. Given that every service has its own entities and database [2], new problem is introduced - when an error occurs in one of the services it is not possible to do a rollback in all services, since it is a distributed transaction. SAGA pattern [3] is used for long-lived transactions, organizing them as a sequence of local transactions, where update of database in one service emits event or message that triggers next local transaction. In case of error rollback is done as sequence of local transactions, but in reverse order. SAGA pattern can be implemented using choreography or event orchestration.

In case of choreography, each service works independently, and when local transaction is finished event is emitted, which other services wait for to start their transactions. This process continues until the last service doesn't emit any event. Orchestration uses central orchestrator, which behaves as "parent" service, listens to all events emitted by local transactions and based on them triggers the next local transaction.

Chapter 2 presents Orkes Conductor in detail, including its basic elements used for implementing orchestration. Chapter 3 introduces Apache Kafka, which is used for implementing choreography. Chapter 4 provides details on the implemented solution and a comparative performance analysis of these two implementation approaches for the SAGA pattern. Chapter 5 contains references to previous works on this topic, while chapter 6 contains contribution of this research. Chapter 7 summarizes the topics covered.

2. Orkes Conductor

Orkes Conductor [4] represents an example of event orchestration. It is a framework developed on top of Netflix Conductor and was moved to open source in 2016. In addition to core functionality additional features and improvements were added to make it easier to deploy and manage workflows in the production environment.

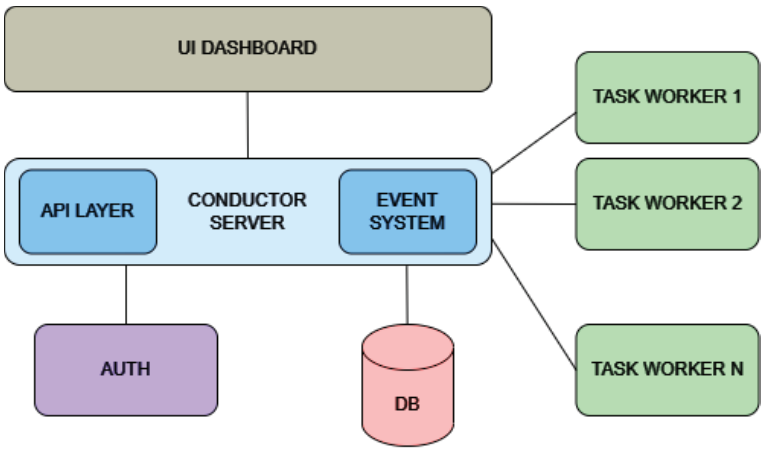


Figure 1. Orkes Conductor architecture

Figure 1. represents visualization of Orkes Conductor architecture. UI Dashboard is human-machine interface (HMI) that allows users to visualize, configure and manage workflows and tasks. It communicates with the Conductor server to display workflow status and control task execution. Conductor server is the central coordination engine that coordinates task execution across distributed workers. It has two subcomponents: API layer and event system. API layer provides RESTful or gRPC endpoints for client and the dashboard to interact with the system. Event system handles asynchronous communication between services, implemented using Orkes Queues to trigger tasks based on events. Task workers pull tasks from Event System, process them, and send back the results to the Conductor server. Increasing the number of task workers increases horizontal scalability. Authentication provides identity and access management, and it works with API layer to enforce security policies. Database is accessed by the Conductor server for storing and retrieving status of workflows and tasks.

2.1. Core concepts

Task represents unit of work or a step in workflow, like creation of HTTP call, sending email, data processing or execution of business logic. It is a basic building block of Conductor workflow, and it can be categorized into three types: operators, system tasks and worker tasks. Operators are control flow primitives, similar to programming language constructs like loops, switch cases or fork/join blocks. System tasks are built-in tasks designed for common use, like calling HTTP endpoint, invoking AI model, or listening for event of an external system. Worker tasks are custom code in application, also known as simple tasks. They are implemented by custom tasks workers that run in separate environment than Conductor.

Workers are code in charge of task execution. Conductor executes operators and system tasks, while custom worker tasks are executed by applications that implement them. Each worker follows following patterns:

- Defined input/output - each worker executes specific tasks and produces expected output for defined input
- Statelessness - workers are without state and don’t implement workflow logic
- Idempotency - workers are idempotent in order to facilitate retries and task rescheduling
- Decoupling - workers don’t implement logic for retries, timeout, this is done by Conductor

A workflow is a sequence of operators and tasks, with defined order and execution. This execution occurs in hybrid ecosystem which combines serverless functions, services and monolithic applications. They manage state, handle retries and provide centralized control over distributed systems. This makes Conductor suitable for agentic AI systems, such as:

- Retrieval-Augmented Generation (RGA) - coordination of multiple AI services into reliable, observable pipelines
- Statelessness - workers are without state and don’t implement workflow logic
- Agentic Workflows - empowers AI agents to take actions, call APIs, and perform multi-step reasoning by integrating them into deterministic, auditable workflows

- Human-in-the-Loop interactions - integration of human approvals or feedback into automated processes for hybrid decision-making

2.2. AI tasks

Generative AI is a type of artificial intelligence capable of creating new “human-like” content, based on pre-trained models that were exposed to large amounts of similar data. Human interaction is still needed to direct models to what needs to be generated - better direction yields better results. Models are directed by sending prompts - textual instructions. Gen-AI response is textual as well.

Large language models [LLM) [5] are deep learning algorithms trained on large amounts of data. They perform various NLP tasks, such as generation, translation, chat-bots, AI assistants, et. Some of popular LLM providers are Open AI, Azure Open Ai, Google Vortex AI, Google Gemine AI, AWS Bedrock Cohere, AWS Bedrock Titan, Mistral, Grok, et.

2.3. Event handler

An event handler processes incoming messages and executes actions based on their details. The trigger for an event handler can be activated by subsequent actions, such as:

- Complete task- marks a task as finished
- Terminate workflow - ends an active workflow
- Update variables - modifies environment or workflow variables
- Fail task - marks a task as failed, triggering appropriate recovery or alert mechanisms
- Start workflow - initiates a new workflow based on the event details

In essence, the event handler ensures that the system can respond dynamically to various conditions by performing the necessary actions to maintain system integrity, flow, and performance.

2.4. Access Control

Orkes Conductor offers role-based access control (RBAC) for users of the Orkes platform and applications utilizing the Conductor API. RBAC ensures access to metadata related to workflows, tasks, secrets, environment variables, integrations, prompts, user forms, event handlers, schedules, webhooks, and domains.

A user represents an individual interacting with Conductor through the Orkes platform and is authenticated using a Single Sign-On (SSO) provider or via email/password. Each user can be assigned one or more roles.

A group represents a set of users and serves as a quick way to assign permissions to a larger number of users. Each group can be associated with one or more roles, and it may also be assigned a set of permissions, providing access to certain resources. When a user is added to a group, they automatically inherit all roles and permissions associated with the group. If a user is removed from the group, they lose all the roles and permissions inherited from it.

An application represents an app interacting with the Conductor server via an API or SDK. Applications can be assigned permissions to ensure access to specific Conductor resources. Each application may have one or more key/secret pairs used to authenticate and grant access.

A tag represents a key-value pair that can be associated with the metadata of a resource. Tags serve as shortcuts for sharing permissions across multiple resources or users.

A role defines a set of default, broad permissions for resources. Roles can be assigned to users, groups, or applications. If multiple roles are assigned, permissions from each role are applied.

In addition to role-based permissions, granular permissions can be assigned to groups or applications. These permissions provide additional access beyond the user's or application's role-based permissions.

A domain is used to grant access to all tasks within a particular domain. It is useful for granting mass permissions to a worker application to perform all tasks, without needing to add each individual task and define its domain.

2.5. Task routing

For each configured task type, the Conductor server maintains a queue and distributes tasks to all workers connected to the server. There is also an option for routing the same task to a different set of workers based on a concept called Task to Domain. This value is passed along with the workflow when it is started, and if present, it indicates that tasks are routed differently from the default routing method.

2.6. Metrics and worker scaling

Scaling and tuning worker performance depend on the following metrics: number of pending tasks, throughput per worker and total number of active workers.

2.7. Error handling

Conductor is designed with at least one delivery guarantee: all messages can be persisted, are durable, and will be delivered to workers at least once. This model ensures two main things: once a workflow starts, it will be completed if all tasks are completed successfully and if task execution fails due to retries or other issues, the message will be delivered to another live and responsive worker node. Timeouts may occur if there are no available workers for the given task type, if a worker takes over a task but does not complete it before terminating and the task remains incomplete, or if the worker finishes processing but is unable to communicate with the Conductor server due to network issues or server unavailability. In all these scenarios, Conductor will attempt retries or reroute the task to ensure eventual completion, thereby providing fault tolerance and system resilience

3. Apache Kafka

Publish/subscribe [6] is an architectural pattern that enables asynchronous communication between different components or services. It is characterized by the fact that the sender (publisher) does not send a message to any recipient directly but classifies the message, and the receiver (subscriber) subscribes to receive specific types of messages. Pub/sub systems most commonly include a broker (a central location where messages are published) that manages this process.

Apache Kafka [7] is a distributed data streaming platform that allows for the publishing, receiving, storing, and processing of data streams in real time. It is designed to handle large volumes of real-time information and route it to multiple consumers.

The fundamental unit in Kafka is the message - a sequence of bytes. Messages can include optional metadata, such as a key (also a sequence of bytes), which is used when writing messages to partitions. For efficiency, messages are written to Kafka in batches (collections of messages), which are categorized into topics. Topics are further split into partitions. Messages are written to the end of the topic and read from the beginning.

If a topic has multiple partitions, the order in which messages arrive may not be preserved across the entire topic, but it will be guaranteed within each partition. Partitions provide scalability, as each partition can reside on a different server, meaning a single topic can be horizontally scaled across multiple servers.

3.1. Producer

Producers [8] are applications that create messages and send them to Kafka brokers for consumption. Producers do not write directly to partitions; instead, they create requests for messages and send them to the broker's leader.

Kafka producers can be either synchronous or asynchronous. Synchronous producers after sending a message wait for an acknowledgment from the broker, while asynchronous producers do not wait for confirmation and continue with their operations, allowing for higher throughput. However, they are

more complex to implement, particularly in handling errors, and improper implementation can lead to data loss.

3.2. Consumer

Consumers [8] are applications that consume messages. A consumer subscribes to one or more topics and reads the messages in order they arrived. Kafka consumers track which messages they have already read using an offset. The offset is a metadata integer that continuously increases, and Kafka assigns it to each message as it is published.

By saving the offset of the last consumed message for each partition (in either Zookeeper or within Kafka itself), a consumer can stop and restart without losing data. Consumers are part of a consumer group - one or more consumers working together to consume a topic. The group ensures that each partition is consumed by only one member. This mapping between consumers and partitions is known as partition ownership.

Consumer groups allow for horizontal scaling of message consumption, ensuring that a topic with many messages can be processed efficiently. If one consumer in the group fails, the other members of the group will rebalance the partitions to take over the tasks of the failed consumer.

3.3. Brokers and clusters

A single Kafka server is referred to as a broker. The broker receives messages from producers, assigns them offsets, and commits the messages to disk. It also serves consumers, responding to fetch requests with previously committed messages.

Kafka brokers function as part of a cluster. Within a cluster, one broker acts as the controller, which is automatically chosen from the set of live cluster members. The controller is responsible for administrative operations, including assigning partitions to brokers and monitoring brokers for failures.

A partition [9] is owned by only one broker within a cluster, and this broker is known as the partition leader. However, partitions can be assigned to multiple brokers, which results in replication of the partition.

One of the key features of Kafka is the retention period. Brokers are configured with a default retention period or until the topic reaches a specific size. Individual topics can be configured with their own retention periods, which determines how long messages are retained before being discarded.

3.4. Zookeeper

Apache Zookeeper often serves as a coordinator component in Kafka, acting as an intermediary interface that facilitates communication between the brokers and consumers (Apache, 2023). It is also responsible for maintaining cluster metadata. In more recent Kafka versions, there has been the possibility to run Kafka without Zookeeper using KRaft, and Zookeeper is planned to be removed from the next major Kafka version 4.0.

4. Orkes Conductor and Apache Kafka comparison

To illustrate the difference between orchestration and choreography in microservice architecture, an example system representing an online store has been implemented using Java programming language. The system is composed of the following microservices: ordering service, inventory service, payment service, notification service and shipping service.

4.1. Conductor workflow implementation

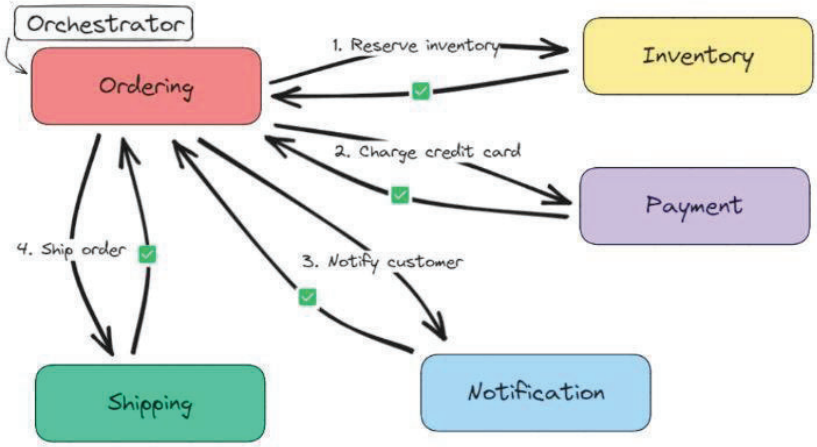


Figure 3. Online shop event orchestration

The ordering microservice takes the role of the orchestrator and coordinates communication between the remaining services. The flow is defined in JSON format and added to the Orkes server. Within the ordering service, a REST endpoint is defined that starts the flow using a WorkflowClient defined via the dependency io.orkes.conductor:orkes-conductor-client. When starting the flow, the name of the flow is specified, as well as the names and values of input variables.
When defining a worker, it must be annotated with @WorkerTask. The annotation includes parameters such as the name of the task, the number of threads used for task execution, and the interval at which the worker polls the server.

4.2. Apache Kafka implementation

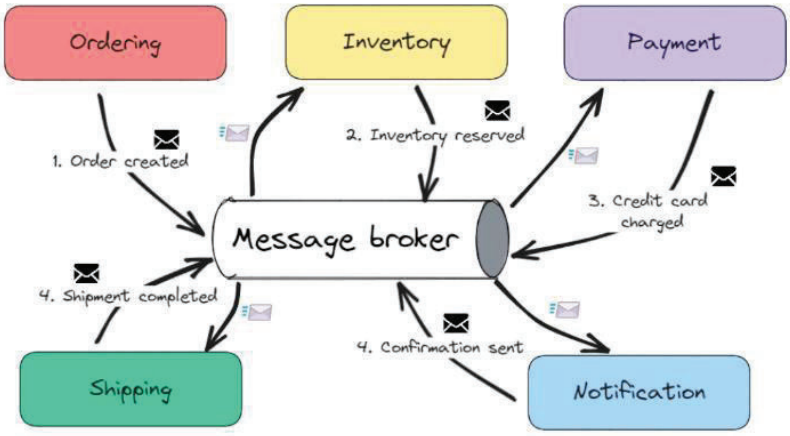


Figure 4. Online shop event choreography

Event-driven communication is used. The Kafka server (Kafka and Zookeeper) is deployed on port 9092 in a Docker container, and using a Java library, KafkaTemplate and ConcurrentKafkaListenerContainerFactory are created in the microservices (only in those where a consumer exists), based on the configuration defined in the application.yml file. Within the ordering service, an endpoint is defined that initiates message sending - this service is the only one without a consumer, as it is the service where the communication starts.

When defining a consumer, it must be annotated with @KafkaListener. The annotation includes parameters such as the consumer ID, the topic being listened to, the group ID - in this case, the service in which it is located, the container factory - defined in Java code during Kafka configuration, and the error handler in case of failure.

4.3. Comparative performance analysis

Considering that the performance of the system can depend on various parameters - such as configuration, hardware resources, and memory, it is difficult to quantify. For the purposes of this work, the project reads order data from five files, each containing a different number of orders.

Table 3:
Comparison results

Number of messages	500	1000	2000	5000	10000
Conductor	10s	15s	26s	49s	95s
Kafka	0.41s	0.31s	0.43s	1.32s	7.24s

The difference in processing a small amount of data is not significant, but it can be observed that Kafka performs better, and the performance gap increases as the amount of data grows.

Since the shipping and notification services are independent of each other, they are defined to run in parallel. This parallelism in Conductor requires additional FORK and JOIN tasks, where the most time-consuming part is the JOIN task. In the version where the Conductor workflow is defined as sequential (first shipping, then notification), performance improves - in the case with 10000 orders, execution time decreased from 95 seconds to 76 seconds. The reasons why the sequential workflow is faster than the parallel one are that the parallelism is logical, not physical, and the orchestration overhead - each task needs to be recorded in the database, the task status is written to the metadata store, the worker must fetch and return the result, which means that for simple workflows, the overhead becomes greater than the benefits of parallelism.

In the Kafka implementation example, it is evident that Kafka does not wait for both notification and shipping service messages to be received before considering the process successfully completed. To gather this information, an additional service - the delivery service - has been introduced, which waits for the successful processing of both messages. Once both messages have been processed, the message exchange is considered successful. With additional service, there is a significant slowdown in message processing when using Kafka, where it now takes 29.9 seconds for 10000 messages.

5. Previous work

Previous studies have also assessed existing technologies with regards to the Saga pattern. The study by (Štefanko et al., 2019) [10] analyzed four different Java-based application frameworks: Axon, Eventuate Event Sourcing and Eventuate Tram and MicroProfile Long-Running Actions (LRA) (based on the Narayana implementation). Evaluation focused on assessing the frameworks' support for the Saga pattern, implementation complexity, and a performance analysis investigating the system's behavior under large load (Štefanko et al., 2019). Another study (Dürr et al., 2021 [11]) used a qualitative analysis to compare two technological solutions: Eventuate Tram and the workflow orchestration engine Netflix Conductor. They consider general characteristics, monitoring, expandability and handling of failures. Study (Dürr et al., 2022 [12]) extends their work by considering additional technological solutions as well as an extended criteria catalog.

6. Contribution

Netflix Conductor was not considered in study [10] which compared technological solutions for the Saga pattern. Štefanko et al. [10] conducted a performance test to measure processing times and throughput. Given that Orkes conductor was built on top of Netflix conductor, there is no study involving it. We performed quantitative evaluation, comparing it to Apache Kafka, as an example of event choreography. This work also provides results on how changes in workflow affect performance of both tools.

7. Conclusions

Conductor itself does not process data directly but acts as a central coordinator that delegates the tasks to workers, who then return the results once completed. This architecture allows the system to remain loosely coupled, with full visibility and control over long running and complex processes. Unlike Kafka, which is optimized for fast and reliable message forwarding between producers and consumers, Conductor focuses on orchestrating workflows and managing state throughout the entire process lifecycle.

In situations where simple message exchange or linear processing is required, Kafka is a more suitable choice. However, in cases with more complex logic, where parallel execution, retries, error handling, conditional branching, or task dependencies related to specific users are necessary, Conductor provides an advantage in terms of declarative modelling, better visibility, advanced error handling, and managing dependencies between tasks - the execution order of tasks depends solely on the workflow definition, not on the implementation in the microservices, allowing dynamic updates to business logic without modifying individual components.

Conductor and Kafka are not mutually exclusive - Kafka can function as the central infrastructure for event handling, while Conductor can serve as the "brain" of the process, orchestrating how these events are processed, transformed, and linked into meaningful outcomes. This hybrid approach allows for leveraging the strengths of both platforms - Kafka for stable message forwarding and Conductor for structured business workflow orchestration, resulting in systems that are both scalable and intelligent.

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