

IPSI Transactions on Internet Research

**Theory and Practice in Data Analysis,
Machine Learning, and Visualization**

**Guest Editor: William Steingartner
and**

**The Future of Digital Transformation
in Business Processes**

Guest Editor: Mirjana Radović-Marković

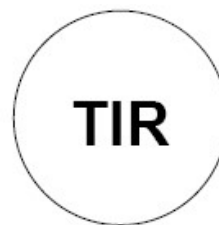
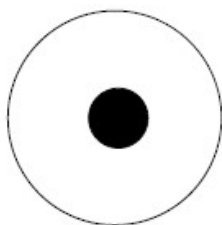
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Editorial

Theory and Practice in Data Analysis, Machine Learning, and Visualization

Guest Editor: William Steingartner

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The Future of Digital Transformation in Business Processes

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Special Report:

**Mester, Gyula: Ranking of Artificial Intelligence
Researchers in Serbia for 2025**

Theory and Practice in Data Analysis, Machine Learning, and Visualization

Guest Editor: William Steingartner

We are preparing this special issue to present recent advances in informatics that bridge theoretical concepts with practical, data-driven methodologies. The contributions included in this issue reflect current research trends in signal processing, machine learning, data analysis, and visualization, addressing challenges that arise when working with complex, noisy, and high-dimensional data.

The special issue brings together works that emphasize both methodological rigor and applicability to real-world problems, ranging from human–computer interaction and biomedical signal analysis to exploratory data analysis and correlation modeling. By combining perspectives from applied machine learning and graph-based data visualization, the issue aims to highlight innovative approaches to extracting meaningful information from data and to stimulate further research at the intersection of theory, experimentation, and application.

After careful consideration, we invited experts whose research aligns with this vision. The resulting contributions demonstrate diverse yet complementary approaches to modeling, analyzing, and interpreting complex data, underscoring the interdisciplinary character of contemporary informatics research.

1. The paper “**Motion Intention Prediction Using Wireless Surface EMG Sensors**” by J. L’ach, N. Ferencík, W. Steingartner, L. Bednarčíková, T. Bálint, and R. Hudák focuses on the prediction of finger motion intention based on surface electromyography (sEMG) signals. The authors investigate signal preprocessing techniques, time–frequency feature extraction, and the application of supervised machine learning models, including Support Vector Machines, Random Forests, and XGBoost. The paper highlights the inherent challenges related to noise and variability in sEMG data and discusses strategies aimed at improving prediction accuracy and robustness for practical applications in prosthetics, rehabilitation, and human–computer interaction.

2. The paper “**Correlation n-star Graphs**” by A. Dudáš and B. Modrovičová addresses the problem of systematically identifying and interpreting correlation structures in multidimensional datasets. The authors introduce correlation n-star graphs as a novel graph-based visualization model that supports the automatic detection of correlation classes and the organization of attributes into hierarchies. The work covers the conceptual design of the model, its Python-based implementation, and an experimental evaluation on benchmark datasets, demonstrating both qualitative and quantitative benefits for correlation analysis and exploratory data mining.

===== About guest editor =====

Prof. **William Steingartner**, PhD, is an Associate Professor at the Faculty of Electrical Engineering and Informatics of the Technical University of Košice, Slovakia. His research is oriented toward formal semantics and formal languages, theoretical computer science, and software engineering. He is a member of the board of the Slovak Society of Applied Cybernetics and Informatics (SSACI) and president of the branch of SSACI. Email: william.steingartner@tuke.sk, ORCID ID: 0000-0002-2852-9403.

The Future of Digital Transformation in Business Processes

Guest Editor: Mirjana Radović-Marković

This special issue aims to showcase the latest advances and future directions in informatics, featuring cutting-edge research across diverse areas of computer science. It provides a platform for exploring both theoretical concepts and practical implementations, fostering collaboration and the sharing of insights.

3. The paper entitled **“Artificial Intelligence Driven Digital Transformation: Mediating the Relationship between Artificial Intelligence Readiness and Business Process Efficiency”** by Maimoona Salam, Mirjana Radović-Marković, Muhammad Shoaib Farooq, Dušan Marković, and Miloš Vučković offers a timely and conceptually robust contribution to the growing literature on artificial intelligence and digital transformation. The study goes beyond examining artificial intelligence readiness (AIR) as a standalone capability and convincingly demonstrates that its impact on business process efficiency (BPE) is realized primarily through artificial intelligence-driven digital transformation (AIDT). By empirically validating AIDT as a mediating mechanism using data from 227 firms and PLS-SEM analysis, the authors show that AI-related investments translate into operational efficiency only when embedded within a coherent, organization-wide transformation strategy. A key strength of the paper lies in its integration of tangible and intangible dimensions of AI readiness, including infrastructure, data capabilities, human capital, and organizational culture, thereby extending the resource-based view in the context of AI-enabled transformation. The findings emphasize that firms with higher AI capabilities are better positioned to align strategic digital transformation initiatives with efficiency-oriented business processes, ultimately gaining a competitive advantage.

4. The paper entitled **“Impact of Education and Digital Literacy as Factors of Employment in the Republic of Serbia”** by Vujičić, Slađana; Momčilović, Oliver; Nedeljković, Miroslav; Milić, Marko; and Branislava Narančić provides an important and timely contribution to understanding workforce development in knowledge-based economies. The study empirically examines the impact of formal education and digital competencies on employability in Serbia, highlighting the critical role of education in equipping individuals with professional knowledge and key skills necessary to navigate a rapidly changing labor market. The findings confirm a significant relationship between both education and digital literacy and employment, with education having a slightly stronger individual effect, while the combination of education and digital literacy creates a robust model for predicting stable employment outcomes. The paper highlights the synergy between education and digital literacy, showing that higher education levels improve digital skills and employability. It emphasizes the need to integrate digital competencies into formal education and training, providing policymakers with insights on investing in education and digital literacy to foster a skilled, adaptable workforce and support sustainable economic development.

5. The paper **“Technological Aspects of Online Banking in Serbia: User Experiences Across Devices, Usage Trends and Strategic Implications for Managers and IT Professionals”**, authored by Lukić Nikolić, Jelena; Dudić, Branislav; Labus, Pero; and Mittelman, Alexandra, examines users' perceptions of online banking applications in the Republic of Serbia, with a focus on efficiency, availability, and ease of contact. Based on an empirical study conducted on a sample of 181 online banking users, the authors analyze differences in user experience across devices (mobile phones versus computers/laptops), as well as the effects of usage duration and frequency of use. The results indicate that there are no statistically significant differences in perceptions of the examined factors, suggesting a generally uniform user experience among different user groups. The findings provide important implications for managers and IT professionals in the banking sector, highlighting the consistency of user experiences and offering guidance for further improvement of the design and functionality of online banking applications.

===== About guest editor =====

Prof. Dr. **Mirjana Radović Marković** is a distinguished professor in China with extensive experience in education, digital literacy, and workforce development. She examines how education and digital competencies enhance employability and support sustainable economic growth. Prof. Dr. Radović Marković has authored numerous peer-reviewed articles, book chapters and 31 monographs, contributing significantly to her field. Her research bridges theory and practice, providing insights for policymakers, educators, and industry leaders. She is a member of five national and five regional and global academies of sciences. She actively promotes international collaboration and knowledge exchange. Prof. Marković has supervised many master's and doctoral students, emphasizing critical thinking and innovation. She organizes conferences and workshops to foster interdisciplinary dialogue. Her achievements have been recognized with multiple awards for academic excellence and societal impact. Prof. Radović Marković continues to advance research and policy in education and digital innovation worldwide. E-mail: mirjana.radovic.markovic@bba.edu.rs, Orchid ID 0000-0003-2002-8732.

Motion Intention Prediction Using Wireless Surface EMG Sensors*

L'ach, Jakub; Ferencík, Norbert; Steingartner, William;
Bednarčíková, Lucia; Bálint, Tomáš; and Hudák, Radovan

Abstract: *This paper examines how finger movement intentions can be predicted using surface electromyography (sEMG) signals together with supervised machine learning models. sEMG sensors offers a non-invasive way to capture muscle activity and are commonly used in areas such as prosthetics, rehabilitation, and human-computer interaction. The study analyzes different signal preprocessing methods and transformations of time-frequency, with algorithms including SVM, Random Forest, and XGBoost. The results point out challenges related to noise and variability in sEMG data and suggest possible ways to improve prediction accuracy and real world performance.*

Index Terms: *finger motion intention, human-computer interface, prosthetics, signal preprocessing, surface electromyography, time-frequency domain*

1. INTRODUCTION

IN machine systems, electromyography (EMG) signals are known as a form of neural interface, since they reflect the activity of motor neurons responsible for muscle activation [6]. A commonly used variant, surface EMG (sEMG), enables the acquisition of these signals in a non-invasive manner, which makes it practical for use in areas such as rehabilitation, telemedicine, research, and human-machine interaction.

Compared to intramuscular techniques, sEMG provides lower specificity; however, its ease of application and reduced risk make it more suitable for many real-world scenarios. One important application is motion intention prediction [14],

where the aim is to determine a user's intended movement from measured muscle signals. This concept is widely applied in domains including prosthetic control, functional electrical stimulation, and human-computer interfaces [4], [13]. When movement intention can be decoded in real time, it becomes possible to design systems that assist or restore motor function, improve user accessibility, and support more intuitive interaction with technology.

However, developing reliable motion intention prediction systems based on sEMG remains challenging due to several important factors. One of the main issues is that sEMG signals are highly dynamic and vary significantly between individuals [3]. In addition, their quality can be influenced by multiple external and physiological conditions, such as muscle fatigue, skin impedance, temperature changes, or slight variations in electrode placement [10], [12], [9].

Another challenge lies in accurately associating extracted sEMG features with intended movements (i.e., translating signal patterns into meaningful motor actions). This requires advanced algorithms capable of processing noisy and non-stationary signals, while still being efficient enough for real-time operation.

To address these challenges, this paper explores the use of supervised machine learning (ML) to map sEMG data to finger motion data obtained through visual tracking to predict motion intention. The aim of this work was to evaluate the potential and limitations of using visual hand tracking as a reference for training supervised machine learning models based on data collected from wireless low-cost sEMG sensors. To achieve this point, several steps were carried out, including signal preprocessing, exploratory data analysis, feature extraction, and model evaluation.

The research presented in this paper builds upon and further develops the results reported in the Master's thesis Motion intention prediction using wireless surface EMG sensors [15], extending the original approach with additional analysis, methodological refinements, and updated experimental evaluation.

The paper is organized as follows. Section 2 covers an overview of methods acquired during this research work. Next, Section 3 is a detailed

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summary of reached results with their analysis. Section 4 is a broader view on the reached results and the Section 5 finally concludes our paper.

2. METHODS

This section outlines the approach adopted to investigate finger motion intention prediction using surface electromyography (sEMG). It describes the procedures for data collection, the steps of signal preprocessing and feature extraction, the selection and training of machine learning algorithms, and the strategies applied for model evaluation. Taken together, these stages establish a systematic workflow ensuring both reproducibility and methodological rigor.

Figure 1 provides an overview of the complete data processing pipeline used in this study. It visually summarizes the methodological steps described in the subsequent subsections: starting from the acquisition of raw sEMG and motion-tracking signals, continuing through preprocessing and feature engineering, and culminating in the training and evaluation of machine learning models. This integrated workflow ensures that each component of the methodology is clearly situated within the overall system architecture.

2.1. Data Collection

sEMG data were collected using the uMyo sensor (Figure 2.) developed by Ultimate Robotics, an open-source, open-hardware, wireless sEMG device designed for real-time monitoring of muscle activity [8]. The uMyo sensor supports both dry and standard wet gel electrodes, with the former being used in this study. The sensors have built-in high-pass, low-pass, and notch filters. The notch filter removes the 50/60 Hz powerline interference by filtering out that specific harmonic frequency, thereby reducing noise and improving signal quality [1]. The device records EMG signals and performs frequency-domain analysis using an 8-bin Fast Fourier Transform (FFT). The processed data are then transmitted wirelessly to the recording system.

The sensors were positioned on the upper forearm in areas corresponding to the flexor digitorum profundus, flexor digitorum superficialis, and extensor digitorum communis muscles. These muscle groups are primarily responsible for finger movement, specifically flexion and extension. The flexor digitorum profundus is involved in flexing the distal interphalangeal joints, while the flexor digitorum superficialis controls flexion of the proximal interphalangeal joints. In contrast, the extensor digitorum communis is responsible for extending the metacarpophalangeal (MCP) joints.

Simultaneously, motion data were collected using the MediaPipe Hand Landmarker task [7], which tracks 21 three-dimensional landmarks on the hand from live video input. For this study, only

the y (image height) and z (depth) coordinates were used to determine finger flexion and extension while excluding both abduction and adduction movements. For each finger, three landmarks, the fingertip, MCP joint, and the wrist landmarks, were used to calculate the angle of flexion/extension. The angle α in Figure 3. was calculated using the law of cosines, based on the Euclidean distances between the three landmarks:

The sEMG dataset consisted of 18,492 rows, with each row containing data from four sensors, including sensor ID, timestamp, and raw FFT-transformed bin values. Signals were transmitted wirelessly from the sensors to a USB receiver base equipped with an nRF52832 microcontroller, a CP2102 USB interface chip, and a custom RF communication protocol. To ensure data integrity and handle sensor dropout, the acquisition program continuously verified the presence of active sensors through their sensor IDs. The motion tracking dataset consisted of 6,481 rows, with each row containing the four calculated finger joint angles derived from raw estimated coordinate values, along with the corresponding timestamp.

During data acquisition, sEMG electrodes were securely placed on the subject's forearm, and a 30 frames per second (FPS) camera (Redmi Note 7) was positioned to capture hand movements. Both EMG signals and motion tracking data were recorded simultaneously over a continuous five-minute session, during which the subject performed repetitive flexion and extension movements of the fingers. The EMG data are sampled at 1150 Hz, offering high temporal resolution to capture muscle activity. However, increasing the number of active sensors leads to longer transmission intervals for each sensor. As a result, the effective sampling rate per sensor decreases with scaling, representing a trade-off between spatial resolution and temporal resolution.

To enable real-time synchronization, the video feed was transmitted to a computer using the DroidCamApp. Data processing was carried out on a Windows 10 machine equipped with an Intel(R) Core(TM) i7-4770K CPU (3.50 GHz) and an NVIDIA GeForce GTX 660 GPU.

2.2. Data Processing

The collected EMG and motion data were pre-processed to remove artifacts, missing values, and duplicates. A 550-ms sliding time window of EMG data was mapped to the finger angle label recorded approximately 150 ms later, accounting for image capture, USB transmission latencies, Mediapipe processing, and electromechanical delay (EMD). The time intervals were determined through visual exploratory analysis of the raw signals. The sliding window advanced at the image capture rate (roughly 50 ms). To map each window

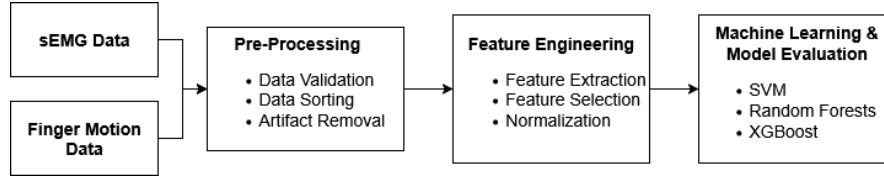


Figure 1. Data processing workflow. Raw data from sEMG sensors and motion tracking are pre-processed, transformed through feature engineering, and subsequently used as input for machine learning algorithms to train predictive models.

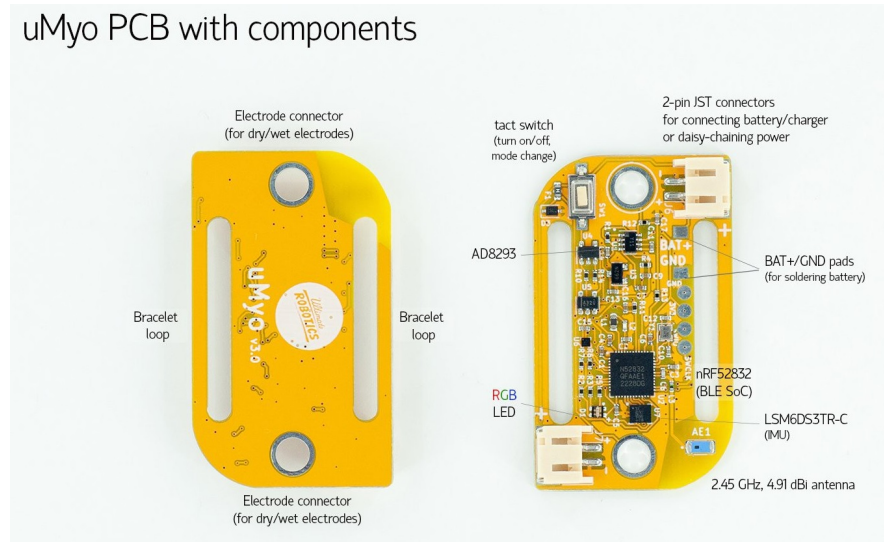


Figure 2. uMyo EMG sensor with its main components, including electrode connectors, attachment loops, power interfaces, and control switch. The AD8293 amplifier is used for EMG signal processing, while the nRF52832 BLE SoC enables wireless communication [8].

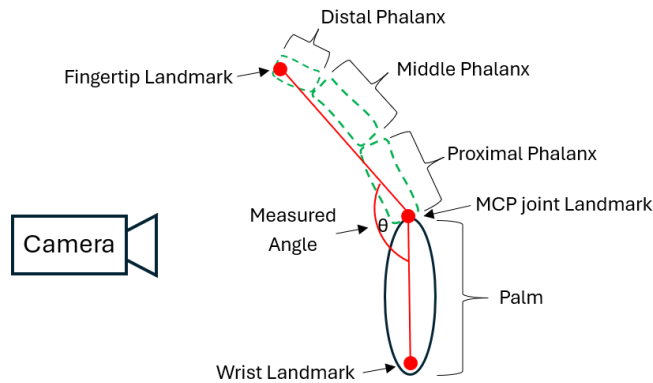


Figure 3. Finger joint tracking and angle estimation using a camera-based approach. Key landmarks, including the wrist, metacarpophalangeal (MCP) joint, and fingertip, are used to track finger motion. The angle (θ), expressed in degrees, represents flexion and extension of the finger.

to a single label, statistical features were computed to summarize temporal patterns of muscle activity and to reduce noise.

2.3. Machine Learning

Finger motion estimation was performed using structured data to train and compare three regression models: Random Forest (RF), Support Vector Machine (SVM), and XGBoost, all implemented using the Scikit-Learn and the XGBoost libraries.

The SVM regressor was applied to capture nonlinear relationships between input features and output variables, where the tuned hyperparameters were the regularization parameter (C) and the epsilon-insensitive loss parameter (ϵ). Input data were standardized to ensure that the learning rate is not dominated by larger value ranges. The RF regressor was used as an ensemble approach that combines multiple decision trees to reduce overfitting, with tuning of the number of estimators, minimum samples to split a node, minimum samples per leaf, and maximum features [5]. Finally, XGBoost regressor was used as a boosting algorithm that sequentially refines each tree, where the learning rate and number of trees were optimized [2].

An 80/20 split was applied to divide the dataset into training and testing subsets.

2.4. Model Evaluation

After training, the models were used to generate predictions on the test data, that were then evaluated using the R^2 metrics. To account for model complexity, the adjusted R^2 was also computed by considering the number of input variables. Model performance was more assessed using additional error measures, including mean absolute error (MAE), root mean squared error (RMSE), and median absolute deviation (MAD). These metrics together provide a more complete overview of the predictive performance of each model.

3. RESULTS

This section reports the outcomes of the study, beginning with exploratory data analysis to characterize the sEMG signals, followed by the presentation of regression results evaluating model performance.

3.1. Exploratory Data Analysis

To better understand the relationship between muscle activity and finger motion, exploratory data analysis was conducted (Figure 4.). The visualization focused on both finger flexion/extension and corresponding EMG signals, allowing key patterns to be identified. This step was also useful for examining electromechanical delay (EMD) and the time lag between muscle activation and the resulting movement. In addition, the analysis guided the choice of an appropriate sliding window for EMG

signal processing. This ensured that statistical features were computed over a time interval that properly aligns with each label value.

Figure 4 shows time offset between muscle activity and finger motion. The EMG signal tends to rise shortly before finger flexion begins and decreases back to baseline after the extension phase. This delay can be explained by a combination of electromechanical delay and additional latencies introduced by the measurement system. Part of this delay originates from data transmission, which includes image capture, processing, and transfer via USB, and was estimated to be around 40 ms. Further delay is introduced by the MediaPipe framework, with an average processing time of approximately 50 ms. Together, these factors contribute to a total system latency of about 90 ms. When this is combined with the natural electromechanical delay, it explains the observed misalignment between EMG signals and tracked finger position. Compared to EMG, detecting a similar relationship using other sensing modalities could be more difficult, especially on visual inspection.

Feature engineering was performed on the sEMG signals using a sliding time-window approach (Figure 5.). For each window, a set of statistical features was extracted to characterize the signal. Specifically, the computed features included the mean, standard deviation, minimum, maximum, and median values, as well as slope sign changes and waveform length. This approach reduced noise and random fluctuations while preserving overall patterns of muscular activity. To account for EMD and data transmission latencies, time-shifting was applied to better align the sEMG features with the corresponding finger flexion and extension angle values.

3.2. Regression Results

An SVM regression model with a radial basis function (RBF) kernel was employed, with its hyperparameters tuned via grid search using 5-fold cross-validation. The hyperparameters tested were $C \in \{1, 10, 100, 1000, 10000\}$ and $\epsilon \in \{0.1, 0.2, 0.3, 0.4\}$. The best results were achieved with $C = 1000$ and $\epsilon = 0.1$.

Figure 6 shows a line plot of predicted and actual values for all fingers measurements, using the SVM regression model. The comparison highlights how closely the model outputs follow the true values across the test dataset, providing into predictive performance. The model achieved an MAE of 7.93 and an RMSE of 13.05.

For the Random Forest (RF) regressor, hyperparameter tuning was carried out using grid search combined with 5-fold cross-validation. The number of estimators was evaluated across values of 100, 200, and 300. In addition, different settings were tested for the minimum number of samples required to split a node (2, 5, and 10) and for

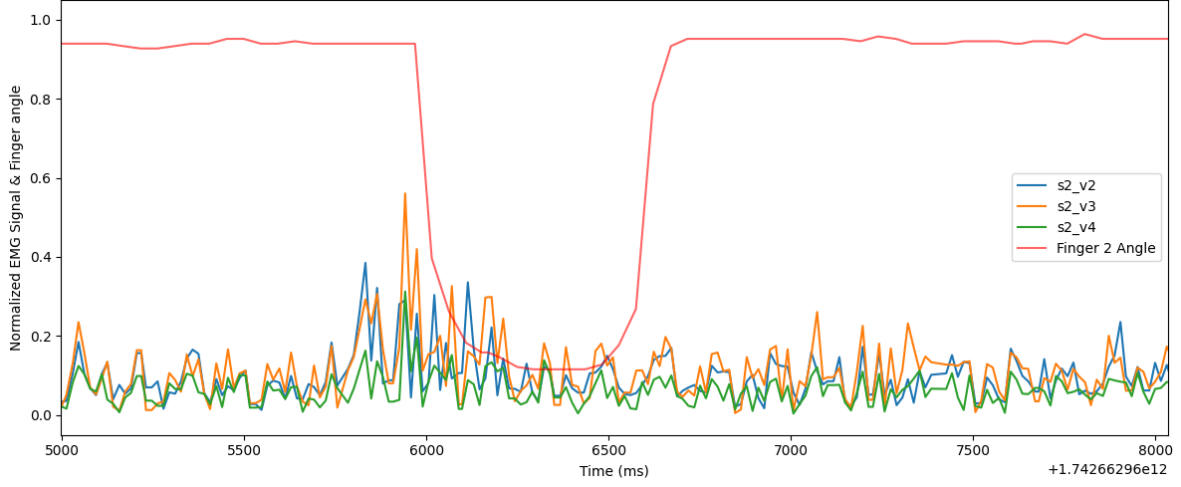


Figure 4. Time-series plot of normalized raw EMG feature values (blue, orange, green) and with finger 2 label (red). The plot highlights increased EMG activity during finger flexion. The horizontal axis shows time in milliseconds (Unix Epoch), while the vertical axis displays normalized EMG features together with finger position values. Larger angle values correspond to finger extension, whereas smaller values indicate flexion.

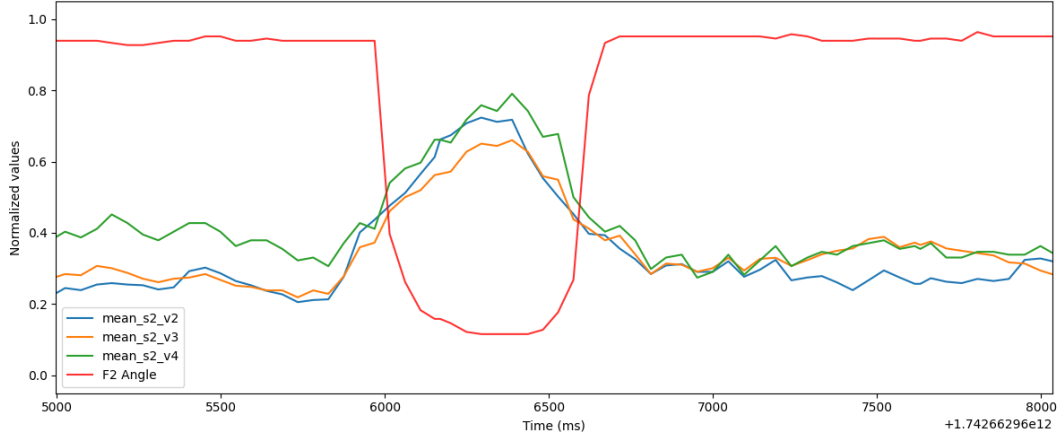


Figure 5. Time-series plot of processed sEMG features (mean values only) and finger angle labels after feature engineering and time-shifting.

the minimum number of samples in a leaf node (1, 2, and 4). To maintain a balance between predictive performance and computational cost, the *max_features* parameter was fixed at 0.3, limiting the number of features considered at each split. The optimal configuration corresponded to 300 estimators, a minimum of 2 samples required for node splitting, and 1 sample per leaf node.

For the XGBoost regression model, early stopping was applied to identify the appropriate number of trees and to avoid both overfitting and underfitting. The final configuration used 279 estimators with a learning rate of 0.2.

Table 1 shows the regression summaries for the three models that were tested, XGBoost, SVM, and RF. The SVM regressor produced the lowest RMSE and MAE scores of 13.05 and 7.93 degrees, respectively. The RF model achieved the lowest MAD score of 2.57 degrees.

Table 1
REGRESSION SUMMARIES

Machine Learning algorithm	Performance metric		
	RMSE	MAE	MAD
Support Vector Machine	13.05	7.93	4.81
Random Forest	16.62	8.44	2.57
Extreme Gradient Boosting	16.65	8.25	3.04

4. DISCUSSION

Despite being more susceptible to noise and crosstalk than intramuscular electrodes, sEMG sensors can still enable accurate finger kinematics prediction when paired with robust ML techniques. EDA was instrumental in identifying temporal shifts between EMG activation and finger motion, due to electromechanical delay and system transfer latencies. This informed the windowing strategy and label alignment during feature

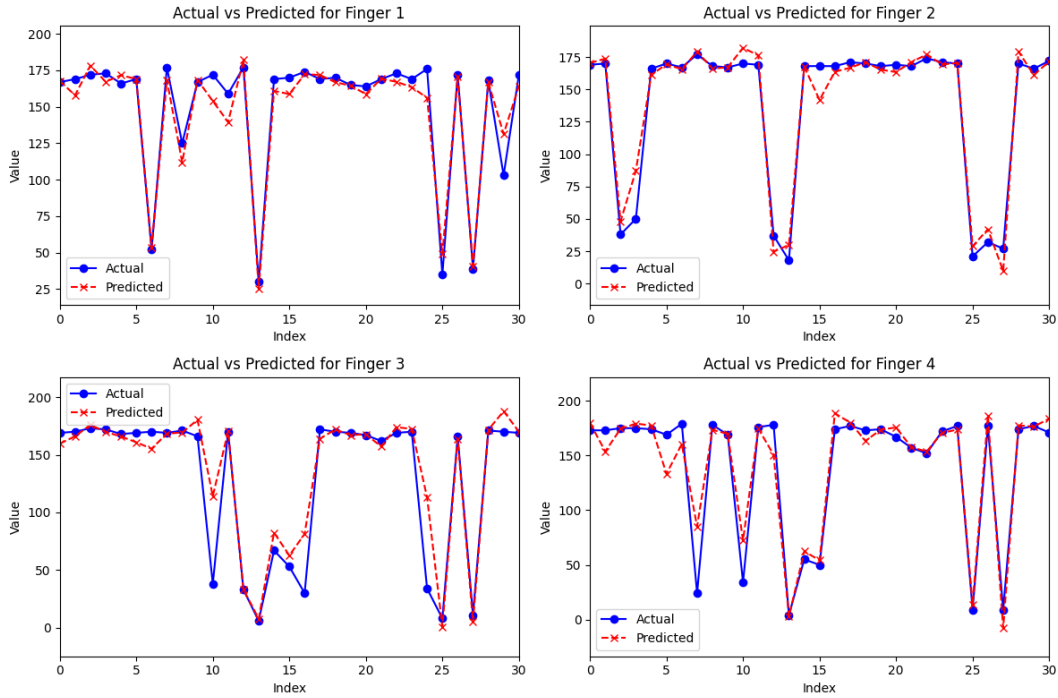


Figure 6. SVM regression model line plot of the first 30 data points showing actual versus predicted values in degrees for all four fingers. Where finger 1 is the index finger, finger 2 is the middle finger, finger 3 is the ring finger, and finger 4 is the little finger.

engineering.

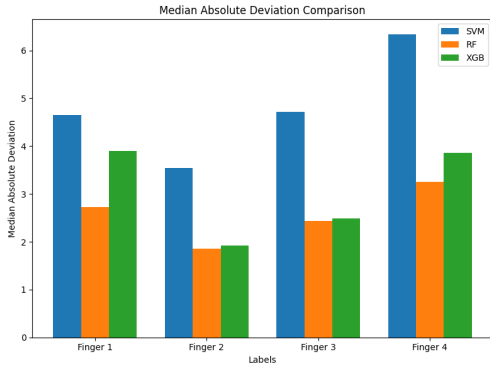


Figure 7. Median Absolute Deviation (MAD) values for the SVM, RF, and XGBoost regression models are presented. For the SVM model (blue), the MAD values for Fingers 1–4 were 4.65, 3.54, 4.71, and 6.33, respectively. The RF model (orange) achieved lower values of 2.72, 1.85, 2.43, and 3.26, while the XGBoost model (green) produced MAD values of 3.89, 1.92, 2.49, and 3.86 for the same fingers.

Three models, SVM, RF, and XGBoost regressors were evaluated. SVM achieved the lowest MAE (7.93), but higher RMSE values across models indicated sensitivity to outliers. To complement this, the MAD was used (Figure 7.), revealing that the RF model had the most consistent distribution of error residuals (2.57). This could be attributed to RF's implicit feature selection. In contrast, SVM and XGBoost used the full feature set, making them more prone to overfitting.

The fixed forearm posture during data collection limited model generalizability. Future work should include varied postures and free-hand motion. Improved filtering, including adaptive, comb, or wavelet-based techniques, could improve signal quality.

Fast fourier transform was used for time-frequency analysis. However, methods like Continuous Wavelet Transform (CWT) may better capture the non-stationary nature of EMG signals. Higher frame-rate cameras and GPU-accelerated processing (e.g., CUDA for MediaPipe) could further reduce label latency and improve alignment.

Ultimately, deploying the pipeline on mobile devices could reduce hardware-induced latencies, although processing limitations must be considered. Future directions include testing longer recording durations, deep learning models, varying time windows, and cross-limb training to assess generalizability in prosthetic control scenarios.

A key limitation of the proposed framework is the requirement for subject-specific model training. In this study, models were trained using data from the same individual, which limits direct generalization across users. Furthermore, the training procedure required data collection from the intact hand. For prosthetic applications, this raises an important question of whether models trained on one hand can be effectively transferred to predict movements of the contralateral, missing hand.

The proposed framework has potential appli-

cations in real-time human–machine interfaces, such as robotics and virtual reality control. In rehabilitation, the framework could be integrated with EMG-controlled functional electrical stimulation to support movement restoration. In this approach, recorded muscle activity is used to trigger stimulation of weakened muscles, which can improve mobility in individuals with impaired gait patterns [11].

5. CONCLUSION

This study demonstrated that uMyo sEMG sensors, combined with visual hand tracking using the MediaPipe library, can be effectively used for motion intention prediction with supervised machine learning. Compared with approaches that require collecting finger kinematic data from physical devices, the use of visual tracking offers a more practical and accessible solution. Despite the sensor limitations, effective preprocessing and model selection enabled accurate muscle-to-motion mapping. The SVM regression model produced the lowest MAE, whereas the RF model exhibited a more stable error distribution.

A major limitation was the fixed hand posture during data collection, which may affect real-world applicability. Future work should include dynamic hand positions. Enhancing finger tracking with higher frame rates and GPU acceleration could further refine EMG-to-motion alignment. Long-term goals include testing deep learning models, varying feature length windows, and exploring inter-limb generalization for prosthetic control applications.

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The work included the analysis of signal preprocessing techniques, feature extraction in both time and frequency domains, and the application of machine learning models such as Support Vector Machines, Random Forest, and XGBoost. The results identified key challenges related to noise and inter-subject variability in sEMG signals and proposed approaches to improve prediction accuracy and the practical usability of sEMG-based control systems.

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Correlation n -star Graphs

Dudáš, Adam and Modrovičová, Biana

Abstract: *When working with correlation analysis and the visualization of its results and processes, the systematic identification of correlation classes is often overlooked. Such classes can be described as sets of attributes of the studied dataset that share similar correlation patterns – like the strength and direction of the relationship measured between a pair of attributes – and can be used as a method of identification of significant and insignificant correlations while introducing an attribute hierarchy for automated predictive analysis. This work proposes correlation n -star graphs, a graph-based visualization model designed to support automatic identification of these classes in multidimensional datasets. The work focuses on the design of the visualization model, a Python implementation of the proposed concept, and an experimental evaluation on three benchmark datasets assessing both qualitative and quantitative aspects of the visualization and correlation classification.*

Index Terms: *correlation structures, correlation classes, correlation analysis, visualization, predictive analysis, data analysis*

1. INTRODUCTION

Correlation analysis represents one of the foundational components of data analysis and machine learning [10] [15] [6]. By quantifying the strength and direction of relationships between pairs of attributes, correlation measures

inform tasks such as feature selection, dimensionality reduction, anomaly detection, and the construction of predictive models [13].

Visualization also plays a crucial role in making the correlation analysis more utilizable by translating numerical relationships into visual structures that analysts can examine and gain knowledge from [4] [16] [17]. Techniques such as correlation heatmaps or graphical representations of correlation analysis make patterns of association, heterogeneity, and structure immediately visible and aid in analytical processes and scenarios [2]. Many of these models explicitly target pseudotransitivity – the tendency for pairwise correlations to imply higher-order, chain-like associations across attributes, which can be used as a regression error minimization tool in predictive analysis.

However, there is a task related to correlation analysis, which is often overlooked and neglected – the systematic identification of correlation classes as groups of attributes that share similar correlation patterns across the dataset. Correlation classes are usable as a way of filtering the significant and insignificant correlation values in data and to introduce a type of hierarchy to the relationships present in the studied dataset. Their omission also constrains the automatization of the correlation analysis process, where only significant correlation classes can be utilized for further predictive analysis.

1.1 Objective of the Work

The main focus of the presented work is on the design, implementation, and evaluation of the correlation n -star graphs – a graph-based visualization model usable in the context of automatic identification of correlation classes in multidimensional datasets. Therefore, the main contributions of the work can be described as follows:

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- The design of a novel visualization model for the identification of correlation classes in data based on graph theory and clustering methods.
- Implementation of the proposed model in the *Python* language as an open-source solution.
- Experimental evaluation of the concept on case studies utilizing three benchmarking datasets, examining qualitative and quantitative aspects of the visualization and correlation classification.

This objective, the basic theoretical background of the area, and the original proposed model are described in the four main sections of the presented work. In Section 2, the basics of correlation analysis – correlation coefficients, matrices and classes – are presented. Section 3 then focuses on the conventional and graphical models of correlation analysis visualization and presents the design of correlation n -star graphs, which are the main focal points of the work. The model proposed in Section 3 is then experimentally evaluated in Section 4 using three benchmarking datasets. Finally, Section 5 concludes the study, summarizes the main findings, and proposes some of the possible future work directions.

2. CORRELATION ANALYSIS, COEFFICIENTS, MATRICES, AND CLASSES

Correlation analysis refers to a set of statistical techniques and approaches used for the identification of prediction potential stored in the values of attributes in a studied dataset [11]. Since the presented concept of correlation n -star graphs is used for the identification of correlation classes in data, this section of the work focuses on the introduction to correlation coefficients for numeric measurement of predictive potential in data, correlation matrices as a model of summarization of correlation coefficients in a dataset, and correlation classes for division of values of correlation coefficients.

2.1 Correlation Coefficients

The correlation coefficient measures the strength and direction of functional relationships between the values of two attributes from a common dataset [11]. This coefficient acquires a value from $[-1, 1]$ interval, while [21]:

- The absolute value of the correlation coefficient signifies the strength of the relationship – the closer to the extremes of the interval, the stronger the relationship,
- The sign of the value of the correlation coefficient denotes the direction of the relationship – both values of attributes increase or decrease in unison for positive values of the coefficient (so-called correlation), or the values of one attribute increase while the values of the other decrease for the negative values of the correlation coefficient (so-called anticorrelation).

Commonly, there are three basic correlation coefficients used in data analysis – the Pearson correlation coefficient, used for the measurement of the strength and direction of linear relationships between pairs of attributes, and Spearman and Kendall rank correlation coefficients, used for the measurement of these properties when non-linear monotone relationships are present in data.

Pearson correlation coefficient r measured between the values of attributes A and B is computed as [11]:

$$r(A, B) = \frac{\sum_{i=1}^m (A_i - \mu(A))(B_i - \mu(B))}{\sqrt{\sum_{i=1}^m (A_i - \mu(A))^2} \sqrt{\sum_{i=1}^m (B_i - \mu(B))^2}} \quad (1)$$

where μ denotes the mean value of attribute and m is the number of measurements of attributes A and B in the dataset.

The non-linear monotone coefficients are based on the concept of ranking of values of the studied attributes. This ranking can be described as a simple determination of descending order for values of attributes; hence, the highest value gets the ranking of one, and the lowest value gets the ranking of m . Spearman

rank correlation coefficient ρ for the values of attributes A and B can be computed as [11]:

$$\rho(A, B) = 1 - \frac{6 \sum d_i^2}{m(m^2 - 1)} \quad (2)$$

where d_i denotes the difference between rankings of i -th measurements of the studied attributes.

Lastly, the computation of the Kendall correlation coefficient τ is defined as follows [11]:

$$\tau(A, B) = \frac{n_c - n_d}{\frac{m(m-1)}{2}} \quad (3)$$

where n_c denotes the number of concordant pairs of attribute rankings, and n_d denotes the number of discordant pairs of such rankings.

Regardless of the type of correlation coefficient, one can only measure the strength and direction of the relationship between a pair of attributes. Yet, datasets commonly contain many more than two attributes – often tens or even hundreds – and therefore correlation coefficient analysis of the whole dataset needs to be constructed using some type of summarization of pairwise correlation coefficient measurement. Such a summarization can be done via a correlation matrix, where the rows and columns of the matrix are indexed using attributes of the dataset and individual elements of the matrix contain the values of the correlation coefficient measured between the indexing attributes [22]. Matrix (4) presents a generalized example of this summarization for a dataset of a attributes.

2.2 Correlation Classes

All human-computer interaction requires a certain amount of interpretation of precise numerical outputs resulting from computations into a somewhat vague or fuzzy manner natural for humans. In the context of correlation analysis, the conventional practice is to split the correlation coefficient's $[-1, 1]$ interval into sub-intervals, often called correlation classes [20]. A very simple example of such partitions is the following binary division [13]:

$$\text{corr}_{class}(A, B) = \begin{cases} \text{significant}, & \text{if } |\text{corr}(A, B)| \in [0.8, 1], \\ \text{insignificant}, & \text{if } |\text{corr}(A, B)| \in [0, 0.8) \end{cases} \quad (5)$$

Based on this concept, an analyst assigns one of two labels to a pair of attributes A and B – either they are considered to have a significant correlation when the absolute value of the correlation coefficient exceeds 0.8, or they are deemed to have an insignificant correlation in all other cases.

This binary approach, however, is rather coarse and omits finer distinctions; therefore, a more granular classification is proposed in [20]. The authors divide the correlation coefficient range into five categories – neutral, weak, moderate, strong, and very strong – as follows:

$$\text{corr}_{class}(A, B) = \begin{cases} \text{neutral}, & \text{if } |\text{corr}(A, B)| \in [0, 0.2), \\ \text{weak}, & \text{if } |\text{corr}(A, B)| \in [0.2, 0.4), \\ \text{moderate}, & \text{if } |\text{corr}(A, B)| \in [0.4, 0.6), \\ \text{strong}, & \text{if } |\text{corr}(A, B)| \in [0.6, 0.8), \\ \text{very strong}, & \text{if } |\text{corr}(A, B)| \in [0.8, 1]. \end{cases} \quad (6)$$

Beyond these fixed, rule-based categorizations, several adaptive methods that use standard central tendency measures have been suggested. For example, a two-level classification based on dataset-wide statistics is introduced in [2]:

$$\text{corr}_{class}(A, B) = \begin{cases} \text{significant}, & \text{if } |\text{corr}(A, B)| \geq \frac{\mu(|\text{corr}(\mathbb{C})|) + \max(|\text{corr}(\mathbb{C})|)}{2}, \\ \text{insignificant}, & \text{otherwise.} \end{cases} \quad (7)$$

Here $\mu(|\text{corr}(\mathbb{C})|)$ denotes the mean of the absolute correlation coefficient values summarized in the correlation matrix $\mathbb{C}$, and $\max(|\text{corr}(\mathbb{C})|)$ is the largest off-diagonal absolute correlation in that matrix.

Similarly, one can construct dynamic groupings using other central-tendency-based cutoffs – for instance, a three-tier classification based

$$\begin{array}{cccccc}
& A_1 & A_2 & A_3 & \dots & A_a \\
A_1 & \text{corr}(A_1, A_1) & \text{corr}(A_1, A_2) & \text{corr}(A_1, A_3) & \dots & \text{corr}(A_1, A_a) \\
A_2 & \text{corr}(A_2, A_1) & \text{corr}(A_2, A_2) & \text{corr}(A_2, A_3) & \dots & \text{corr}(A_2, A_a) \\
A_3 & \text{corr}(A_3, A_1) & \text{corr}(A_3, A_2) & \text{corr}(A_3, A_3) & \dots & \text{corr}(A_3, A_a) \\
\vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
A_a & \text{corr}(A_a, A_1) & \text{corr}(A_a, A_2) & \text{corr}(A_a, A_3) & \dots & \text{corr}(A_a, A_a)
\end{array} \tag{4}$$

on tertiles of correlation values in the studied dataset can be defined as:

$$\text{corr}_{class}(A, B) = \begin{cases} \text{low}, & \text{if } |\text{corr}(A, B)| \in [0, T1), \\ \text{middle}, & \text{if } |\text{corr}(A, B)| \in [T1, T2), \\ \text{high}, & \text{if } |\text{corr}(A, B)| \in [T2, 1]. \end{cases} \tag{8}$$

where $[0, T1)$ denotes the value of the correlation coefficient in the first tertile (lowest third) of all correlation values in the dataset, $[T1, T2)$ denotes the values of the second tertile of the dataset, and $[T2, 1]$ denotes the values of the third tertile of the data.

2.3 Related Works

As stated above, the research presented in this work aims towards the use of graph theory-based visualization in combination with correlation analysis and the use of such a model in the identification of correlation classes in the context of predictive analysis. Therefore, this section of the presented text briefly describes some of the modern results from the related areas.

The main objective of the work presented in [7] is focused on multi-label learning tasks, which typically involve complex correlation between labels, often spanning across multiple levels. The mainstream multi-label methods often only capture statistical label correlations and miss hierarchical, multi-level relationships, which can reduce predictive performance and interpretability of decision-making models. Authors of the work present a model that uses three-way concept-cognitive operators to structurally represent hierarchical label concepts, map their extents into feature concepts, and

fuse those feature concepts to form label cognition. Extensive comparisons show the method improves prediction performance and enhances interpretability, demonstrating superiority and versatility over baseline approaches.

In the work [18], authors focus on so-called key performance indicator-related monitoring methods like partial least squares, correlation analysis and orthonormal subspace analysis. The effectiveness of all of these methods declines with high dimensionality of studied data, causing irrelevant information to mix into key performance indicator components and key performance indicator signal to leak into residuals. Hence, the authors propose Independent Variable Analysis, which identifies the true data structure and extracts independent components to avoid this problem. Simulation tests (including a vehicle engine model) show that the proposed method accurately recovers key performance indicator-related components, attains high detection of key performance indicator-related faults, and avoids alarming key performance indicator-unrelated faults.

This work [23] explores correlations among multiple categories of design arts by combining principal component analysis with an intelligent art-image recognition algorithm to build an art-design model. The authors solve a one-dimensional transient image-information transfer equation under diffuse-reflection boundary conditions, analyze albedo effects on hemispherical reflectance and transmittance, and treat transient transfer between double-layer plates, providing a calculation example. The analyses reveal strong correlations across design-art categories and underscore the multifaceted roles that artistic design can play.

Missing label distributions in semi-supervised label-distribution learning make

mining reliable label correlations difficult and can bias correlation estimates. To address this, the authors of [24] propose two complementary strategies – global matrix completion via Independent Component Analysis and a locally improved $k - NN$ that uses known label-distribution constraints to guide unknown samples – and integrate them into a semi-supervised algorithm. Experiments show the method outperforms existing approaches in 67.27% of cases and yields statistically significant improvements in two-sample t -tests.

3. VISUALIZATION IN THE CONTEXT OF CORRELATION ANALYSIS

After the construction of a correlation matrix for the purposes of summarization of correlation coefficient values in the studied dataset, the visualization is conventionally done using correlation heatmaps [1]. This visualization translates the specific values of the correlation coefficient to colors from a previously defined color scale, while the extremes of the scale correspond to the extremes of the correlation coefficient interval using a smooth gradient for all other values. Figure 1 visualizes an example of a correlation coefficient heatmap of a dataset consisting of n attributes using a pink-to-purple color scale for the coding.

Other than the visualization of correlation analysis through correlation heatmap, this work focuses on alternative – less common – visualization approaches based on the concepts from the theory of graphs, which use the correlation matrix as a weighted adjacency matrix for graphical structures called correlation structures [2] [3].

3.1 Graphical Structures and Correlation Analysis

Correlation structures are based on a so-called correlation graph, which is defined as an undirected graph built on a dataset D consisting of $\#A$ attributes, while vertices of the graph denote individual attributes of the dataset and edges between these vertices are weighted using the correlation coefficient value [2]. For the purposes of the data analysis, only edges where

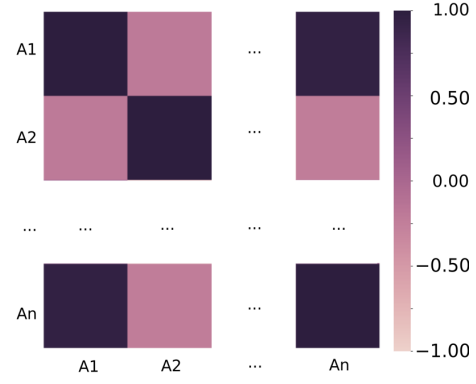


Figure 1: An example of a correlation heatmap of a dataset with $A_1, A_2, \dots, A_n$ attributes

the weight is higher than the computed border of significance are visualized, which leads to a pruning of the correlation graph and, therefore, presentation of only interesting relationships in the studied data. Figure 2 presents an example of a correlation graph with the values of the correlation coefficient neglected for better readability.

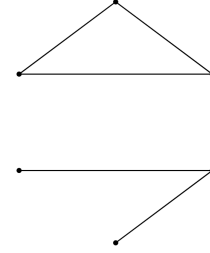


Figure 2: Example of a correlation graph

Several sub-graphs of the correlation graph were identified as structures of interest. First of these sub-graphs are correlation chains defined as a finite sequence of edges of the correlation graph from attribute A_i to A_j without repetition of any of the vertices or edges in the sequence [2]. An example of such a correlation chain is presented in Fig. 3, where the chain is using full lines, the edges, which are not taken into account, are presented using dotted lines, and the starting and ending attributes are denoted by the empty vertices.

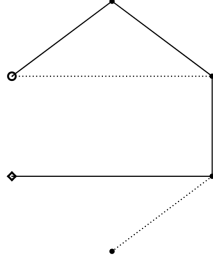


Figure 3: Example of correlation chain

The second of the sub-graphs of the correlation graph are correlation n -ptychs – complete subgraphs of the correlation graph consisting of n vertices – attributes [2]. Example presented in Fig. 4 showcases the correlation n -ptych for $n = 4$ (tetraptych) and $n = 5$ (pentaptych). The original study of n -ptychs considers $n \in \{2, 3, 4, 5, 6\}$ for the construction of readable (yet not always planar) structures.

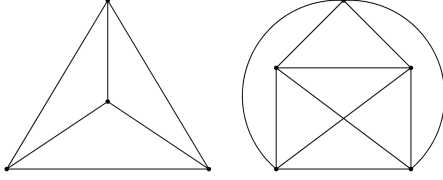


Figure 4: Example of correlation n -ptychs for $n \in \{4, 5\}$

The last of the graphical structures used in the context of correlation analysis can be labelled as correlation cycles. These cycles of size c are typical, as defined in graph theory, identified in the correlation graph, which consist of n vertices (attributes) of the dataset [3]. An example of the correlation cycle of $c = 5$ is presented in Fig. 5.

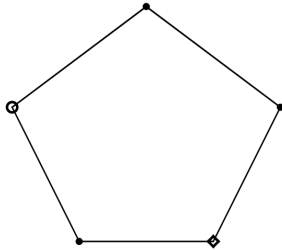


Figure 5: Example of correlation cycle

These graphical structures can be used in a number of analytical scenarios besides the visualization of correlation analysis itself. The most typical task conducted with the use of correlation structures is the study of pseudotransitivity of prediction potential in data, identification of prediction sequences based on correlation analysis, identification of subsets of attributes which influence significant portions of dataset values, or minimization of regression model errors. The concept of representing the attributes of a dataset as vertices of a graph interconnected via weighted edges is key to the visualization model, usable in visualization of correlation classes, presented in this work.

3.2 Correlation n -star Graphs

Based on the previously introduced graphical models for correlation analysis purposes, this work focuses on the design and implementation of the correlation n -star graphs for the identification of correlation classes in a studied dataset. In graph theory, star graphs are composed of one central vertex interconnected via edges to all other vertices of the graph, while these vertices are not interconnected [5] (see Fig. 6).

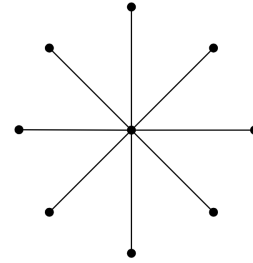


Figure 6: Example of a star graph

For the purposes of correlation analysis, the n -star graphs utilize the concepts from the previous graphical models, where vertices represent attributes of the dataset and edges are weighted by the correlation coefficient value measured between a pair of attributes, while the analysts themselves define the attribute of interest which is studied. This attribute of interest then serves as the central vertex for a set of star graphs, while each star graph represents a single correlation class of the dataset.

Hence, the n -star graph can be defined as a graph consisting of a set of n interconnected star graphs as presented in Fig. 7, while attributes of the dataset with similar values of correlation coefficient in relation to the attribute of interest are grouped to the same star, and therefore class.

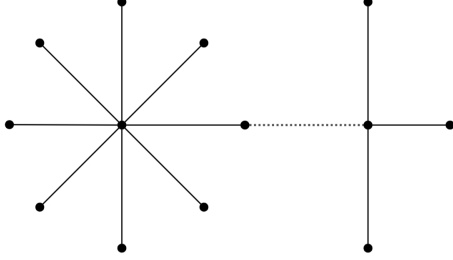


Figure 7: Example of an n -star graph for $n = 2$

This description of n -star graphs directly points to several significant notes related to the implementation of the concept:

- The number of stars or recognised correlation classes (n) in the studied data and the attribute of interest are defined by the user, in this case data analyst.
- The identification of correlation classes is conducted via clustering of correlation coefficient values into n clusters.
- As mentioned above, the n -star graph is constructed from a set of n interconnected star graphs. These components of the graph are interconnected via edges containing the strongest value of the correlation coefficient between a pair of attributes from neighbouring correlation classes (hence not creating any cycles).

In this way, a single graph of n interconnected stars is constructed, in which one can identify two types of edges. The first type can be labelled as *intra – star* edges constructed between the attribute of interest and other attributes in a selected class, which denote the membership of an attribute to one specific correlation class. The second type of edges are the *inter – star* edges connecting pairs of correlation class stars to produce one holistic graph

and – more critically – to allow for the study of relationships between individual correlation classes of the dataset via pseudo-transitivity of prediction potential [2]. The whole process described above is presented in the schema in Fig. 8.

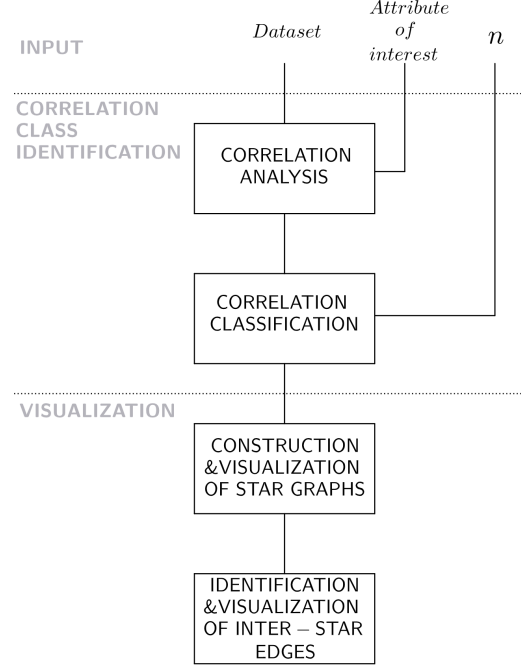


Figure 8: Schema of the proposed approach

In order to construct this visualization, the presented work utilizes $K - Means$ algorithm [9] for the clustering of correlation coefficient values measured between the attribute of interest and all other attributes in the dataset into the correlation classes. Since the correlation classes are commonly labelled with a title of class as presented in section 2.2, for these purposes, the mean absolute value of the correlation coefficient (μ) in the class is used. This μ metric is also used for the sorting of the correlation classes from the weakest correlation class (lowest μ) to the strongest (highest μ).

4. CASE STUDIES OF n -STAR GRAPHS

Based on the description of the correlation n -star graphs from the previous section of the work, the concept has been implemented in *Python* language using *pandas* and *numpy* packages for the processing of input data,

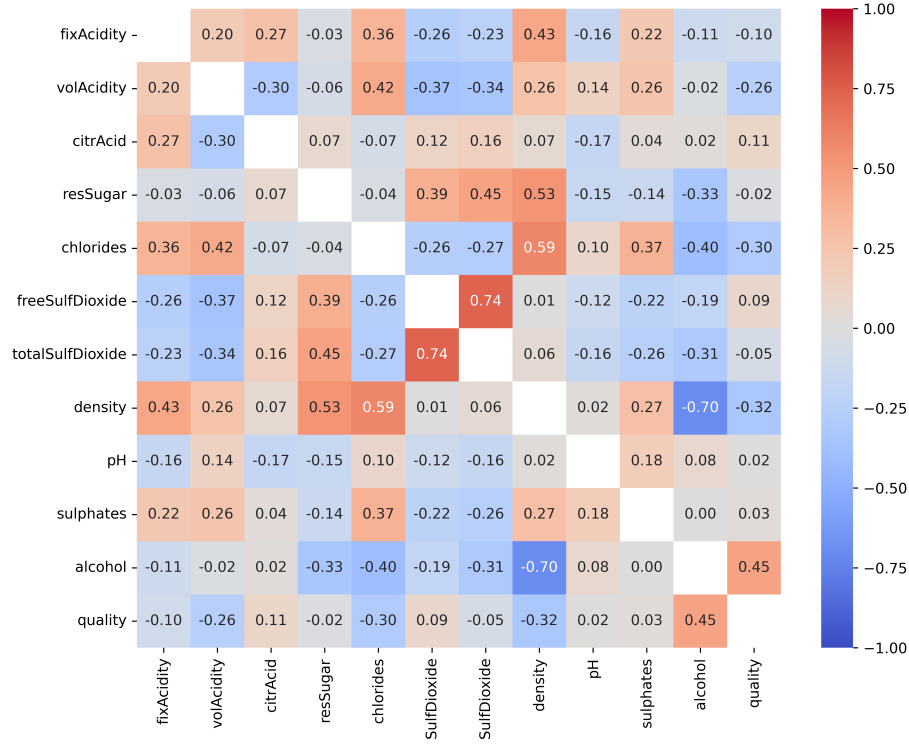


Figure 9: Correlation heatmap of Spearman type for Wine Quality Datasets

sklearn package for clustering of the processed data via *K – Means* algorithm, and *networkx* and *matplotlib* packages for composition and visualization of the graphs themselves.

For the evaluation of the proposed method, three commonly used benchmarking datasets were utilized:

- Wine Quality Dataset [12] – dataset describing chemical properties of red and white vinho verde wine from the northern regions of Portugal. For the presented analysis, this dataset serves as the smallest of the datasets, containing 13 attributes measured on 4 898 entities. The basic visualization of the correlation properties of the dataset is presented in the heatmap in Fig. 9.
- Appliance Energy Dataset [8] – in this dataset, experimental data concerning the use of appliances in a low energy building are stored. The dataset is medium in size, consisting of 29 attributes and 19 735 measurements. Cor-

relation heatmap of the dataset is presented in Fig. 10.

- Superconductivity Dataset [19] – the largest of datasets describes superconductors and their relevant features, such as their critical temperatures or chemical formulas. The dataset describes 21 263 of such superconductors via 82 attributes. To visualize the relationships in this dataset, Fig. 11 presents its correlation heatmap.

These datasets were selected as a way of illustrating data originating in drastically different domains – chemical wine properties, energy performance in green housing, and physical properties of superconductors. The other critical property of the datasets is the variation in their dimensionality, with the number of attributes ranging from 13 to 82. Hence, these datasets provide a broad spectrum of application areas and demonstrate how the proposed method scales across diverse domains, which is crucial from the point of view of the visualization and computation effectiveness.

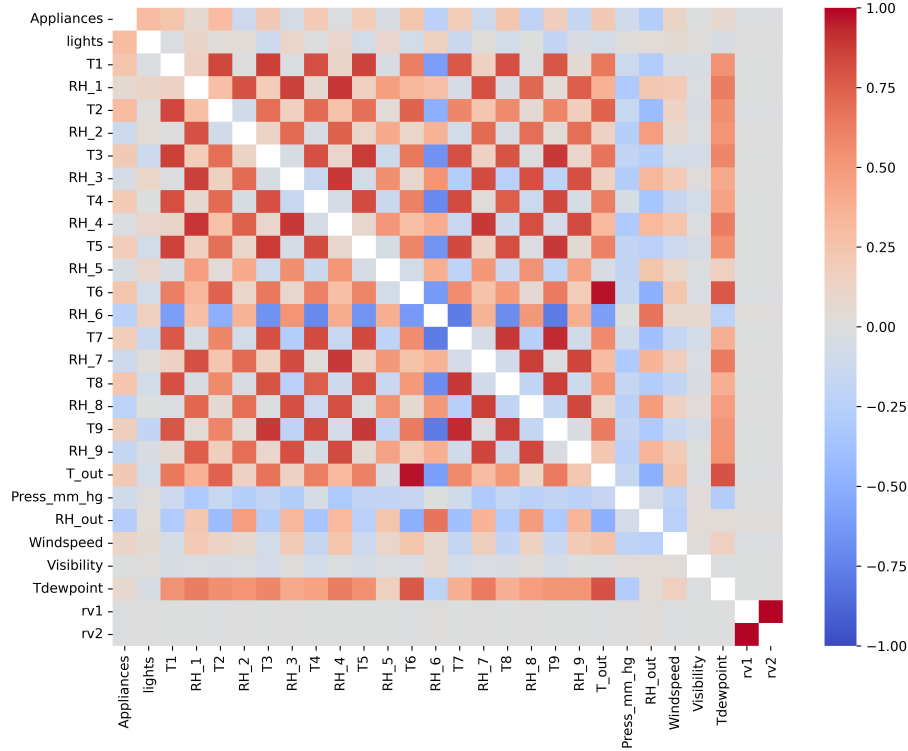


Figure 10: Correlation heatmap of Spearman type for Appliance Energy Dataset

Therefore, using these datasets, two aspects of the proposed visualization model are examined. Firstly, the visualization of these datasets via the model of n -star graphs is conducted for various values of the n parameter (the number of stars) and qualitative aspects of the visualization based on the criteria defined in [14] are evaluated. Secondly, quantitative properties of the proposed model are examined, and the fitting number of classes for each of the studied datasets and attributes of interest is determined.

4.1 Visualization of n -star graphs

Since, for the presented visualization, the K – *Means* clustering requires input value describing the number of clusters (or stars), the following study presents correlation classification into various number of classes for all three of the considered datasets.

Figures 12 and 13 focus on the visualization of n -star graphs for the Wine Quality Dataset with the attribute of interest set as *density* of wine. For the study purposes, the n is set to 2

and 4, respectively. As seen in Fig. 12 the two identified correlation classes described by the stars are fairly well distinguishable – the first class labeled as $\mu = 0.145$ contains attributes with low correlation coefficient values measured between the attribute of interest and all other attributes of the dataset, while the class labeled with $\mu = 0.563$ contains medium to high values of the correlation coefficient. The two classes are interconnected using the correlation between *total Sulfur Dioxide* contained in the wine sample and the amount of *residual Sugar* in the sample.

Naturally, the classification of data into two correlation classes is often insufficient, since it lacks nuance. Hence, more finer division of attributes based on their correlation coefficient values is presented in Fig. 13, where four correlation classes can be seen – low correlations where $\mu = 0.038$, marginal correlations with $\mu = 0.286$, middle correlations marked by $\mu = 0.517$, and high correlation coefficient values in $\mu = 0.699$.

Classification of correlation data into a

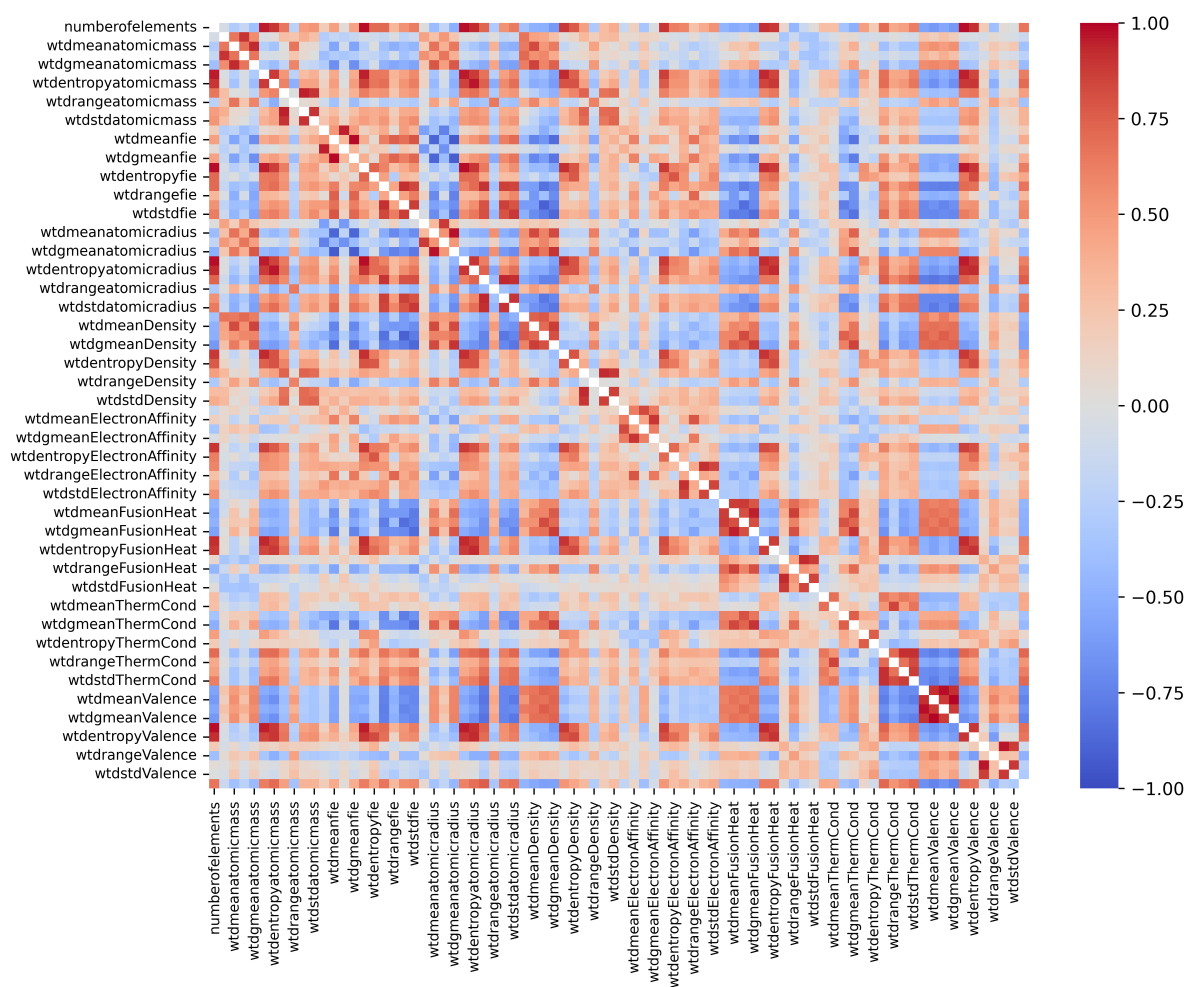


Figure 11: Correlation heatmap of Spearman type for Superconductivity Dataset

higher number of correlation classes is presented in Figures 14 and 15, constructed on Appliance Energy and Superconductivity datasets. Fig. 14 focuses on the visualization of 5 correlation classes for the *Tdewpoint* attribute selected as the attribute of interest. One can see a fairly clear separation between the identified classes based on the μ value, while the number of attributes in individual classes varies from 2 to 10.

On the other hand, the division of the correlation classes in Fig. 15 can be considered nuanced, but there can also be identified minor redundancy. Specifically, the classes of $\mu = 0.313$ and $\mu = 0.398$ are quite close to each other in a subset of correlation coefficient values (eg, one class contains the correlation coefficient value of 0.33 and the other the value 0.36). A similar, but less severe, situation exists in the $\mu = 0.611$ and $\mu = 0.698$ classes.

4.2 Qualitative Aspects of the Visualization

From the point of view of qualitative analysis of the proposed model, we focus on the evaluation of two distinct aspects relevant to the quality of the method:

- Evaluation of qualitative aspects of visual models via Qualitative Result Inspection and Visual Data Analysis and Reasoning based on [14].
- Comparison of the proposed approach to the conventionally used method of correlation class identification — static 5-tier classification and dynamic tertile-based classification.

The main objective of Qualitative Result Inspection is to evaluate the image quality and visual encoding of information created by the proposed model, while Visual Data Analysis and Reasoning aims to explore how the model supports analysis and reasoning about data and helps to derive relevant knowledge in the domain. In the case of correlation n -star graphs, one can see a clear division of correlation classes into the stars themselves, which are color-coded and interconnected via the dotted edges representing the strongest inter-star correlation value

between neighbouring correlation classes. Besides the color, each correlation class is identified by a μ value, which helps in fast understanding of class hierarchy. Since the visualization is inherently partially interactive, meaning there is a possibility of zooming in and out of individual correlation classes, analysts can focus their study on specific parts of the dataset.

When working with datasets containing a high number of attributes — such as the Superconductivity dataset (Fig. 15) —, we can see certain crossings of graph elements. As an example, we can note the class defined by $\mu = 0.398$, where more than 20 attributes were classified, and the labelled vertices of the star cross each other, therefore making the analysis harder. However, this deficiency is easily bypassed by the abovementioned zooming in to the class itself.

The second aspect of the qualitative assessment of the proposed model focuses on the comparison of the results reached with the use of the proposed n -star method and conventional correlation class identification methods. In the presented case, the comparative analysis is conducted using static 5-tier classification and dynamic tertile-based classification presented in Section 2.2.

Tables 1 and 2 contain the division of attributes of all three of the considered datasets into correlation classes based on the correlation coefficient value measured between the attribute of interest and all other attributes based on equations (6) and (8). For comparison purposes, the same attributes of interest were selected across the considered datasets, specifically *density* for the Wine Quality dataset, *Tdewpoint* for the Appliance Energy dataset, and *criticalTemp* for the Superconductivity dataset.

From the tables, we note some of the interesting properties of the basic correlation class identifications. When using the static approach, it is quite common that some of the classes do not contain any attributes, hence are not necessary, eg, the class *strong* and *very strong* in the Wine Quality dataset or the class *very strong* in the Superconductivity dataset utilizing *criticalTemp* as the attribute of interest. On the other hand, when the dy-

dynamic approach based on correlation coefficient value tertiles is utilized, one can note the fact that each class is approximately the same size (similar number of attributes).

Utilizing n -star graphs, the classification yields similar results to other approaches, yet when compared to the static approach, the proposed model does not create empty classes, and from the point of view of comparison to the dynamic method, the classes are of different sizes, which is fitting from the point of view of division of the coefficient values. Additionally, the proposed model has the strong advantage of visualization, which can be done using any of the classifications, but it isn't done natively on any of the models, except the correlation n -star graphs.

4.3 Quantitative Aspects of the Visualization

As a last part of the evaluation of the proposed approach, the quantitative study of the similarity of correlation classes created using n -star graphs is presented. Table 3 contains the results of n -star graph construction for $n \in \{2, 3, 4, 5, 6, 7\}$ for all three of the considered datasets and for the same attributes of interest as in the previous comparative analysis (Tables 1 and 2).

For the identification of correlation classes in data, the objective is to create clearly separable, dissimilar classes. For the purposes of the presented research, the Δ measure is used for the measurement of similarity of correlations in two neighbouring correlation classes. This metric can be described as the lowest difference between the values of the correlation coefficient in neighbouring classes, hence:

$$\Delta(C_i, C_{i-1}) = \min(C_i) - \max(C_{i-1}), \quad \forall i \in 2, 3, \dots, n \quad (9)$$

where C_i is the i -th correlation class of the n -star graph. Then, the natural objective is to maximize Δ value while identifying the highest possible n , which leads to a high number of dissimilar correlation classes. Since the Δ is a simple numerical value used for the overall evaluation of a correlation class, some border of satisfactory dissimilarity (*diss*) of classes needs

to be defined. From the perspective of correlation analysis, such a border can be set to 0.05, so that:

$$\text{diss}(C_i, C_{i-1}) = \begin{cases} \text{satisfactory}, & \text{if } \Delta(C_i, C_{i-1}) \geq 0.05 \\ \text{unsatisfactory}, & \text{otherwise.} \end{cases} \quad (10)$$

The results presented in Table 3 point to several interesting findings and properties of the proposed model and the studied data itself. For the Wine Quality dataset and the *density* as the attribute of interest, the dissimilarity of correlation classes is comparatively high with Δ value close to 0.1 for $n \in \{2, 3, 4, 5\}$. In other cases, such a high value is reached only for $n = 2$, except for the Superconductivity dataset, where the highest Δ reached 0.0224. If adhering to the defined border of 0.05 for the measurement of dissimilarity of two correlation classes, one can observe satisfactory results for $n \in \{2, 3, 4, 5\}$ in the Wine Quality dataset. As mentioned before, in the Superconductivity dataset, there were no Δ values higher than or equal to 0.05 and for the *Tdewpoint* in the Appliance Energy dataset, only $n = 2$ yielded satisfactory classification of correlation values.

From these results, one can conclude:

- The proposed method creates the clearest classification of correlation coefficient values for $n \in \{2, 3, 4, 5\}$, while the value of Δ dropped significantly in all studied cases, where $n \in \{6, 7\}$.
- The specific value of n used to create the proposed visualization model can be determined via the utilization of the Δ value.
- Correlation values measured between *criticalTemp* and all other attributes of the Superconductivity dataset are similar, and therefore their proper division into the classes is challenging.

5. CONCLUSION

The concept of correlation n -star graphs represents a simple and visual method for the iden-

Table 1: Correlation classes of the studied datasets constructed via static 5-tier classification

Dataset	Attribute of interest	Class	Attributes in class
Wine Quality	density	neutral	freeSulfDioxide, pH, totalSulfDioxide, citrAcid
		weak	volAcidity, sulphates, quality, fixAcidity
		moderate	resSugar, chlorides, alcohol
		strong	—
		very strong	—
Appliance Energy	Tdewpoint	neutral	rv2, rv1, Visibility, RH.out, lights, Appliances, RH.5, Windspeed
		weak	RH.6, Press.mm.hg, T8, T7
		moderate	RH.3, T4, RH.8, T9, RH.2, RH.9, T1, T5, T2, T3
		strong	RH.4, RH.1, RH.7, T6
		very strong	T.out
Superconductivity	criticalTemp	neutral	gmeanfie, wtdstdFusionHeat, rangeFusionHeat, meanatomicradius, wtdgmeanElectronAffinity, wtdentropyThermCond, wtdmeanElectronAffinity, entropyThermCond, rangeValence, meanatomicmass, stdFusionHeat, wtdrangeElectronAffinity, stdDensity, meanfie, gmeanatomicradius
		weak	meanElectronAffinity, gmeanatomicmass, stdValence, wtdrangeDensity, wtdentropyElectronAffinity, wtdstdValence, wtdstdDensity, wtdrangefie, rangeDensity, wtdrangeatomicradius, stdatomicmass, stdElectronAffinity, wtdstdatomicmass, wtdmeanatomicradius, wtdrangeatomicmass, gmeanThermCond, wtdmeanatomicmass, rangeElectronAffinity, gmeanElectronAffinity, wtdgmeanfie
		moderate	wtdrangeFusionHeat, wtdstdElectronAffinity, wtdmeanThermCond, wtdmeanfie, wtdgmeanatomicmass, wtdentropyfie, meanThermCond, wtdgmeanThermCond, wtdentropyDensity, wtdgmeanatomicradius, meanFusionHeat, meanDensity, rangeatomicmass, wtdrangeValence, wtdmeanFusionHeat, gmeanFusionHeat, entropyElectronAffinity, wtdgmeanFusionHeat, entropyDensity, wtdrangeThermCond, wtdmeanDensity, stdfie, wtdgmeanDensity, gmeanDensity, wtdstdfie
		strong	entropyatomicradius, stdThermCond, entropyfie, wtdentropyFusionHeat, entropyatomicmass, stdatomicradius, entropyFusionHeat, gmeanValence, rangefie, wtdentropyValence, numberofelements, wtdstdatomicradius, meanValence, wtdentropyatomicradius, entropyValence, wtdentropyatomicmass, wtdstdThermCond, rangeThermCond, wtdgmeanValence, wtdmeanValence, rangeatomicradius
		very strong	—

Table 2: Correlation classes of the studied datasets constructed via dynamic classification based on tertiles

Dataset	Attribute of interest	Class	Attributes
Wine Quality	density	1. tertile	freeSulfDioxide, pH, totalSulfDioxide, citrAcid
		2. tertile	volAcidity, sulphates, quality
		3. tertile	fixAcidity, resSugar, chlorides, alcohol
Appliance Energy	Tdewpoint	1. tertile	rv1, rv2, Visibility, RH.out, lights, Appliances, RH.5, Windspeed, RH.6
		2. tertile	Press.mm.hg, T8, T7, RH.3, T4, RH.8, T9, RH.2, RH.9
		3. tertile	T1, T5, T2, T3, RH.4, RH.1, RH.7, T6, T.out
Superconductivity	criticalTemp	1. tertile	gmeanfie, wtdstdFusionHeat, rangeFusionHeat, meanatomicradius, wtdgmeanElectronAffinity, wtdentropyThermCond, wtdmeanElectronAffinity, entropyThermCond, rangeValence, meanatomicmass, stdFusionHeat, stdrangeElectronAffinity, stdDensity, meanfie, gmeanatomicradius, meanElectronAffinity, gmeanatomicmass, stdValence, wtdrangeDensity, wtdentropyElectronAffinity, wtdstdValence, wtdstdDensity, wtdrangefie, rangeDensity, wtdrangeatomicradius, stdatomicmass, stdElectronAffinity
		2. tertile	wtdstdatomicmass, wtdmeanatomicradius, wtdrangeatomicmass, gmeanThermCond, wtdmeanatomicmass, rangeElectronAffinity, gmeanElectronAffinity, wtdgmeanfie, wtdrangeFusionHeat, wtdstdElectronAffinity, wtdmeanThermCond, wtdmeanfie, wtdgmeanatomicmass, wtdentropyfie, meanThermCond, wtdgmeanThermCond, wtdentropyDensity, wtdgmeanatomicradius, meanFusionHeat, meanDensity, rangeatomicmass, wtdrangeValence, wtdmeanFusionHeat, meanFusionHeat, entropyElectronAffinity, wtdgmeanFusionHeat, entropyDensity
		3. tertile	wtdrangeThermCond, wtdmeanDensity, stdfie, wtdgmeanDensity, gmeanDensity, wtdstdfie, entropyatomicradius, stdThermCond, entropyfie, wtdentropyFusionHeat, entropyatomicmass, stdatomicradius, entropyFusionHeat, gmeanValence, rangefie, wtdentropyValence, numberofelements, wtdstdatomicradius, meanValence, wtdentropyatomicradius, entropyValence, wtdentropyatomicmass, wtdstdThermCond, rangeThermCond, wtdgmeanValence, wtdmeanValence, rangeatomicradius

Table 3: Study of similarity of correlation classes based on Δ measure

Dataset	Attribute of interest	n	Δ
Wine Quality	density	2	0.1113
		3	0.0925
		4	0.1087
		5	0.0925
		6	0.0416
		7	0.0416
Appliance Energy	Tdewpoint	2	0.1096
		3	0.0378
		4	0.0378
		5	0.0394
		6	0.0219
		7	0.0219
Superconductivity	criticalTemp	2	0.0224
		3	0.01
		4	0.0224
		5	0.0087
		6	0.0091
		7	0.0175

tification of correlation classes in multidimensional datasets. These classes are obtained by clustering of the absolute correlation values (using $K - Means$) and labelled and sorted using the class mean absolute correlation μ , while being interconnected by the strongest inter-class correlations selected so as to avoid cycles, producing an interpretable, hierarchical visualization.

Evaluation of the model on three benchmark datasets demonstrates both qualitative and quantitative strengths of the model. Qualitatively, the visualization clearly separates correlation classes through color coding, μ labels and explicit inter-star connections, and it supports focused analysis through its interactive elements. Compared to static 5-tier and dynamic tertile-based classifications, n -star graphs avoid empty classes common in static classifications and produce class sizes that better reflect the underlying distribution of correlation strengths than simple tertiles, while simultaneously providing a native, easy-to-interpret visual encoding. Quantitative results indicate that the proposed method produces clear and most dissimilar classification for $n \in \{2, 3, 4, 5\}$ across the studied datasets.

Future work should address the limitations of the model and extend the method in several directions:

- develop automated methods to select an appropriate n so analysts are guided

rather than required to choose n a priori,

- improve layout and labelling for high-dimensional attribute sets (edge-routing, adaptive label placement, or interactive filtering) to reduce visual crossing of graph elements,
- conduct user studies to quantify the model's effectiveness for real analytical tasks versus conventional correlation-classification methods,
- and study other representations of direct and indirect relationships in correlation structures and substructures, such as embedded or naturally occurring trees.

CODE AND DATA AVAILABILITY

The code for the proposed visualization model is available at:

github.com/AdamDudasUMB/n-starGraphs

The datasets used in the experiments presented in this study are freely available at:

archive.ics.uci.edu/dataset/186/wine+quality

archive.ics.uci.edu/dataset/374/appliances+energy+prediction

archive.ics.uci.edu/dataset/464/superconductivity+data

In case of any questions, don't hesitate to contact the authors of the work via e-mail adam.dudas@umb.sk

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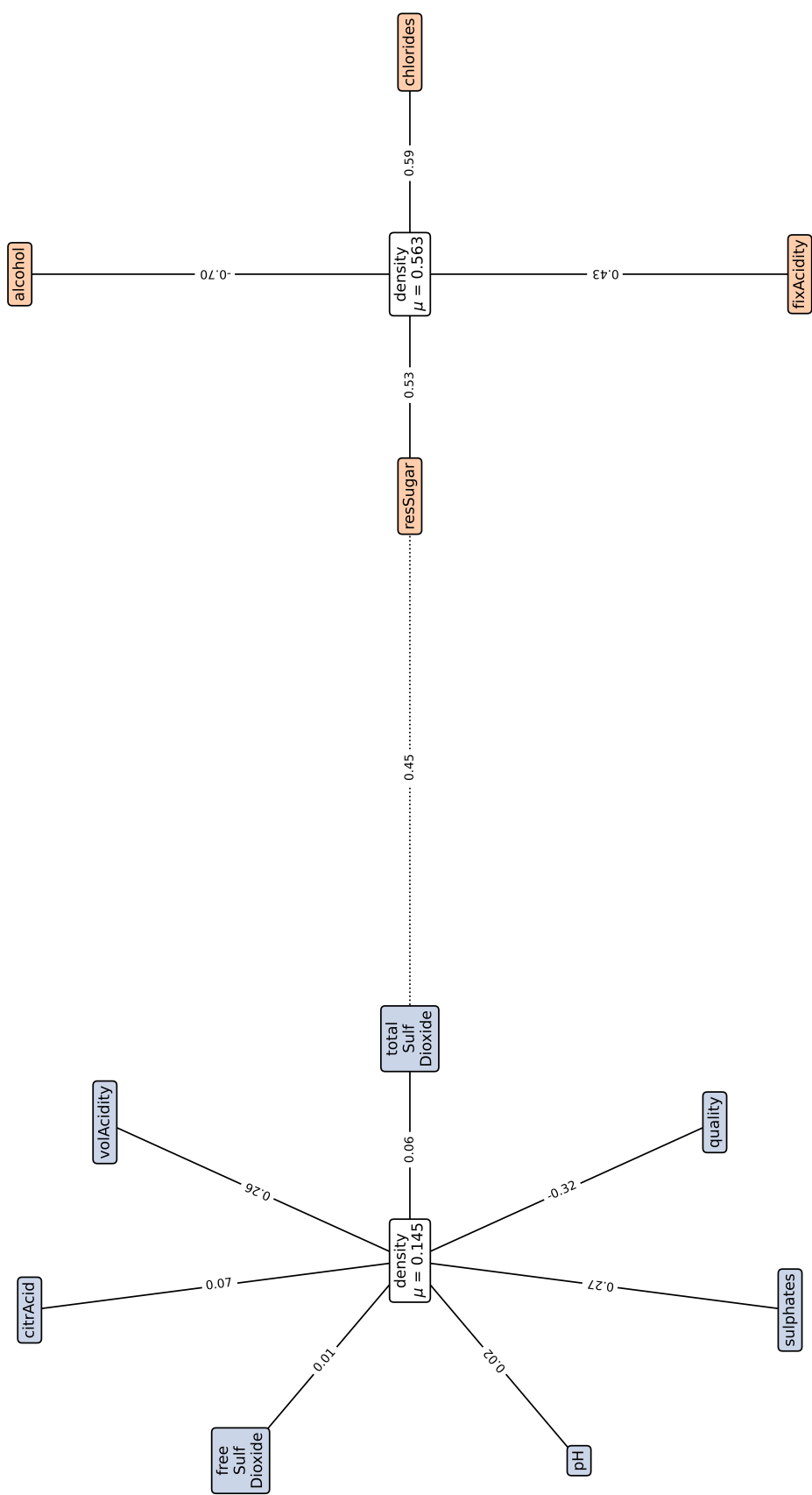


Figure 12: Visualization of Wine Quality Dataset correlation n -star graph for $n = 2$

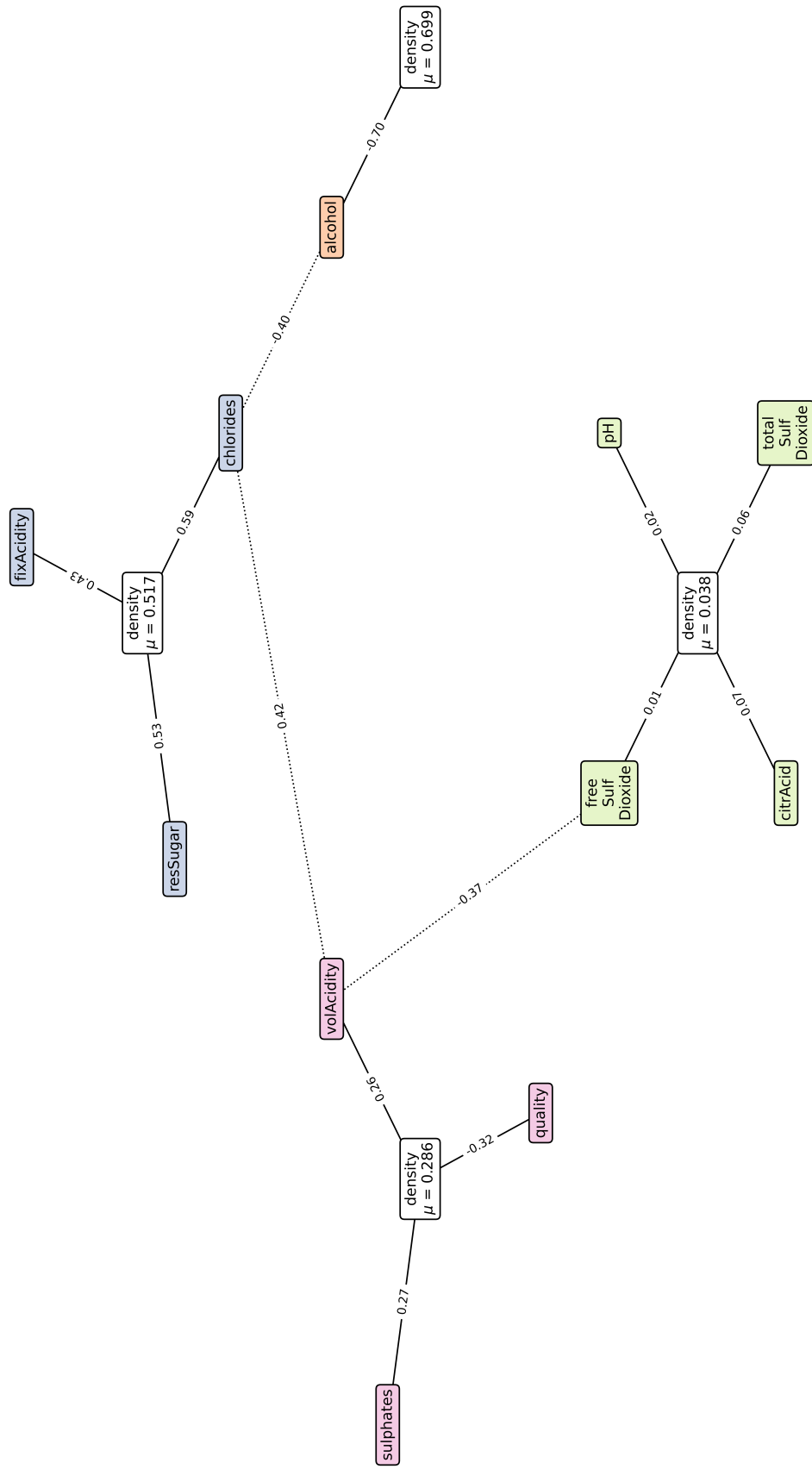


Figure 13: Visualization of Wine Quality Dataset correlation n -star graph for $n = 4$

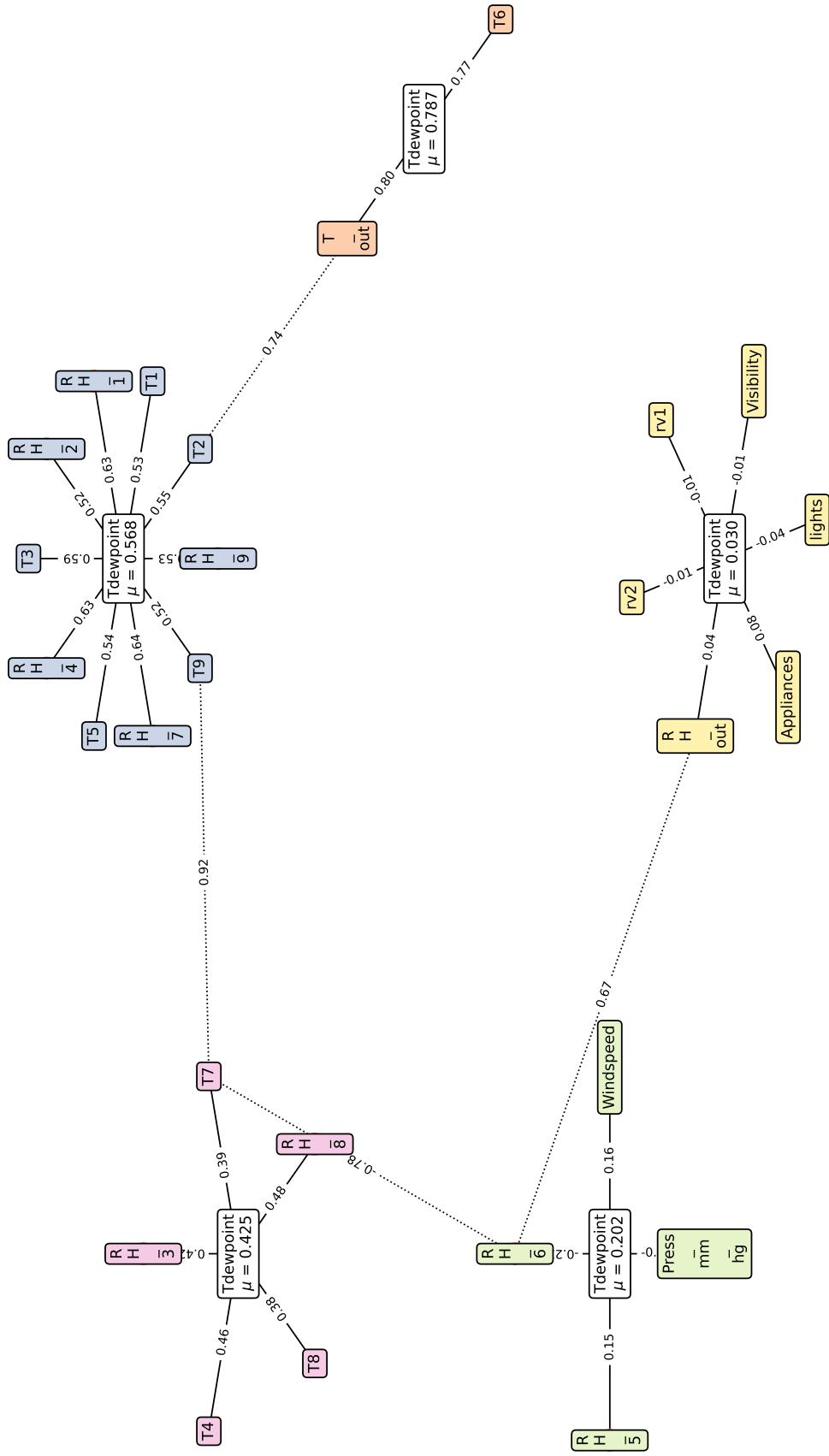


Figure 14: Visualization of Appliance Energy Dataset correlation n -star graph for $n = 5$

Artificial Intelligence-Driven Digital Transformation Mediating the Relationship Between Artificial Intelligence Readiness and Business Process Efficiency

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Abstract: *This study presents a novel account of artificial intelligence-driven digital transformation (AIDT) in the proposed relationship between artificial intelligence readiness (AIR) and business process efficiency (BPE). Data gathered from 227 firms were analysed with the PLS-SEM approach for testing the proposed AIDT model. Results confirmed that the link between AIR and BPE is positive and significant. Furthermore, it is confirmed that AIDT significantly mediates the positive relationship between AIR and BPE. Further, discussion on tangible and intangible aspects of AIR offers deep AI-related theoretical insights into the AIDT related concept of organizational resource-based view. Policymakers and AI practitioners can use the AIDT model as a driver for enhancing BPE.*

Keywords: *Artificial Intelligence, Digital Transformation, AI Readiness, AI-Driven Digital Transformation, Business Process Efficiency*

1. INTRODUCTION

Technological integration and digitalization are long known for enhancing the operational capacity and efficiency of production processes [1], [2]. However, with the latest developments in artificial intelligence (AI), there is a new race towards artificial intelligence-driven digital transformation (AIDT) across industries [3]. Building on this argument, the present paper has focused on exploring the significant role of artificial intelligence readiness (AIR) and AIDT in determining the overall cross-industry business process efficiency (BPE) [4]. Focusing on AIR as a prerequisite of modern AIDT race, we have argued that firms that have prepared themselves in terms of tangible and intangible AI-related assets will reap the benefits of AIDT in the long run [5]. AIR is a quite new concept [6], [7]; therefore, its role and significance are relatively unexplored in AI literature [4]. Recently, Naheed et al. [7] presented a multidimensional AI model to help understand the preliminary AIR in small and medium-sized organizations [8], [9]. Their

preliminary AI model can help businesses assess and figure out how much they are ready for the deployment of AI-enabled applications in their routine operations [7]. Among many other AI-related factors, Naheed et al. [7] focused on the preemptive AI technological areas, computer skills, and internal information systems, for presenting an organized AI-driven approach for SMEs to understand, improve, and evaluate their capabilities to deploy AI applications effectively [7].

Further, Shonhe [10] explored organizational AIR requirements for AI record keeping and AI information management related practices and proposed a conceptual outline assessing the AI adoption related approach [8], [11]. However, these studies [7], [10] failed to connect AIR with organizational digital transformation [4]. The present study suggests that AIR can foster AI-driven restructuring in key business processes [4], which can digitally transform the way a business executes its routine operations [12], [13]. In this regard, Kraus et al. [14] presented a review of existing research on digital transformation to understand how factors of AI related digitalization and organizational transformation are being addressed in the context of modern businesses and management practices [4]. Their findings identified that some major factors (e.g., attitude towards technological adoption, AI data handling strategies, and organizational practices towards AI change management, etc.) can offer a deep insight into how modern businesses are technologically evolving in response to AI and digitalization trends [4], [14]. Moreover, Farooq et al. [15] in their UTAUT3 theory noted that the element of personal innovativeness also helps in digital transformation and adoption of tech-focused practices [4], [16]. In line with personal innovativeness, the present AIDT model study suggests that AIR has a significant connection with AIDT [4].

Furthermore, the present study also connects AIR with anticipated business efficiency [4], [17]. Business process innovation [13] and BPE are central for maintaining competitiveness in the business domain [12], [18]. Adoption of AI at an early stage can help in accomplishing technological competitive advantage through BPE and AI-driven innovation [4], [12]. According to Qiu et al. [19], BPE is a result of long-term organizational planning and requires efficient networking skills. In this regard, Qiu et al. [19] have proposed an introductory conceptual model for efficient business operations [11], [20]. According to them, this efficiency model is designed to significantly improve the operational BPE [19]. Survival in a competitive business environment requires not only efficiency in production along with BPE, but it also warrants a continuous learning attitude [12], [19]. Therefore, Qiu et al. [19] have emphasized the elimination of redundancies and continuous entrepreneurial efficiency development [13]. The current study suggests that AI can help in reducing these redundancies caused by manual work for achieving BPE through AIDT [12]. Therefore, we present the AIDT model that connects AIR with BPE with a mediating role of AIDT [4]. Further review of AI literature for AIR, AIDT, and BPE continues in the next section.

2. THEORETICAL OVERVIEW

AIR involves both tangible (e.g., hardware infrastructures) and intangible (e.g., human skills, software applications) aspects required for beneficial corporate deployment of artificial intelligence-enabled devices [1]. AI-enabled devices are capable of enhancing the processing capacity [4] and help in calculated and accurate decision making [18], [21]. Holmström [21] has presented a conceptual framework focusing on AIDT and AIR. His framework has emphasized the drivers of AI-led digital transformation, reshaping the current corporate landscape [16], [21]. Further, Issa et al. [22] designed an AI framework that helps in exploring the agricultural and tech-oriented companies to prepare for AI-readiness [4], [23]. They identified the factors that agri-businesses need to have in place (e.g., IT skills for AI, computer systems for using AI tools, and digitalization strategy for promoting AI applications, etc.) for successful adoption of AI tools in their routine business operations [22], [23]. Similarly, Jöhnk et al. [24] argued that even if some businesses are not ready for AI adoption today [12], they cannot evade the consequences of not being ready when AI finally comes into the mainstream businesses [13], [24]. Further, the explored the AIR factors that make companies

truly prepared to bring AI deployment into their routine operations [24]. Moreover, by speaking with AI experts and industry professionals, they identified some key AIR areas (e.g., AI strategy, resources for AI, and AI acceptance culture, etc.) for offering businesses and policymakers a clear way to evaluate where they stand in terms of AIR before diving into full-scale AI adoption [24], [25]. Further, Issa et al. [22] deeply looked into the points that make agri-technology companies feel ready to deploy AI tools and applications powered by AI algorithms [4]. Offering a practical guide that was based on in-depth surveys, discussions, and interviews of experts, Issa et al. [22] discussed AI tools, skills required for AI usage, and organizational AI related strategies that agri-firms might need for successfully bringing new AI capabilities for their enhanced working efficiency [13], [22]. Further, in terms of AIR, Wang et al. [26] studied the AI-related educational technologies from the perspective of teachers' AIR and preparedness to use AI applications in the education industry [4], [27]. They described that many teachers who reported feeling confident about AIR and had a positive approach to using AI-related applications were more creative with AIR and tended to be happier with AI usage at their workplace [18], [26]. Further, Wang et al. [26] noted that those teachers who felt unsure about AIR or were feeling threatened by AI-enabled applications were less likely to adopt them in their lectures [4]. Since AIR is a comprehensive phenomenon, Tehrani et al. [28] decoded the organizational factors that often affect the AIR at large-scale AI adopting corporations [12], [28]. Through AI focused qualitative approach based on AIR-related interviews of more than fifty managerial position holders, Tehrani et al. [28] confirmed that data acquisition [13], investment in AI applications [16], and AI infrastructure [18] are among the key factors reflecting the organizational AIR and preparedness towards AI deployment [28].

2.1 ARTIFICIAL INTELLIGENCE DRIVEN DIGITAL TRANSFORMATION (AIDT)

Over the last two decades, the concept of digital transformation has stayed perched on the acquisition of traditional computing power [23]. However, the emergence of the recent wave of AI-led applications has once again shattered this balance, giving rise to AIDT [4], [12]. Digital transformation is a broad concept [23] that denotes the corporate-level integration of various technologies [13] into different areas and effects of routine operational activities of a

business [29]. Digital transformation represents fundamental changes in the organizations' operations [12], majorly focusing on how organizations operate and how they offer value to their end users [30]. Fenwick et al. [3] have noted that the current modern wave of AIDT is a completely different and out-of-the-box opportunity to rethink the business models and processes with AI in mind [3], [4]. Reporting AIDT as a reshaping paradigm shift towards the adoption of cutting-edge and human-centric AI-enabled features, Fenwick et al. [3] have highlighted the role of AI-enabled human resource practices as well [3], [4]. Further, Holmström [21], noticing the dearth of AIR, has discussed the critical role of organizational digital transformation (i.e., referred here as AIDT) driven by AI advancements [4], [12].

Holmström's [21] framework for AIR has emphasized sequential AI deployment for gradual and systematic technological transition from corporate-level AIR to AIDT-based organizations [4], [21]. Further, while highlighting AIDT as AI-led organizational digital transformation, Jin [5] has argued that the humanness of AI applications as well as their conversational eeriness both drive towards AIDT and deployment of AI technology in modern-day digitalized organizations [3], [12]. Further, Jin [5] noted that organizations must respond to technological AI changes either by complying with these modern AI-led changes or by themselves leading the wave of AIDT and AI-driven technologies [5], [31]. Further, Liao and Feng [29] suggested that organizational digital transformation is also linked with the size of the digital network and AIDT capacity that organizations have [4]. They reported that having a tech-focused, broad, and robust forward-looking digital network, along with the presence of scholarly educational technology connections, helps foster the organization-level digital transformation and AIDT [29].

These digital transformation related arguments in the context of AIDT [13] seem to hold ground for companies that particularly put more emphasis on AI-led process innovation and adeptness in BPE [12], [29]. Furthermore, Taherizadeh and Beaudry [30] presented an AI-led digitalization and AI-based transformation perspective of AIDT through grounded theory and explored the practices of Canadian SMEs for dealing with AIDT in the current wave of AI-based transformation [6]. Their findings revolved around AIDT and major elements of organizational ability to assess the AI-driven transformation in the external environment, by checking their perceived AIR, for testing the suitability of new technologies, while focusing on expanding BF

with the usage of AI in business operations, and leading the AI technology-driven corporate changes [4], [30]. According to Taherizadeh and Beaudry [30], the process of digital transformation is often gradual, and similarly, AIDT is continuously evolving in its nature [1], [16]. Therefore, we suggest that AIDT requires top management to adapt their AIR and entrepreneurial AI practices [4]. AIR evolves with their long-term AIDT plans and operational business strategies over time [13]. Furthermore, AIDT and AIR are both reshaping the changing landscape of technological and entrepreneurial orientation towards BPE derived from modern AI technologies [13], [30].

2.2 BUSINESS PROCESS EFFICIENCY (BPE)

Process efficiency has always remained a sought-after element of digitalized contemporary businesses and management practices [13]. According to Bhaskar et al. [2], the techno-functional features of a business, along with its operational and occupational AIR aspects, play an important role in the maximization of production and overall optimization of BPE in the corporate arena [4]. Specifically with regard to modern AIDT and industrialization, they noted that technological efficiency helps in the exploration of operational BPE-related technicalities and remains an extremely desired element of functional industrial aspects in digital business management [2], [4]. Further, Duah et al. [32] have examined the plausible influence of green and environmentally sustainable HR related practices on BPE in the form of delivery of services and process efficiency for improving the performance of the local government associations [13]. Their BPE-related findings have confirmed that the practices of knowledge sharing can enhance the adeptness of BPE by promoting significant innovation at the workplace [32]. Moreover, it is observed that the functioning effectiveness of organizational BPE is further strengthened with AIR and AIDT [13]. Specifically, BPE is boosted in such AIR based organizational cultures where employees actively collaborate for AIDT and share their technological knowledge with peers [13], [32]. Therefore, with regard to BPE, it is suggested that process efficiency is also linked with business process innovation, digitalization, and AIR for AIDT in production-related industries [12], [13].

The desired level of elimination of the barriers hindering the AIR and access to organizational digitalization knowledge required for AIDT is not sible without placing significant operational protocols [4], [19]. It is observed that BPE

achieved through digitalization can lead to a smoother flow of operational activities [12]. Further, BPE, along with AIDT, can improve on-ground strategic decision-taking abilities with the usage of AI applications [12]. Further, Tomar and Grover [33] explored the use of robots for BPE through AIR and automation of operational activities resulting in AIDT in laborious routine businesses [10], [33]. They reported that deployment of AIR-based robots helps in streamlining AIDT while dealing with redundant manual activities at the workplace and can influence BPE in a positive way [4], [33]. AI-enabled robots influence BPE by leveraging on AIR and AIDT [12], and are prolifically effective for offering a practical and tangible AI-driven boost in overall corporate productivity [4]. Further, AI-driven BPE is enhanced by allowing human employees to keep their mental focus on AIR, AIDT, innovative, conceptual, and more value-oriented practical operational tasks [33]. Thereby, achieving BPE by leaving non-cognitive, laborious, and repetitive tasks for AI-powered robots [12], [33]. This review of AI and BPE literature suggests that BPE is achievable by eliminating redundant tasks with the help of AIR and AIDT [12]. Discussion on our proposed AIDT model for achieving AI-driven BPE continues in the next section.

2.3 AIDT MODEL AND HYPOTHESES DEVELOPMENT

The AIDT model aims to test AIR and AIDT as predictors of AI-driven BPE. Building on the AIR, AIDT, and BPE literature, this study connects the missing dots of digital transformation in this era of AI advancement [23]. According to Almalki et al. [1], the perceived level of AIR has a significant impact on the satisfaction of end users [16]. Specifically, AIR is discernibly important when it comes to the delivery of education services [1], [4]. With the eruption of the AI bubble, the concept of AIDT has rapidly evolved along with BPE in all sectors of the digital corporate ecosystem [21]. The conversationally convenient and interactive nature of AI-enabled devices can enhance BPE [4]. Owing to advanced anthropomorphism, driven applications have shown remarkable conversational abilities [16]. Therefore, the ability of AIDT to offer digitally unmatched, groundbreaking BPE-related decision-making solutions cannot be denied [4], [16].

For that reason, AIDT has gained an unparalleled attention for BPE driven by AIR in various fields ranging from academics to manufacturing and digital service sectors as well [21], [24]. Furthermore, Landeta Echeberria [25] also

explored BPE-related integration of AI applications and elaborated on how new businesses can practically boost their AIDT [4]. AIDT helps in digitally reshaping the business processes [3], for enhancing them efficiently by integrating them with AI-enabled new technologies [25]. Moreover, Landeta Echeberria [25] discussed AI integration-related findings for AIDT [34], and highlighted the need to integrate [35] and align new AI technologies [36] with operational business goals for achieving BPE [16], [25]. Since BPE can be achieved by encouraging process innovation through AIR, and by investing in the development of AIDT-related technical skills of workers [25]. Therefore, hypothetically connecting AIR, AIDT, and BPE, we have theorized their relationship in the form of the AIDT model (see **Figure 1**). The AIDT model is built on the following hypotheses:

H1a AIR has a positive impact on AIDT

H1b AIR has a positive impact on BPE

H2 AIDT has a positive impact on BPE

H3 AIDT mediates the relationship between AIR and BPE

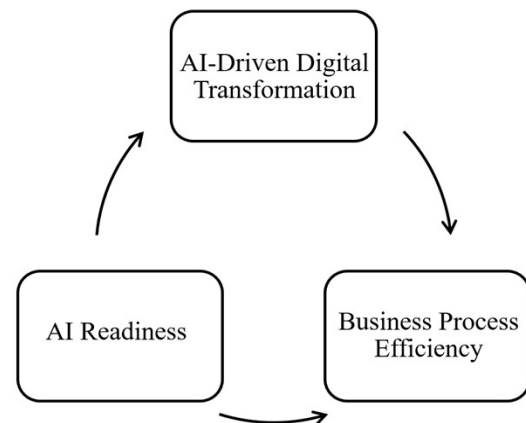


Figure 1: AIDT Model

Source: Authors

3. RESEARCH METHODOLOGY

Since AIR and AIDT are such constructs that are going to impact all BPE-seeking industries across the board [5]. Therefore, AIR driven disruptive nature of AIDT is also noted in multiple previous studies [1], [7]. Furthermore, many sectors have reported BPE that has been achieved through digital transformation [4], [24]. Therefore, this study aimed to collect data from various industries, ranging from different segments of the economy, for better AIDT-related implications [13], [25]. Hence, considering AIR, BPE, and the broad practical nature of the AIDT model, we used the directory of the Lahore

Chamber of Commerce and Industry (LCCI) for inviting one key informant from LCCI-registered firms. Using a simple random sampling approach, we reached out to 600 LCCI-registered firms to participate in the AIDT model analysis. After two reminders to key informants of contacted LCCI registered firms, we received 245 completed responses. 18 incomplete responses were discarded, and the remaining 227 responses, making a 37.8% response ratio, were used for AIDT model analysis.

Measurement scales for AIR, AIDT, and BPE were carefully developed by the authors with the help of BPE professionals, AIR enthusiasts, and AIDT-related academicians. During AIR related literature review, we observed four main dimensions of AIR (i.e., leadership commitment towards AIR, organizational culture towards AI and AIR, investment in technological AI infrastructure, and employees' AI-related skills). Therefore, AIR was measured with a four-item Likert-type scale encompassing all aforementioned four AIR-related dimensions. Secondly, regarding AIDT we developed a six items scale that covered following key aspects of AIDT (i.e. AI as driving force towards digital transformation, optimization and automation of business through AIR, use of AI for personalized customer experience, leveraging AI for enhancing customer experience, use of AI in multiple departments for organization-wide digital transformation, and promoting the culture of AI driven digital innovations). Finally, for BPE we prepared a four-item scale commissioned to assess the following four BPE-related dimensions (i.e. reduction in service or product delivery time via AI, AI-driven improvement in accuracy of business operations, reshaping digital business value proposition through AI-driven reduction in redundant tasks, and efficient AI-guided response to market changes and digital customer needs).

Using PLS-SEM, we tested the AIDT model in a cross-industry setting. An overview of 227 firms participating in the AIDT model analysis (see **Table 1**) shows 36% software / IT services providers, 17% hospitality firms, 14% financial services providers, 11% firms dealing in consumer goods, and 10% education-related firms. Regarding age, 33% firms were less than 5 years old, 37% firms were 5 to 10 years old, and 30% firms were more than 10 years old. Further, 18% had less than 20 employees, 26% had 20 to 50 employees, 19% had 50 to 100 employees, and the remaining 37% reported having more than 100 employees. After this preliminary assessment of sample characteristics, the AIC model was tested with the following two steps

(i.e., AIDT measurement model and AIDT structural model).

Table 1: Overview of Sample Characteristics

Sample Characteristics	N = 227	Percentage
Industry		
Software / IT services	82	36%
Hospitality	38	17%
Financial Services	32	14%
Consumer Goods	26	11%
Education	22	10%
Others	27	12%
Firm Age		
Less than 5 years	76	33%
5 to 10 years	84	37%
More than 10 years	67	30%
No. of Employees		
Less than 20	41	18%
20 to 50	60	26%
50 to 100	42	19%
More than 100	84	37%

Source: Authors

4. RESULTS

Cronbach's alpha for AIDT measurement models, i.e., 0.728 for AIR, 0.901 for AIDT, and 0.884 for BPE, is in an acceptable range. Similarly, AVE values, i.e., 0.550 for AIR, 0.669 for AIDT, and 0.690 for BPE, are also acceptable. Furthermore, outer loadings (see **Table 2**) for all items belonging to AIR, AIDT, and BPE are higher than the 0.50 threshold [4]. These results of the AIDT measurement model confirm that the scales used for AIR, AIDT, and BPE are reliable. A complete list of these results of AIR, AIDT, and BPE scale items is presented in **Table 2**.

Table 2: Construct Reliability and Validity

Constructs	Scale Items	Outer loadings	Cronbach's Alpha	Composite Reliability	AVE
Artificial Intelligence Readiness (AIR)			0.728	0.830	0.550
AIR-1	Our top management is committed towards AI adoption and supports AI usage	0.672			
AIR-2	Our organizational culture nurtures experimentation	0.782			

	n, innovation, and openness towards new technologies like AI				
AIR-3	Our organization has invested in necessary technological infrastructures (i.e., hardware and AI software applications) for AI implementation	0.753			
AIR-4	Our employees are skilled and are trained to learn, work, and adapt with AI	0.755			
Artificial Intelligence Driven Digital Transformation (AIDT)			0.901	0.924	0.669
AIDT-1	AI has transformed our ways of approaching digitalization and customer experience	0.746			
AIDT-2	We have optimized the digitalization process with AI, resulting in reduced manual work and automation via AI	0.855			
AIDT-3	AI has digitally transformed our customer engagement through personalized experiences	0.806			
AIDT-4	Our organization has leveraged AI to enhance and create new digital services, products, and solutions	0.775			
AIDT-5	Cross-departmental implementation of AI has contributed to our competitive edge	0.834			
AIDT-6	AI-driven innovations have fostered the integration of continuous	0.882			

	exploration and transformation, reshaping our key business processes				
Business Process Efficiency (BPE)			0.884	0.899	0.690
BPE-1	AI usage has significantly reduced the resources and time required for accomplishing our key business processes	0.826			
BPE-2	Adoption of AI has significantly improved the consistency and accuracy of our key business operations	0.851			
BPE-3	AI has reshaped our digital value propositions and strategic activities by automating repetitive tasks	0.836			
BPE-4	AI-driven efficiency has enabled us to respond to market changes and customers' needs in a more efficient manner	0.809			

As presented in **Table 3**, the results of H1a, i.e., β 0.642, t-value 19.651, p-value 0.000, confirmed a significant AIR to AIDT relationship. Secondly, results of H1b, i.e., β 0.127, t-value 2.443, p-value 0.015, confirmed a significant AIR to BPE relationship [37]. Likewise, results of H2, i.e., β 0.674, t-value 16.364, p-value 0.000, confirmed a significant AIDT to BPE relationship [38]. Further, results of H3, i.e., β 0.432, t-value 14.792, p-value 0.000, confirmed significant mediation of AIDT between AIR and BPE [37]. Finally, the structural AIDT model was tested for the R² value of BPE, i.e., 0.580. A brief overview of the structural AIDT model is presented in **Figure 2**.

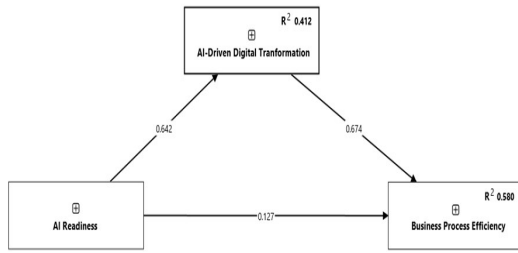


Figure 2 Assessment of the AIDT Model
Source: Authors

Table 3: Test of Research Hypotheses

		β	S.D.	t-value	p-value
H1a	AIR $\rightarrow$ AIDT	0.642	0.033	19.651	0.000
H1b	AIR $\rightarrow$ BPE	0.127	0.052	2.443	0.015
H2	AIDT $\rightarrow$ BPE	0.674	0.041	16.364	0.000
H3	AIR $\rightarrow$ AIDT $\rightarrow$ BPE	0.432	0.029	14.792	0.000

5. DISCUSSIONS

While focusing on AIDT as a determining outcome of AIR, this study has emphasized corporate AI protocols for enhancing BPE [39]. According to Salam et al. [16], AIR is critical for BPE in operational matters [40]. As a driver, AIR has proven its significance for both AIDT and BPE in the proposed AIDT model [41]. Through our AIDT model, empirical assessment of AIDT is presented as a first effort that highlights its mediation between AIR and the proposed BPE [42]. Findings of H1a and H1b in our AIDT model have confirmed that AIR makes organizations successful in the current era of digital AI-based transformation [43]. Further, during structural AIDT assessment, it is observed that AIR helps in strategic and technological AI alignment for attaining BPE through infrastructural AI transformation [44]. Confirmation of H1a and H1b in the AIDT model underscores that AIR requires human skills [4], talent, and AI technology-friendly internal culture [2] for promoting AIDT and BPE-focused initiatives [2]. Owing to the AIDT model's described connection between AIR and organizational AIDT and plausible BPE, we suggest that organizational readiness is an indication of AIDT in the long term [3], [12]. Additionally, top management responsible for AIDT should take necessary steps for AIR that can ensure operationalization of AI digitalization for achieving BPE [2], [16]. Further, H2 in the AIDT model regarding the relation between AIDT and BPE is also confirmed

[38]. Findings suggest that organizational AIDT can significantly boost BPE [45]. These AIDT model findings support the role of AIR and AIDT in optimizing corporate decision making [28] and enhancing BPE through well-organized productivity [12], [13]. Further, the AIDT model's argument regarding minimization of redundancy [5] and repetitive laborious tasks [3], [6] is also supported by the relation between AIDT and BPE [5], [28]. AIDT enhances overall responsiveness and boosts organizational agility by translating long-term AIR into the improved BPE [19]. This perspective of AIDT was missing in previous UTAUT3 and UMUM models [4], [15]. Finally, the mediating role of AIDT was also explored [46]. H3 in the AIDT model shows how AIDT strengthens the relation between organizational AIR and BPE. These outcomes of AIDT mediation suggest that AIR and AIDT both are essential for structural BPE-related transformation [32], [33]. With a perspective of AIR, our AIDT model shows how organizational resources can be utilized for achieving BPE [14]. This connection of AIR, AIDT, and BPE also links the concept of competitiveness and AI readiness [7], [12] with resource-based view theory [32]. By framing AIR-related capabilities as an important technological resource, our AIDT model has deployed AIDT mediation as an outcome of strategic AIR and competitive digital resources [4]. Hence, AIR and AIDT can serve as important organizational resources [28] as depicted in the AIDT model, for achieving sustainable technological competitive advantage in terms of BPE [18], [32]. The proposed concept of AIR in the AIDT model has incorporated both intangible (e.g., software-related) [33] and tangible (e.g., computer infrastructure) [19] aspects for AIDT and BPE [19], [33]. Further, findings from the AIDT model suggest that as part of AIR, organizations should strategically invest more in practical human skills [2], for supporting contemporary AI integration and BPE [25]. These results of the AIDT model offer a practical AIR approach regarding AIDT [3], [14] and recommend technological investments for going beyond AI integration for achieving organizational BPE [14], [33]. Finally, the novelty of the AIR and BPE relation in the AIDT model offers a comprehensive understanding regarding the potential operationalization of AIR and AIDT [2], [10]. Hence, the AIDT model can be used for achieving AIDT through AIR [10]. Further, the AIDT model has offered meaningful developments in terms of AIR and AIDT for understanding their BPE-related pathway [2], [4].

The AIDT model has confirmed that AIR and AIDT both play a significant role in enhancing BPE. AIDT has depicted both direct and mediating influences on BPE. Outcomes of the AIR and BPE relationship in the AIDT model confirmed that organizations with higher AI-related capabilities would benefit from competitive digital transformation [47]. AIDT model confirmed that higher AI capabilities are an indication of strong AIR and help in aligning strategic AIDT for a BPE supportive culture [48]. It is confirmed that AIR helps in better equipping the transformative AIDT and BPE through cutting edge AI-related applications. As a result, investment in AIR is aligned with organizational AIDT related goals [2], [10], and can subsequently help in improving operation BPE [2], [4]. Empirical validation of AIR, AIDT, and BPE-related propositions in the AIDT model has underscored the connections among technological readiness [26], organizational transformation [14], and overall business efficiency [2], [4]. These findings of the AIDT model offer significant and valuable AIR related insights from AI programmers and BPE academicians [1]. Overall, it is confirmed that AIR has a strategic importance in the transformational digital landscape [29], and enables improved BPE through the prospective modern wave of AIDT [2], [21].

6.1 Practical Implications and Future Research Directions

Exploration of AIR and AIDT offers crucial and practical BPE-related implications for AI policymakers [17]. As a practical outcome of the AIDT model, BPE requires creating a sense of readiness and urgency towards the deployment of AI infrastructure [21]. Further, the AIDT model necessitates readiness of AI driven ecosystem for BPE that is built with AI-driven human capital. Since the creation of AIR requires improvement in AI capabilities and human skills [5]. Therefore, AI policymakers may leverage AIR and BPE-related findings of the AIDT model for indoctrinating AIDT across industries [49]. More AIR-related AIDT frameworks can promote the significance of readiness supportive digital workplace culture [9]. Therefore, future studies on AIR can expand this AIDT and BPE analogy by broadening the applicability of our AIDT model in different AI settings [25]. Moreover, longitudinal research on AIR, AIDT, and BPE is also warranted in future AI studies. Furthermore, the incorporation of market volatility factors [12] and external AI regulatory measures [24] in our AIDT model can also offer deeper AIR and BPE-related insights [50].

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The Impact of Education and Digital Literacy as an Employment Factor in the Republic of Serbia

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Abstract: *Education in modern business conditions plays a strategic role in the development of knowledge-based and innovation-driven societies. Investment in education represents one of the key determinants of democratization and the economic empowerment of individuals. The goal of contemporary education is to strengthen professional knowledge and to develop key competencies, including digital skills, which enable individuals to be prepared for new professional challenges and actively participate in current socio-economic trends. This paper aims to analyze, through conducted empirical research, the impact of formal education and acquired digital competencies on employability in the Republic of Serbia. Special emphasis is placed on the relationship between the level of education, digital literacy, and employment opportunities, to provide recommendations for improving educational policies and professional training programs.*

Index Terms: education, digital skills, competencies, employability, labour market

1. INTRODUCTION

Searching for and finding a suitable job has always been a challenging and complex task, both for the job-seeking candidate and for the employer company [1]. In today's labour market, education has become a key factor in the development of employee competencies. Constant market changes and major challenges of the modern age have led to a shift in the concept of education, giving rise to the notion of "lifelong learning" [2].

In Serbia, the fundamental strategic document in the field of employment is the National Employment Strategy for the period 2021 to 2026. Within this strategy, one of the identified problems is the low overall employment rate and the slow pace of creating quality jobs. The primary reason for this situation is the rapidly changing demands of the labour market, which lead to a mismatch between the knowledge, skills, and competencies of the workforce.

Human resource management represents a comprehensive and systematic approach to managing people, focusing on attracting,

motivating, developing, and retaining quality personnel to achieve better business performance [3].

Many authors have analyzed factors that influence unemployment, such as age, level of education, the possession of necessary knowledge, and gender. Nickell [4] analyzed the relationship between education and the duration of unemployment. He concluded that each additional year of schooling shortens the expected duration of unemployment by more than 4%, and that obtaining qualifications at a regular or higher level reduces the expected duration of unemployment by 12%.

In the literature, education is viewed as an investment in human capital, which is expected to reduce the likelihood of remaining unemployed. Gonzalez Vazquez et al. [5] state that digital skills have become one of the essential components of workers' competitiveness and employability in the labour market. Bergoč and Novak [6] argue that continuous education and the acquisition of new skills are becoming crucial for career advancement and job stability.

Đorđević et al. [7] emphasize that digital skills are increasingly important for enhancing employability, as they enable individuals to meet the ever-growing demands of the modern workforce. Continuous learning and knowledge acquisition under current conditions contribute to the development of competencies that help increase employability. Employee competencies are considered one of the most important organizational resources, regardless of the sector in which the organization operates.

2. EDUCATION AND DIGITAL LITERACY IN TODAY'S BUSINESS ENVIRONMENT

Many authors [8][9][10][11][12] [13][14] [15][16][17] emphasize the importance of technological advancement, innovation, and education across all areas of business activity. To model an individual as an employee within an organization, we must understand the organization itself, its organizational units, job positions, and their requirements, as well as the employees' educations, skills, work experiences, and capabilities [18].

Human resources have emerged as the most important factor in building a knowledge-based society. Focusing on their development requires education and training for life and work in such a society. Education can be considered a key and priority area in the fight against poverty. The entire world, both developed and developing countries, is facing increasing demands in the field of education. In nearly all countries, the organization and functioning of the education system is the subject of ongoing debate and comprehensive analysis by experts in the field.

Modern education is under significant pressure, facing serious challenges brought about by social, economic, and personal demands. Education, when connected with research and innovation, plays a crucial role in the development of both individuals and society, and consequently, in the creation of highly qualified human capital.

Education and professional development are essential for individual progress, as learning, whether through formal or informal education, various courses or training programs, provides individuals with knowledge that helps them succeed in the labour market.

The International Labour Organization (ILO) defines employability skills as the skills, knowledge, and competencies that enhance a worker's ability to obtain and retain a job, advance in their career, adapt to change, secure new employment if desired or necessary, and re-enter the labour market at different life stages. This viewpoint highlights the necessity of lifelong learning to acquire the skills and knowledge needed for sustainable employment.

Radović Marković [19] points out that “even where employment opportunities exist, many people are unable to find a job because they lack the appropriate education or skills,” and emphasizes that “education must be aligned with new employment needs and aimed at reducing the gap between labour supply and the demands of the economy.”

Tošović and Jovancai [20] note that young people in Serbia, among other challenges, lack the basic knowledge and practical skills necessary for entrepreneurship.

Bandalović et al. [21] argue that the increasing availability of ICT enables individuals to use information more effectively and to develop information and digital literacy through internet use and its associated benefits. Especially for the younger workforce, the topic of digitalization and artificial intelligence and their effects on employment is crucial. The skills that companies seek are rapidly evolving, as digital technologies and AI systems become increasingly integrated into corporate processes [6].

3. UNEMPLOYMENT IN THE REPUBLIC OF SERBIA

The duration of unemployment is a characteristic that indicates how long an unemployed person has been registered with the Employment Service from the moment of entry into the register until the reporting date or the date of removal from the register [22].

The labour market in Serbia in 2024 shows positive developments compared to the previous year. According to data from the Statistical Office of the Republic of Serbia, the total number of people aged 15 and over in the Republic of Serbia amounted to 5.64 million, which represents a slight decrease compared to 2023. The number of employed persons reached 2.9 million, marking an increase of 2%, while the number of unemployed individuals declined by over 8%, totalling just over 270,000 persons. The number of people outside the labour force also decreased by 2.3%, amounting to just under 2.47 million individuals. The employment rate in 2024 reached 51.4%, which is an increase of 1.2 percentage points compared to the previous year.

Figure 1 shows the unemployment rate in the Republic of Serbia over the period from 2005 to 2024.



Figure 1: Unemployment Rate in the Republic of Serbia from 2005 to 2024

Source:

<https://www.statista.com/statistics/440532/unemployment-rate-in-serbia/>

At the same time, the unemployment rate decreased to 8.6%, while the share of the population outside the labour force fell to 43.8%.

A total of 2.55 million people were formally employed, representing an increase of more than 60,000 compared to 2023. The number of informally employed individuals was around 349,000, which is 6,000 fewer than the previous year.

The Labour Force Survey conducted by the Statistical Office of the Republic of Serbia

revealed that the unemployment rate among the population aged 15 and over at the national level was 8.6%. The Labour Force Survey indicates that in 2024, compared to 2023, the unemployment rate decreased in all regions, with the most significant drop recorded in the Region of Šumadija and Western Serbia, where the rate declined by 1.3 percentage points, reaching 8.5%. In the Belgrade Region, the unemployment rate fell by 0.9 percentage points to 6.2%. In the Region of Vojvodina, the decrease was 0.6 percentage points, resulting in a rate of 8.4%, while in the Region of Southern and Eastern Serbia, the unemployment rate dropped by 0.7 percentage points to 12.1%.

According to data from the Statistical Office of the Republic of Serbia (SORS, 2025), the number of unemployed individuals aged 15–24 decreased by 3,500 compared to the previous year, totalling 50,100. The youth unemployment rate was 23.0%, which represents a decrease of 2.0 percentage points. The youth unemployment rate decreased across all regions compared to the previous year, except in the Belgrade Region, where it remained virtually unchanged.

4. EMPIRICAL RESEARCH ON THE IMPACT OF EDUCATION AND DIGITAL LITERACY ON EMPLOYMENT IN THE REPUBLIC OF SERBIA

In order to determine the role of education and digital literacy in employment in the Republic of Serbia, an empirical study was conducted using a survey questionnaire consisting of 22 statements, on a sample of 356 respondents, during the period from February to May 2025. The questionnaires were distributed to respondents either in written or electronic form.

Figure 2 presents the research model.

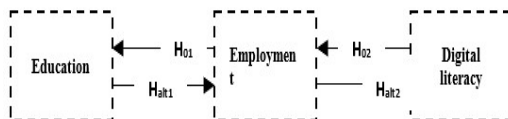


Figure 2. Research Model

The following hypotheses have been formulated:

H₀₁: Education does not affect employability

H_{a1}: Education does affect employability

H₀₂: Digital literacy does not affect employability

H_{a2}: Digital literacy does affect employability

H₀: Education and digital literacy do not affect employability

H_a: Education and digital literacy affect employability

For each question in the questionnaire, respondents were asked to evaluate the extent to

which they agree with the given statement using a five-point Likert scale:

1 – Very little,

2 – Little,

3 – Moderate,

4 – Significant,

5 – Very significant.

Variables (abbreviations):

- Edu.– Education (6 statements)
- Dig. – Digital literacy (8 statements)
- Employ. – Employability (8 statements)

5. CORRELATION ANALYSIS

The opinions and analysis of respondents' attitudes toward the statements from the questionnaire designed based on the Research Model (Figure 2) are presented through the interpretation of Pearson correlation values shown in the Scatterplot Matrix (Figure 4).

The directions of all possible relationships between the variables are positive, indicating that there is a positive correlation among them.

The highest correlation coefficient, i.e., the strongest relationship between variables in the proposed model, is found between the variable Edu. (Education) and Employ. (Employability), with a value of 0.8467, which is considered strong. The coefficient of determination, which indicates how accurately we can predict the variable *Employ.* based on *Edu.*, is 0.7169, or 71.69%.

The lowest correlation coefficient in the model is between the variables Edu. (Education) and Dig. (Digital Literacy), with a value of 0.7052, which is considered moderately strong. The coefficient of determination in this case is 0.4973, or 49.73%, meaning that nearly half of the variability in *Dig.* can be explained by *Edu.*

The positive direction of all correlations indicates that all relationships among the variables are positive.

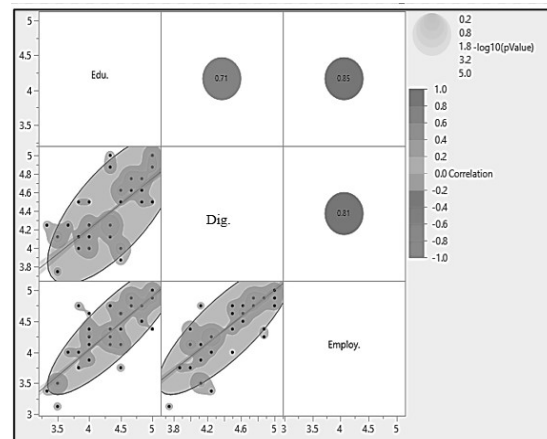


Figure 3: Scatterplot Matrix

6. REGRESSION ANALYSIS

Based on the developed Theoretical System Model (Figure 2), the evaluation of the statistical significance of the impact of independent variables on the dependent variable is presented in Table 1, including: ANOVA results, standardized Beta coefficients, R-Square (in %), relationships between variables, hypotheses, and regression equations.

Table 1. Statistical Significance Estimates of the Impact of Independent Variables

Variables	ANOVA	Std Beta	RSquare u (%)	Correlation	Hypothesis	Regression equation
Edu. / Employ.	[F(1,354)=896,4614 p<0,0005]	0,8467	71,69	Very positive	H_{01} refuses, H_{alt1} accepts	$y_1 = -0,61 + 0,86 \cdot x_1$
Dig / Employ.	[F(1,354)=699,3005 p<0,0005]	0,8148	66,39	Very positive	H_{02} refuses, H_{alt2} accepts	$y_2 = -0,39 + 0,89 \cdot x_2$
Promenljive	ANOVA	Std Beta	RSquare u (%)	Correlation	Hypothesis	Multiple regression equation
Edu. & Dig. / Empl.	[F(2,353)=758,2377 p<0,0005]	0,9006	81,11	Very positive	H_0 refuses, H_{alt} accepts	$y = -0,56 + 0,56 \cdot x_1 + 0,57 \cdot x_2$

Figure 4 presents both linear regression equations for the dependent variable Employ. and the independent variables Edu. and Dig.

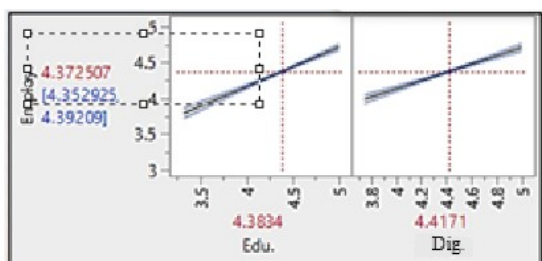


Figure 4: Graph of the Linear Regression Equations for the Dependent Variable Employ. and the Independent Variables Edu. and Dig.

Figure 5 presents the Multiple Linear Regression Equation for the Dependent Variable Employ. and the Independent Variables Edu. and Dig.

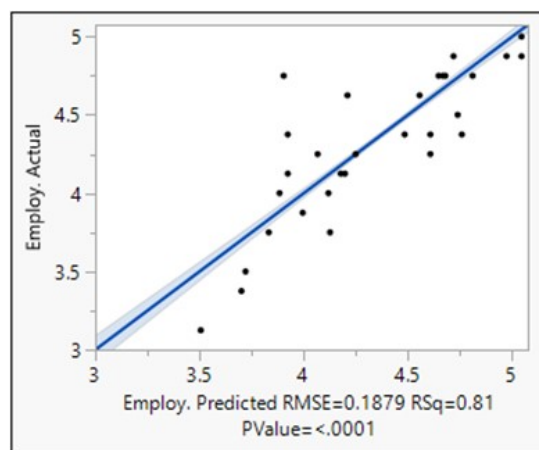


Figure 5: Graph of the Multiple Linear Regression Equation for the Dependent Variable Employ. and the Independent Variables Edu. and Dig.

7. COMPARATIVE AND SECTORAL PERSPECTIVE ON THE ROLE OF EDUCATION AND DIGITAL COMPETENCES IN EMPLOYABILITY

Contemporary literature increasingly emphasizes that the impact of education on employability cannot be considered in isolation from the level of digital competencies. Formal education provides the foundation for employability; however, its effectiveness in modern conditions largely depends on individuals' ability to apply acquired

knowledge in a digitalized working environment. In this sense, digital competences become a key link between educational outcomes and the real needs of the labour market. The OECD [23] and the European Commission [24] point out that the effects of education and digital competences on employability are conditioned by the level of economic development, the structure of the economy, and the dominant employment sectors. The results of this study for the Republic of Serbia, which indicate a positive relationship between higher levels of education and employability, can be further interpreted through the findings of international studies confirming that education achieves its full effect only when combined with well-developed digital skills [23][24]. Research by Đorđević et al. (2025) shows that the possession of digital skills—particularly in the areas of information and data literacy, communication and collaboration, digital content creation, and security—has a significant positive impact on employability, as it enables individuals to meet the increasingly complex demands of the contemporary labour market and opens opportunities for long-term participation in the workforce [7]. Furthermore, the literature on labour market changes emphasizes that technological change does not affect all occupations equally. Within the framework of the “skill-biased technological change” approach (Acemoglu & Autor [26]) and its later elaborations (Autor [26]), it is emphasized that technology increases the demand for skills that are complementary to digital tools, while routine tasks can be partially substituted. Vidas-Bubanja et al. [27], analysing reskilling and upskilling in the digital age through a case study of Western Balkan countries, stress the need for higher education to more actively follow labour-market trends and for study programmes to be aligned with “new business trends” characterized by the intensive use of digital technologies, together with the importance of continuous employee training. This analysis directly supports the argument that the relationship between education, digital skills, and employability is not an isolated phenomenon in Serbia, but rather a regional structural process. At the level of young people and educational institutions, Pecić et al. [28], in a study comparing the skills required by the labour markets of Serbia and the EU, show that the attitudes of students in Serbia largely correspond to those of young people in the EU regarding skills deficits. The authors propose short programmes and faster recognition of non-formal and informal learning outcomes as instruments for reducing the skills gap. This is significant because it clearly introduces a comparative logic (Serbia–EU) and shows that the “skills gap” is a common issue, while policy

instruments (training, recognition, short programmes) are particularly important in economies that are entering highly digitalized sectors at a later stage. Prlić [29] explicitly emphasizes that the labour market is increasingly no longer seeking exclusively “pure IT” profiles, but rather workers who apply digital tools within their respective domains, such as education, healthcare, finance, logistics, marketing, the public sector, and manufacturing. This is important because it highlights that digital competences function as a horizontal “general-purpose technology” that increases productivity across different sectors, albeit with varying intensity. Dimitrić [30] shows that security and trust in digital systems represent key prerequisites for the adoption of digital services, innovation capacity, and investment, which directly influences the competitiveness of organizations and national economies across all sectors of the digital economy. For Serbia, it is particularly relevant that the infrastructure and availability of digital-competence development programmes are uneven between formal and non-formal education, as well as across different levels of education. Matović [31] provides a systematic mapping of digital-competence programmes in Serbia, covering schools, accredited programmes, higher education, and non-formal training, emphasizing that the results represent the first comprehensive “mapping” of the state of digital-competence programmes in Serbia. This finding makes it possible to extend the sectoral discussion to the issue of “channels of supply” of digital skills: in sectors where firms invest more in internal training, digital competences can be improved more rapidly even if formal education lags behind; in sectors with fewer training opportunities, the lack of competences remains a more persistent barrier to employability.

When the findings from Serbia are placed in a comparative and sectoral context, three clear implications emerge that strengthen the scientific contribution of the study: first, the results are no longer interpreted as a local specificity, but as part of a broader process of labour-market transformation in the knowledge economy, in which digital competences, adaptability, and lifelong learning jointly shape employability [30]. At the organizational level, Prlić [32] shows that leadership and innovation are key sources of competitive advantage in contemporary organizations, implying that investments in employee competences, including digital skills, indirectly affect the stability and quality of employment through the strengthening of firms’ innovation capacities.

The findings of this study for the Republic of Serbia are therefore not isolated, but are consistent with the empirical results obtained for the Western Balkans [33][27] and for the European Union [28], as well as with the study by Prlić [29], which demonstrates that digital competences make a statistically significant contribution to employability in the domestic context.

8. CONCLUSION

The results of the conducted empirical research clearly confirm that education and digital literacy are strong and statistically significant determinants of employability in the Republic of Serbia. High values of the correlation and determination coefficients, particularly in the combined model of education and digital skills ($R^2 = 81.11\%$), indicate that employability cannot be adequately explained without considering these two factors. These findings are consistent with contemporary human capital theory [34], as well as with more recent approaches that emphasize the role of digital competences as a key form of functional capital in the knowledge economy [23][24][7]. When the results for Serbia are viewed in a comparative context, they show a high degree of consistency with findings from European Union countries and the Western Balkan region. Pecić et al. [28] confirm that the skills gap is a common problem in both Serbia and the EU, while Hajdari and Fetai [33] demonstrate that the level of education significantly affects employment in other Western Balkan countries as well. This study therefore empirically confirms that Serbia follows the same structural patterns as other economies undergoing a transition toward a digitalized and knowledge-based labour market.

A particularly important contribution of this study lies in the simultaneous consideration of education and digital literacy. While formal education remains the foundation of employability, digital competencies act as a multiplier of its effects. This finding is fully consistent with international studies showing that digital skills have a direct and independent impact on employability [7], as well as with works emphasizing that technology favours workers whose skills are complementary to digital tools [25][26].

The sectoral perspective further clarifies these relationships. As emphasized by Prlić [29] and Dimitrić [30], digital competences today function as a horizontal “general-purpose technology” that increases productivity and employability across almost all sectors—from education and healthcare, through finance and logistics, to manufacturing and public administration.

However, the intensity of this effect varies: in sectors with higher levels of digital integration and greater investment in training, employability grows more rapidly, while in traditional sectors, a lack of digital skills becomes a persistent barrier to labour market entry. This inequality is particularly pronounced in Serbia, where, as shown by Matović [31], the infrastructure and availability of digital competence development programmes vary significantly between formal and non-formal education, as well as across sectors. In this sense, the findings of this study also have clear public policy implications. If sustainable increases in employability are to be achieved, education policy and labour market policy must be integrated with digital transformation policy. Short programmes, flexible forms of learning, faster recognition of informally acquired skills, and systematic investment in reskilling and upskilling represent key instruments for reducing the gap between the supply and demand of skills, as also confirmed by regional studies [27][28].

Finally, the results of this research show that Serbia is not an exception, but rather part of a broader European and regional process of labour market transformation. Education and digital literacy together form the foundation of employability in the contemporary economy, and their interconnection is becoming a key factor of competitiveness for both individuals and national economies. In this way, the present study not only confirms the relevance of its empirical findings but also clearly positions them within an international and sectoral context, thereby fully meeting the reviewer’s requirements for a comparative and deeper analytical approach.

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Technological Aspects of Online Banking in Serbia: User Experiences Across Devices, Usage Trends and Strategic Implications for Managers and IT Professionals

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Abstract: *This paper examines users' perceptions of online banking applications in the Republic of Serbia, focusing on the scales of efficiency, availability, and ease of contact. The research aims to examine user experiences across different devices, the effect of the length of use, and the influence of frequency of use on perceptions of online banking applications. The questionnaire was completed by 181 online banking application users, in the period from August 2024 to March 2025. The results of statistical tests, including the Mann-Whitney and Kruskal-Wallis, revealed no statistically significant differences between mobile and computer/laptop users in terms of efficiency, availability, and ease of contact; the length of time using online banking did not affect users' perceptions of these factors; and the frequency of use also had no significant impact on users' experiences. The findings suggest that users across different usage patterns generally have similar experiences and perceptions regarding online banking applications in the Republic of Serbia. The study's implications are relevant for both researchers and practitioners aiming to enhance the design and user experience of online banking applications.*

Index Terms: *Online Banking Applications, User Perceptions, User Experience, Efficiency, Availability, IT Professionals*

1. INTRODUCTION

In the contemporary environment, technological solutions and innovations are not only transforming business operations [1], but also influencing human behavior and redefining the way business is conducted [2], [3], [4]. To deliver high-quality services and stay competitive in an ever-evolving market, banks are increasingly investing in the development of diverse distribution channels, particularly online banking [5]. Online banking represents one of the technological innovations that offers numerous

benefits to both customers and banks. It makes it easier for users to manage their finances by providing quick access to various banking services [6]. Furthermore, it enhances productivity, performance, and efficiency, while saving time, offering ease of control, user-friendliness, clarity, and flexibility [7]. Overall, online banking as a special type of digital servitization has the potential to foster business growth, strengthen competitive advantage, and create value, while also contributing to environmental and social advancements [8]. However, the successful adoption of such innovations depends not only on their ability to deliver these benefits but also on how easily they can be integrated into users' lives. This brings us to the concept of effort expectancy, which refers to the perceived ease or difficulty of using a new technology [9]. Effort expectancy refers to the degree of effort a user perceives is needed to learn, operate, and interpret a technology. The easier and more intuitive the system feels, the greater the likelihood of user acceptance [10].

Effort expectancy, particularly perceived ease of use, plays a critical role in shaping a user's experience and adoption of a new system. Users tend to prefer systems that are easier to use, especially when performance expectations are similar. The perception of ease of use is influenced by factors such as self-efficacy and external features that improve system usability [11]. The ease of use of an online banking application includes features like quick navigation, intuitive functionality, and clear menu navigation. These elements enable users to complete tasks more efficiently, aligning with the concept of perceived ease of use from the technology acceptance model [12]. Research on digital and mobile banking has demonstrated a strong relationship between user satisfaction and the application's ease of use [13].

This research aims to examine and analyze users' perceptions of online banking applications in the Republic of Serbia, with particular attention to efficiency, availability, and ease of contact. It examines user experiences across different devices, the impact of usage duration, and the influence of usage frequency on overall perceptions of online banking applications.

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The significance of this research lies in its ability to provide valuable insights into key factors, efficiency, availability, and ease of contact that shape users' perceptions and satisfaction with online banking applications. By examining these elements, the study deepens our understanding of their influence on user experiences. Furthermore, by analyzing differences across devices, as well as the impact of usage duration and frequency, the research offers a comprehensive perspective on the determinants of user perceptions of online banking platforms. The findings can support the optimization of online banking services, guiding financial institutions in enhancing their applications to better align with user needs and expectations, while also contributing to the broader body of knowledge on technology adoption and user behavior in digital banking.

The paper is organized as follows. It begins with an introduction, followed by a literature review that highlights the key attributes valued by clients in online banking applications and synthesizes findings from previous studies. The next section outlines the research methodology, including the research questions, the questionnaire used to collect primary data, data collection procedures, and the statistical tools applied in the analysis. The results and discussion are then presented. Finally, the conclusion summarizes the main findings, discusses their implications, acknowledges the study's limitations, and offers recommendations for future research.

2. LITERATURE REVIEW

Banks were among the first to integrate mobile applications into their service offerings, ahead of many other industries. However, the success of these applications heavily relies on client acceptance [14]. Most research on consumer behavior regarding mobile applications has focused on aspects such as user satisfaction, retention, and reuse behaviors, with particular attention given to the features, technological benefits, design, and usability of these applications, as well as their functional elements [15], [16]. Research revealed that the factors of perceived benefit and perceived compatibility positively influenced young consumers' intention to use mobile banking applications. However, the dimensions of perceived ease of use, social impact, facilitating conditions, relative advantage, and perceived risk did not significantly affect their behavioral intention to adopt mobile banking applications [14]. The study, which analyzed 21,526 user reviews from customers of private and state banks in Türkiye, aims to better

understand customer experiences with mobile banking applications. By examining the reviews, the research identified 11 key topics, with perceived usefulness, convenience, and time-saving being the most significant factors influencing application ratings [17]. The study, which is conducted to examine the factors influencing the use of mobile banking applications among Malaysian consumers, focuses on security concerns, service quality, technological factors, and convenience. Data was collected through an online survey of 152 mobile banking application users in Malaysia. The findings highlight key elements that affect application usage, emphasizing the critical roles of security and convenience in encouraging consumer adoption. The study suggests that banks and application developers should prioritize these factors in their development and marketing strategies to increase the usage of mobile banking applications [18]. The study, which applied a technology acceptance model to examine mobile banking adoption among 202 university students in Serbia, found that "perceived usefulness" and "perceived security" are the most significant predictors of adoption of mobile banking [19]. Another study also aimed to identify the key factors influencing mobile banking adoption in Serbia using the technology acceptance model. Conducted with 167 respondents through an online survey in June-July 2020, the results revealed that "information on mobile banking," "perceived usefulness," and "perceived security" are statistically significant factors influencing users' intention to adopt mobile banking in the future [20].

Given the significance of these factors in shaping consumer behavior, it is important to explore how different user groups perceive online banking applications. Considering this, the hypotheses proposed in this research are the following:

Hypothesis 1: Mobile and computer/laptop users have different perceptions regarding the usability of online banking applications, specifically in terms of efficiency, availability, and ease of contact.

This hypothesis challenges the assumption that different devices (mobile vs. computer/laptop) may lead to significantly different user experiences when interacting with online banking applications. The type of device used to access online banking services can significantly affect how users perceive the efficiency, availability, and ease of contact of the application. There are findings that mobile applications have a stronger positive influence on customer engagement, customer experience,

and ultimately relationship quality, and loyalty [21], [22]. The study found that consumers' interactions with brands through mobile applications are more likely to foster higher levels of engagement and experience, which in turn enhances their loyalty and relationship quality with the brand [23].

Hypothesis 2: The length of time users have been using online banking applications influences their perceptions of the application's efficiency, availability, and ease of contact.

This hypothesis examines whether the duration of use influences users' perceptions of key factors such as efficiency, availability, and ease of contact in online banking applications. Many studies suggest that with increased experience, users may become more familiar with the system, leading to more positive perceptions of its features. For example, the Technology Acceptance Model (TAM) suggests that familiarity with an application can improve users' perceptions, especially regarding ease of use [12]. The assumption here is that prolonged usage might lead to a deeper understanding of the system, making users feel more comfortable with its functionalities, and in turn, influencing their perceptions of efficiency, availability, and ease of contact. Similarly, the Unified Theory of Acceptance and Use of Technology (UTAUT) indicates that as users gain experience with technology, they are more likely to perceive it as easier to use and more useful [24]. Confirmation of this hypothesis would imply that as users become more experienced with online banking applications, their perceptions of the service quality (efficiency, availability, and ease of contact) may improve.

Hypothesis 3: The frequency with which users access online banking applications significantly influences their perceptions of efficiency, availability, and ease of contact within the application.

The frequency of use is a crucial factor that can significantly influence how users perceive the efficiency, availability, and ease of contact within online banking applications. Research suggests that the more frequent users engage with an application, the more familiar they become with its features, which could, in turn, affect their perceptions of its performance and ease of use. Technology Acceptance Model (TAM) suggests that as users interact with a system more often, their comfort level increases, which may positively influence their evaluations of system attributes, such as ease of contact or availability [12]. Frequent users are more likely to understand the system's functionalities, leading to better assessments of how well the application

performs. Additionally, the Unified Theory of Acceptance and Use of Technology (UTAUT) argues that frequent use allows users to develop more positive attitudes toward technology, improving their perceptions of its efficiency and usability over time [24].

3. RESEARCH METHODOLOGY

The research was conducted using a questionnaire filled out by users of online banking services in the Republic of Serbia. The questionnaire consisted of three parts. The first part included questions related to the respondents: gender, age, and education. The second part focused on questions related to durability, frequency of use, and primary devices for accessing online banking applications. The third part of the questionnaire related to three scales named Efficiency, Availability and Ease of contact. Scales consisted of statements related to functionalities of online banking applications and were based on research [25]. The statements are presented in tables 6, 7 and 8.

The average time of filling out the questionnaire was 15 minutes. The questionnaire was distributed through professional and social networks. The respondents voluntarily participated in the research, with full consent for the use of their data for scientific research. In the period from August 2024 to March 2025, a total of 181 respondents answered the questionnaire.

The responses collected were analyzed using Microsoft® Excel® 2019 and Statistical Software for Social Sciences (SPSS), version 26. To assess the normality of the data distribution, the Kolmogorov-Smirnov test was performed. Since the results showed significance of $\text{Sig.}=0.000$, indicating that the normality assumption was not met, non-parametric methods were applied for statistical analysis. The Kruskal-Wallis test was employed to evaluate differences among three or more groups with a 95% confidence interval, while the Mann-Whitney test was used for comparisons between two groups. In addition to the Mann-Whitney and Kruskal-Wallis tests, effect sizes (r for Mann-Whitney and ϵ^2 for Kruskal-Wallis) were calculated to provide a more robust assessment of the magnitude of group differences. Levene's test for equality of variances confirmed that the assumption of homogenous variance was satisfied in all cases ($p > 0.05$) for the tests assessing group differences. Furthermore, bootstrapping with 1,000 resampling iterations was conducted to enhance the reliability of the estimates and confidence intervals. In addition, multivariate analysis was performed to examine the combined effects of multiple independent variables on the outcomes, thereby providing a more

comprehensive understanding of the relationships within the data.

Table 1 presents the Cronbach' Alpha coefficients for three scales related to online banking applications: Efficiency, Availability, and Ease of contact. All values of Cronbach Alpha coefficients are higher than the threshold of 0.70, indicating good to excellent internal consistency, making these scales reliable for assessing users' perceptions of online banking applications.

Table 1. Cronbach' Alpha coefficient

No	Scales	N	Cronbach' Alpha
1	Efficiency of online banking applications	4	0.876
2	Availability of online banking applications	4	0.814
3	Ease of contact within online banking applications	3	0.757

Table 2 reports the collinearity diagnostics. The variance inflation factor (VIF) was computed for the predictors across all measured scales. The VIF values ranged from 1.075 to 1.200, which are well below the conventional threshold of 5. This indicates that multicollinearity was not a concern, thereby reinforcing the reliability of the analysis.

Table 2. VIF values for predictors used in study

Predictor variable	VIF
Device used for online banking	1.075
Frequency of online banking use	1.200
Duration of online banking use	1.183

Table 3 presents the results of Kaiser-Meyer-Olkin Measure and Bartlett's Test of Sphericity.

The Kaiser-Meyer-Olkin measure of sampling adequacy was 0.612, indicating acceptable suitability for factor analysis. Bartlett's test of sphericity was significant ($\chi^2(3) = 35.373$, $p < 0.001$), confirming that correlations among items were sufficient to justify factor analysis.

Table 3. Measurement validation

		Results
Kaise-Meyer-Olkin results		0.612
Bartlett's test	Approx. Chi-Square	35,373
	df	3
	Sig.	0.000

4. RESEARCH RESULTS AND DISCUSSION

Table 4 presents a detailed overview of the key demographic characteristics of the respondents. In terms of gender distribution, the sample is predominantly female, comprising 62.4% of the respondents, while males make up 37.6%. The age distribution shows that the largest percentage of respondents is between the ages of 35 and 44 (41.5%), followed by respondents aged 45 to 54 years (24.3%). A smaller proportion of respondents are younger, with only 16.0% falling within the 18 to 24 years range, and 11.0% within the 25 to 34 years range. The least represented age group is those above 54 years, comprising only 7.2% of the sample. Regarding educational background, the sample is highly educated, with over half (51.4%) holding university degrees at the bachelor's and master's levels. Additionally, 17.7% of the respondents have completed doctoral studies, while 16.0% have completed secondary school and 14.9% college.

Table 4. Key information about the respondents

	N	%
Gender		
Male	68	37.6
Female	113	62.4
Age		
From 18 to 24 years	29	16.0
From 25 to 34 years	20	11.0
From 35 to 44 years	75	41.5
From 45 to 54 years	44	24.3
Above 54 years	13	7.2
Education		
Secondary school	29	16.0
College	27	14.9
University (bachelor and master studies)	93	51.4
University (doctoral studies)	32	17.7

Table 5 presents the respondents' experience with online banking applications, focusing on the duration of use. The largest group of respondents (38.1%) reports using online banking for less

than one year, indicating a relatively recent adoption of these applications. The second largest group (34.8%) has been using online banking for 5 to 10 years, reflecting a more

established familiarity with the applications. A smaller proportion of respondents (27.1%) have used online banking applications for 1 to 5 years.

Table 5. Answers to the question “How long have you been using online banking applications?”

Answers	N	%
Less than one year	69	38.1
From 1 to 5 years	49	27.1
From 5 to 10 years	63	34.8

Table 6 outlines the frequency with which respondents use online banking applications. The results reveal that nearly half of the respondents (49.8%) use online banking applications every day. A significant portion (35.9%) of respondents use online banking applications once or twice a week, showing that while they may not rely on it daily, they engage with the service regularly. Smaller groups of respondents report using online banking applications less frequently, with 9.9% using it once every two weeks and 4.4% using it once a month.

Table 6. Frequency of using online banking applications

Answers	N	%
Every day	90	49.8
Once or twice a week	65	35.9
Once every two weeks	18	9.9
Once a month	8	4.4

Table 7 illustrates the primary devices used by respondents to access online banking services. A striking 85.6% of respondents primarily use mobile phones to access online banking, indicating that mobile banking has become the dominant platform for managing financial transactions. In contrast, only 14.4% of respondents primarily use computers or laptops to access online banking services. This smaller percentage suggests that while computers and laptops remain an important tool for online banking, they are not as frequently used as mobile devices, likely due to the increasing use of mobile applications designed for quick and easy online banking access.

Table 7. The primary device used by respondents to access online banking services

Answers	N	%
Mobile phone	155	85.6
Computer/laptop	26	14.4

Table 8 provides descriptive statistics regarding the efficiency of online banking applications. For the statement “I can access the online banking application swiftly and with ease,” the mean value is 4.69, indicating a high level of agreement among respondents. The majority, 79.0%, rated this statement as a 5 (strongly agree), while only a small proportion (1.7%) selected a 1 (strongly disagree). For “Using the online banking application is straightforward,” the mean value is 4.62, with 72.9% of respondents strongly agreeing (rating it 5) and only 2.2% expressing strong disagreement (rating it 1). This reflects a similarly positive response, highlighting the ease of use of the application. Regarding the statement “The information in the online banking application is functionally and logically well-organized in terms of user experience,” the mean value is 4.28, suggesting that while most respondents find the organization of information functional, the ratings are slightly more varied. About 50.8% rated it 5 (strongly agree), but a larger proportion, 12.8%, rated it 3 (neutral), indicating that there are possibilities for improvement. Finally, for the statement “The online banking application allows me to quickly complete desired transactions at any time,” the mean value is 4.73, the highest among all statements, demonstrating a strong agreement. A substantial 81.8% of respondents strongly agreed with this statement (rating it 5), indicating that most users find the transaction process to be fast and efficient. Overall, the mean values and percentage distributions demonstrate a strong overall satisfaction with the efficiency of the online banking application, with users expressing approval of its accessibility, ease of use, and ability to quickly conduct transactions. However, the distribution also suggests that there are some areas, particularly in terms of information organization, where users may have varying experiences.

Table 8. Descriptive statistics regarding the efficiency of online banking applications

No	Statements	M	SD	Marks	N	%
1	I can access the online banking application swiftly and with ease.	4.69	0.734	1	3	1.7
				2	1	0.6
				3	8	4.4
				4	26	14.3
				5	143	79.0
2	Using the online banking application is straightforward.	4.62	0.762	1	4	2.2
				2	0	0.0
				3	7	3.9
				4	38	21.0
				5	132	72.9

3	The information in the online banking application is functionally and logically well-organized in terms of user experience.	4.28	0.890	1	2	1.1
				2	6	3.3
				3	23	12.8
				4	58	32.0
				5	92	50.8
4	The online banking application allows me to quickly complete desired transactions at any time.	4.73	0.682	1	2	1.1
				2	2	1.1
				3	6	3.3
				4	23	12.7
				5	148	81.8

Table 9 provides descriptive statistics regarding the availability of online banking applications. For the statement “The online banking application launches easily and without any issues,” the mean value is 4.46, indicating that most respondents have a positive experience with the application’s launch. A significant 61.8% of respondents strongly agreed (rating it 5), and only a small percentage (0.6%) strongly disagreed (rating it 1). For the statement “There are no interruptions or delays while using the online banking application,” the mean value is 4.00, suggesting a generally positive but slightly more varied response. While 40.3% of respondents agreed (rating it 4) and 35.4% strongly agreed (rating it 5), 16.0% gave a neutral rating (3), and a smaller portion (8.3%) expressed dissatisfaction (ratings of 1 or 2). Regarding the statement “The online banking application is always available and functional,” the mean value is 4.40, showing that the majority of respondents find the application to be consistently available. Most respondents (56.9%) strongly agreed (rating it 5), while 32.0% agreed

(rating it 4), indicating that reliability is a strength of the application. Only a small proportion (1.1%) strongly disagreed (rating it 1). For the statement “I consistently receive notifications about scheduled downtime for system upgrades or updates,” the mean value is 4.29, indicating that respondents generally receive notifications as expected. The majority (60.8%) strongly agreed (rating it 5), and 21.0% agreed (rating it 4). However, 8.8% of respondents were neutral (rating it 3), and a few (9.4%) rated it lower, suggesting that while most users are satisfied with the notifications, there is a small segment who may not always receive timely updates.

Overall, the results show strong positive feedback regarding the availability of the online banking application, with respondents particularly appreciating its ease of launch, functionality, and reliability. However, the responses also reveal slight variations, particularly concerning interruptions, delays, and notifications about system downtime.

Table 9. Descriptive statistics regarding the availability of online banking applications

No	Statements	M	SD	Marks	N	%
1	The online banking application launches easily and without any issues.	4.46	0.813	1	1	0.6
				2	6	3.3
				3	13	7.2
				4	49	27.1
				5	112	61.8
2	There are no interruptions or delays while using the online banking application.	4.00	0.994	1	5	2.8
				2	10	5.5
				3	29	16.0
				4	73	40.3
				5	64	35.4
3	The online banking application is always available and functional.	4.40	0.842	1	2	1.1
				2	6	3.3
				3	12	6.7
				4	58	32.0
				5	103	56.9
4	I consistently receive notifications about scheduled downtime for system upgrades or updates.	4.29	1.103	1	8	4.4
				2	9	5.0
				3	16	8.8
				4	38	21.0
				5	110	60.8

Table 10 presents the descriptive statistics regarding ease of contact via online banking applications. For the statement “The online

banking application has easily accessible chat support (online chatbot),” the mean value is 3.14, indicating that respondents’ experiences with the

accessibility of chat support are somewhat neutral or mixed. The distribution shows that 21.0% strongly disagreed (rating it 1), and 11.0% disagreed (rating it 2), while 26.5% rated it a 3 (neutral), suggesting that a substantial portion of respondents find the chat support somewhat difficult to access. On the other hand, 25.5% of users rated it as 5 (strongly agree), while 16.0% rated it as 4 (agree), suggesting that a portion of users had positive experiences. For the statement "The online banking application makes it easy to find the phone number or email contact for customer support," the mean value is 3.65, indicating a more positive but still somewhat varied experience. 37.7% of respondents strongly agreed (rating it 5), and 20.4% agreed (rating it 4), suggesting that many users can easily find contact details for support. However, 21.5% were neutral (rating it 3), and 20.4% gave lower marks (1 or 2), implying that a portion of users may have difficulty accessing these contact details. Regarding the statement "The online banking

application makes it easy to find the nearest branches," the mean value is 3.65, similar to the previous statement. 35.9% of respondents strongly agreed (rating it 5), and 21.5% agreed (rating it 4), suggesting that for many users, locating branches is not a significant issue. However, 24.4% rated it neutral (3), and 18.2% gave lower marks (1 or 2), indicating that some users find it challenging to find nearby branches through the application.

Overall, the results show that while the majority of respondents find it relatively easy to contact customer support and locate branch information through the online banking application, there is a notable portion of users who experience difficulty or are neutral about these features. The variation in responses suggests that improvements in accessibility for chat support, as well as contact and branch location details, could benefit some users.

Table 10. Descriptive statistics regarding the ease of contact via online banking applications

No	Statements	M	SD	Marks	N	%
1	The online banking application has easily accessible chat support (online chatbot).	3.14	1.456	1	38	21.0
				2	20	11.0
				3	48	26.5
				4	29	16.0
				5	46	25.5
2	The online banking application makes it easy to find the phone number or email address for customer support.	3.65	1.340	1	18	9.9
				2	19	10.5
				3	39	21.5
				4	37	20.4
				5	68	37.7
3	The online banking application makes it easy to find the nearest branches.	3.65	1.310	1	18	9.9
				2	15	8.3
				3	44	24.4
				4	39	21.5
				5	65	35.9

5. STATISTICAL RESULTS AND HYPOTHESES TESTING

Table 11 presents the results of the Mann-Whitney test, which was used to examine whether there are differences in the responses between users who access online banking via mobile phones and those who access it via computers/laptops. The test compares the mean ranks between the two groups for three different scales: Efficiency, Availability, and Ease of contact. For the Efficiency scale, the mean rank for mobile phone users is 4.62, while for computer/laptop users, it is 4.36. The Mann-Whitney Z value is -1.161, with an asymptotic significance (p-value) of 0.246. This p-value is greater than the typical significance threshold of 0.05, suggesting that there is no statistically significant difference between the two groups in terms of perceived efficiency when using an

online banking application. For the Availability scale, the mean rank for mobile phone users is 4.32, while for computer/laptop users, it is 4.13. The Mann-Whitney Z value is -0.354, with an asymptotic significance (p-value) of 0.723. Again, the p-value is greater than 0.05, indicating that there is no significant difference in how mobile phone and computer/laptop users perceive the availability of the online banking application. Regarding the Ease of Contact scale, the mean rank for mobile phone users is 3.54, while for computer/laptop users, it is 3.12. The Mann-Whitney Z value is -1.596, with an asymptotic significance (p-value) of 0.110. Although the p-value is below 0.05, it is still above the typical threshold of 0.05, indicating that there is no statistically significant difference between the two groups in terms of ease of contact with customer support via the online banking application.

Based on the findings from the Mann-Whitney

tests, hypothesis 1 is not confirmed - no statistically significant differences were found between mobile phone and computer/laptop users across the scales of efficiency, availability, and ease of contact. Effect size calculations ($r=-$

0.086 for efficiency, $r=-0.026$ for availability, $r=-0.119$ for ease of contact) indicate that observed differences are negligible, confirming the stability of the non-significant results.

Table 11. Mann-Whitney test results (device by which users access an online banking application)

Scale	Answers	N	Mean (M)	Median (Md)	Mann-Whitney	Z	Asymp. Sig.
Efficiency	Mobile phone	155	4.62	4.75	1743.000	-1.161	0.246
	Computer/laptop	26	4.36	4.75			
Availability	Mobile phone	155	4.32	4.50	1929.000	-0.354	0.723
	Computer/laptop	26	4.13	4.50			
Ease of contact	Mobile phone	155	3.54	3.67	1623.000	-1.596	0.110
	Computer/laptop	26	3.12	3.17			

Table 12 presents the results of the Kruskal-Wallis test, which was used to examine whether there are significant differences in the responses regarding the length of time users have been using online banking services. The Kruskal-Wallis test for the Efficiency scale shows a p-value of 0.171, which is above the 0.05 significance level. This indicates that there are no statistically significant differences in the perceived efficiency of online banking between users who have been using the service for different lengths of time. The mean ranks for each group (4.65 for less than one year, 4.49 for 1 to 5 years, and 4.57 for 5 to 10 years) are relatively close, suggesting that the length of use does not impact users' perception of efficiency.

The Kruskal-Wallis test for the Availability scale results in a p-value of 0.144, which is also greater than the 0.05 threshold. This suggests that there are no significant differences in how users perceive the availability of online banking services based on how long they have been using them. The mean ranks for the three respondent groups are as follows: 4.45 for users with less than one year of online banking experience, 4.14 for those with 1 to 5 years, and 4.23 for users with 5 to 10 years of experience. However, the lack of a significant difference

suggests that all user groups share similar experiences regarding the availability of online banking applications.

For the Ease of contact scale, the Kruskal-Wallis test yields a p-value of 0.423, which is far greater than the 0.05 significance level. This suggests that the length of time using the online banking service does not significantly affect users' perception of ease of contact with client support. The mean ranks for the three groups are 3.50 for less than one year, 3.63 for 1 to 5 years, and 3.35 for 5 to 10 years, but the lack of a significant difference indicates that all user groups have similar experiences in terms of contacting support.

The results do not confirm hypothesis 2, as they show no significant differences in users' perceptions of online banking services based on the length of time they have been using them. Users with different durations of experience (less than one year, 1 to 5 years, and 5 to 10 years) seem to have similar perceptions across all three scales. Effect size calculations ($\epsilon^2 = 0.009$ for efficiency, $\epsilon^2 = 0.011$ for availability, $\epsilon^2 = -0.002$ for ease of contact) indicate that the observed differences are negligible, confirming the stability of the non-significant results.

Table 12. Kruskal-Wallis test results (length of use of online banking)

Scale	Answers	N	Mean (M)	Median (Md)	Kruskal-Wallis	df	Asymp. Sig.
Efficiency	Less than one year	69	4.65	5.00	3.537	2	0.171
	From 1 to 5 years	49	4.49	4.75			
	From 5 to 10 years	63	4.57	4.75			
Availability	Less than one year	69	4.45	4.50	3.873	2	0.144
	From 1 to 5 years	49	4.14	4.25			
	From 5 to 10 years	63	4.23	4.50			
Ease of contact	Less than one year	69	3.50	3.67	1.720	2	0.423
	From 1 to 5 years	49	3.63	3.67			
	From 5 to 10 years	63	3.35	3.33			

Table 13 presents the results of the Kruskal-

Wallis test examining whether there are

significant differences in the perceptions of efficiency, availability, and ease of contact based on the frequency of use of online banking services. The Kruskal-Wallis test for the Efficiency scale has a p-value of 0.220, which is above the 0.05 significance level. This indicates that there are no significant differences in the perceived efficiency of online banking services based on the frequency of use. The mean ranks for each group are relatively similar (4.63 for daily users, 4.64 for weekly users, 4.28 for bi-weekly users, and 4.16 for monthly users), suggesting that users' perceptions of efficiency do not vary significantly depending on how often they use the service.

For the Availability scale, the Kruskal-Wallis test resulted in a p-value of 0.458, which is also greater than 0.05, suggesting that there are no significant differences in the perceived availability of the online banking service across the different usage frequencies. Users who access the service every day (mean rank of 4.32) report slightly higher perceptions regarding availability than those who use it less frequently (with lower means for weekly, bi-weekly, and monthly users),

but these differences are not statistically significant.

The Kruskal-Wallis test for the Ease of contact scale produced a p-value of 0.153, which is above 0.05. This suggests that the frequency of use does not have a significant impact on users' perceptions of how easily they can contact support. Although the mean ranks for the different groups vary slightly (e.g., daily users reporting 3.56 and monthly users reporting 3.63), the p-value indicates that these differences are not statistically significant.

In summary, the results of the Kruskal-Wallis tests indicate that the frequency of use, whether daily or once a month, does not significantly impact users' perceptions of efficiency, availability, or ease of contact with online banking services, leading to the rejection of hypothesis 3. Effect size calculations for Kruskal-Wallis tests indicated negligible differences across user frequency groups ($\epsilon^2 = 0.008$ for efficiency, $\epsilon^2 = 0.002$ for availability, $\epsilon^2 = 0.013$ for ease of contact). These results confirm that observed differences are minimal and support the robustness of the non-significant findings.

Table 13. Kruskal-Wallis test results (frequency of use of online banking)

Scale	Answers	N	Mean (M)	Median (Md)	Kruskal-Wallis	df	Asymp. Sig.
Efficiency	Every day	90	4.63	5.00	4.416	3	0.220
	Once or twice a week	65	4.64	4.75			
	Once every two weeks	18	4.28	4.75			
	Once a month	8	4.16	4.50			
Availability	Every day	90	4.32	4.50	2.595	3	0.458
	Once or twice a week	65	3.34	4.50			
	Once every two weeks	18	4.10	4.00			
	Once a month	8	3.94	4.13			
Ease of contact	Every day	90	3.56	3.67	5.267	3	0.153
	Once or twice a week	65	3.50	3.67			
	Once every two weeks	18	2.94	3.00			
	Once a month	8	3.63	3.83			

Bootstrapping was applied to assess the stability of the sample estimates. The procedure was conducted with a resampling size of 1,000 iterations, which provided sufficient variability for reliable inference. A 95% confidence interval was specified using a two-tailed approach. In addition, stratified sampling was employed because the age variable was divided into subgroups, ensuring that the resampling process preserved the proportional representation of each age category. Results are presented in Table 14. The mean values for gender ($M = 1.62$), education level ($M = 3.71$), and age category ($M = 2.96$) suggest a sample predominantly composed of middle-aged, highly educated individuals, with a

slight gender imbalance. Bootstrap bias values are negligible, and standard errors are low across all variables, indicating that the sample estimates are robust and not unduly influenced by resampling variability. The narrow 95% confidence intervals further reinforce the reliability of these estimates. However, the lack of variation in the age variable, evidenced by a zero standard error and fixed confidence interval, suggests a potential limitation in demographic diversity. This demographic concentration may affect the generalizability of the findings, particularly in contexts where online banking usage varies significantly across age and education levels.

Table 14. Descriptive statistics and bootstrap estimates for gender, education, and age

			Bootstrap			
			95% Confidence Interval			
Statistic			Bias	Std. Error	Lower	Upper
Gender	Mean	1.62	0.00	0.04	1.56	1.70
	Std. Deviation	0.486	-0.002	0.010	0.461	0.498
	N	181	0	0	181	181
Education	Mean	3.71	0.00	0.06	3.58	3.83
	Std. Deviation	0.941	-0.002	0.041	0.860	1.017
	N	181	0	0	181	181
Age	Mean	2.96	0.00	0.00	2.96	2.96
	Std. Deviation	1.134	0.000	0.000	1.134	1.134
	N	181	0	0	181	181

A multivariate analysis was conducted with the aim of examining the interplay among multiple independent variables simultaneously, rather than assessing each factor in isolation. This approach allowed the study to move beyond simple main effects and to explore whether the combined influence of length of use, frequency of use, and device type shaped user perceptions of efficiency, availability, and ease of contact. While the individual predictors did not yield significant main effects, the multivariate framework provided the opportunity to detect interaction effects that may reveal more complex dynamics. Multivariate results presented in Table 15 indicated no

significant main effects of length of use, frequency of use and device type on perceptions of efficiency, availability, and ease of contact (all p values are significantly higher than 0.05). However, the three-way interaction between length of use, frequency of use, and device type approached significance ($F(12,480) = 1.65$, $p = 0.075$), suggesting that user perceptions may be influenced by the combined effects of these variables rather than by any single factor. This result suggests that user perceptions may be contingent upon the joint influence of these variables.

Table 15. Multivariate effects of Length of use, Frequency of use, and Device type

Effect	F	df (Hyp, Err)	Sig.
Length of use	1.42	(6, 318)	0.207
Frequency of use	1.16	(9, 480)	0.316
Device type	0.27	(3, 158)	0.844
Length × Frequency	0.66	(15, 480)	0.819
Length × Device	1.56	(6, 318)	0.159
Frequency × Device	1.53	(9, 480)	0.134
Length × Frequency × Device	1.65	(12, 480)	0.075

6. DISCUSSION AND IMPLICATIONS

The results obtained from statistical tests provide several insights. Firstly, the Mann-Whitney test revealed no significant differences between users who access online banking services via mobile phones and those who use computers or laptops. Secondly, the Kruskal-

Wallis test assessing differences in perceptions based on the length of use of online banking services found no significant effects across any of the three scales. Lastly, the Kruskal-Wallis test examining the impact of frequency of use on user perceptions also revealed no significant differences. The summary of the findings related to the hypotheses is presented in Table 16.

Table 16. Results of hypothesis testing

Hypothesis	p-values	Decision
Hypothesis 1: Mobile and computer/laptop users have different perceptions regarding the usability of online banking applications, specifically in terms of efficiency, availability, and ease of contact.	0.246 (efficiency) 0.723 (availability) 0.110 (ease of contact)	Not supported
Hypothesis 2: The length of time users have been using online banking applications influences their perceptions of the application's efficiency, availability, and ease of contact.	0.171 (efficiency) 0.144 (availability) 0.423 (ease of contact)	Not supported
Hypothesis 3: The frequency with which users access online banking applications significantly influences their perceptions of efficiency, availability, and ease of contact within the application.	0.220 (efficiency) 0.458 (availability) 0.153 (ease of contact)	Not supported

The findings indicate a high level of consistency in user experiences across different groups, suggesting that factors such as device choice, length of experience, and frequency of use do not substantially influence evaluations of online banking applications. These results are in line with previous research, which highlights the importance of service personalization, a clear value proposition, and strong service quality in driving the adoption of digital banking platforms [26], [27]. Complementary evidence from a study of 196 online banking users in Serbia further revealed that flexibility, transaction speed, and ease of use are the key determinants of client satisfaction [28]. Evidence from a study in Serbia, based on a sample of 25 banks, revealed that institutions prioritizing digital transformation and sustainability achieved greater profitability [29]. In addition, many banks have recognized the necessity of adapting to a rapidly evolving technological environment and embracing strategies that foster a customer-centered approach [30]. This shift is driven by the growing consensus that technology will play a dominant role in shaping customer experiences [31]. Key dimensions of effective online banking include user-friendly interfaces, strong security measures, protection of privacy, well-structured organizational websites, and responsive electronic customer service, all of which are critical to enhancing customer trust and satisfaction [32].

The theoretical implications of this paper suggest that user perceptions of online banking applications may be less influenced by factors such as the device used, length of use, or frequency of use than previously assumed. This challenges the common belief that these factors play a significant role in shaping user evaluations of key aspects like efficiency, availability, and ease of contact. The findings imply that user experiences with online banking applications are more universally shaped by inherent service

quality, rather than external factors. This could prompt a reevaluation of existing theories on user experience in digital banking, highlighting that consistent user satisfaction across diverse usage patterns may stem from the fundamental design and functionality of the service, rather than individual behavioral differences.

From a practical standpoint, the results suggest that online banking service providers may not need to tailor their platforms to different user types or habits. Instead, efforts to improve service quality should focus on enhancing the core features of the platform to ensure a consistent and positive experience for all user groups. IT experts should prioritize enhancing general usability features (efficiency, availability, and ease of contact) that appeal to all users, rather than focusing on factors like usage duration or frequency. The development of online banking applications typically involves several types of IT professionals who work together to design, develop, test, secure, and optimize online banking applications, ensuring they meet user needs while complying with industry standards and regulations. Based on the findings, Software Developers/Engineers should focus on developing a consistent, cross-platform user experience. There is no need to prioritize one platform over the other, as user perceptions are similar across devices. UI/UX designers should ensure that the application design is optimized for both mobile and desktop platforms, offering a seamless user interface and experience across devices. Since frequency of use does not affect perceptions, the key message for Quality Assurance Testers is to focus on ensuring that all user experiences, whether frequent or infrequent, are equally satisfying and functional. DevOps Engineers should ensure that performance and stability are consistent for all users, regardless of usage frequency.

7. CONCLUSION

This paper aimed to investigate various factors influencing user perceptions of online banking applications, specifically focusing on the differences in efficiency, availability, and ease of contact based on the mode of access (mobile phone vs. computer/laptop), the length of use, and the frequency of use. The questionnaire was completed by 181 online banking application users in the Republic of Serbia, in the period from August 2024 to March 2025. The results revealed no statistically significant differences between mobile and computer/laptop users in terms of efficiency, availability, and ease of contact; the length of time using online banking did not affect users' perceptions of these factors; and the frequency of use also had no significant impact on users' experiences. The findings suggest that users across different usage patterns generally have similar experiences and perceptions regarding online banking applications.

While this study offers valuable insights into digital banking usage, certain limitations must be acknowledged. The sample of 181 respondents is largely composed of middle-aged individuals with higher education, reflecting the profile of the most active digital banking users in the Republic of Serbia. This composition enables a detailed case-focused analysis of the dominant user group but limits the generalizability of findings to younger and older populations, as well as those with lower educational attainment. The predominance of respondents aged 35–54 aligns with the fact that professionally active, well-educated individuals are the primary adopters of digital financial services. Their financial capacity and technological literacy make them a critical segment for understanding adoption patterns, and the high proportion of university and postgraduate degree holders enhances the reliability of the data. However, the demographic composition of the sample introduced notable limitations to the study's findings. Specifically, the disproportionate representation of respondents aged 35–54, alongside a high concentration of individuals with university or postgraduate qualifications, limits the generalizability of the results, particularly when considering the global distribution of online banking users, which encompasses a broader range of age groups and educational backgrounds. Consequently, the conclusions drawn may overemphasize the perspectives of more educated, middle-aged participants while underrepresenting categories that differ significantly from these groups. This imbalance underscores the need for caution in interpreting the results and highlights the

importance of achieving more representative sampling in future research. Furthermore, the study relies on self-reported data collected through a questionnaire, which could introduce biases, such as social desirability answers. Future research should incorporate mixed research methods, such as combining self-reported questionnaires with interviews or focus groups, which could offer deeper, more context-rich insights into user experiences with online banking applications.

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Ranking of Artificial Intelligence Researchers in Serbia in 2025

Mester, Gyula

Abstract: *The paper presents the ranking of Artificial Intelligence researchers in Serbia for 2025. The ranking is presented primarily according to the researchers' h-index. Researchers with matching h-index are ranked by the number of citations. The minimum h-index of the 15 ranked researchers is 17. The h-index can be determined from the following online databases: Web of Science, Scopus, Google Scholar and the Publish or Perish program. The h-index, also known as the Hirsch index, is based on references. The ranking will be edited using the Google Scholar web database. Google Scholar is Google's scientific search engine, launched in 2004. We also present the ORCID iD number and the g-index of the researchers.*

Index Terms: *Artificial Intelligence, citations, h-index, Google Scholar, ORCID iD, ranking of Artificial Intelligence researchers in Serbia for 2025.*

1. INTRODUCTION

THE paper presents the ranking of Artificial Intelligence researchers in Serbia for 2025.

Artificial Intelligence is transforming higher education, creating new opportunities and challenges for students, teachers, and institutions. The use of Artificial Intelligence in higher education should not be restricted. Every student uses and every teacher uses Artificial Intelligence.

Publishing new scientific results is one of the manifestations of scientific creativity. Scientific metrics is essential to measure the quantity and quality of scientific output. Science metrics measure the:

- quantity of scientific publications - the number of publications and
- their quality: citation rate, h-index, g-index.

An effective way to measure scientific performance is to measure citations, because if someone is cited by other scientists a lot, they are probably better researchers. The ranking of researchers is primarily presented according to the h-index of researchers.

The h-index is the largest number h , indicating

that h number of publications contain at least h citations. It can be determined from the following online databases/programs: Web of Science, Scopus, Google Scholar, and Publish or Perish.

The h-index, also known as the Hirsch index, is based on references. The h-index was published by physicist Jorge E. Hirsch (University of California, San Diego) in 2005:

"A scientist has index h if h of his/her N papers have at least h citations each, and the other $(N-h)$ papers have no more than h citations each".

Thus, the h-index is the highest h number, indicating that h publications have at least h citations and all other scientific publications by the same author have, by definition, fewer than h citations.

Hirsch suggested that the index was originally intended to compare individual performance only, but that it could also be used to determine the h-index of:

- research groups,
- journals,
- disciplines,
- institutions, and
- countries.

The original h-index does not distinguish between dependent and independent citations, i.e. it also takes self-citations into account.

In the case of a matching h-index, researchers are ranked by the number of citations. The minimum h-index of the top 15 ranked researchers is 17. The ranking is constructed using the Google Scholar database [1] and the Publish or Perish program [2]. Google Scholar is Google's scientific search engine, launched in 2004, which displays the researcher's scientific publications, citations, h-index, and i10-index.

The first chapter is the introduction, the second chapter presents the ranking [3-10] of Artificial Intelligence researchers in Serbia for 2025, and the third chapter summarizes the results of the research.

2. RANKING OF ARTIFICIAL INTELLIGENCE RESEARCHERS IN SERBIA FOR 2025

The paper presents the ranking of Artificial Intelligence researchers in Serbia for 2025.

Artificial Intelligence is transforming higher education, creating new opportunities and challenges for students, teachers, and

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institutions.

The 2025 ranking of Artificial Intelligence researchers in Serbia is presented primarily by the h-index of researchers. The ranking has been constructed using the Google Scholar database [11-19]. Researchers with matching h-index are ranked by the number of citations [20-34]. The minimum h-index of the ranked researchers is 17. Fifteen researchers are included in the list.

We also present the ORCID iD number [3] and

the g-index of the Artificial Intelligence researchers of Serbia for 2025.

The g-index is calculated based on the distribution of citations received by a given researcher's publications, such that given a set of articles ranked in decreasing order of the number of citations that they received. The g-index is the largest number such that the top g articles received together at least g^2 citations [2].

1. Nebojsa Bacanin

h-index = 65,

g-index = 96,

citations: 1412.

ORCID iD: 0000-0002-2062-924X



Nebojsa Bacanin

Faculty of Informatics and Computing, [Singidunum University](#), vice-rector for scientific research

Verified email at [singidunum.ac.rs](#) - [Homepage](#)

[Artificial Intelligence](#) [Swarm Intelligence](#) [Digital Image Processing](#) [Optimization Metaheuristics](#)
[Deep Learning](#)



Cited by

	All
Citations	14012
h-index	65
i10-index	265

2. Vladimir Stojanovic

h-index = 64,

g-index = 92,

citations: 8516.

ORCID iD: 0000-0002-6005-2086



Vladimir Stojanovic

Prof. of Aut. Control, Faculty of Mechanical and Civil Eng. in Kraljevo, Univ. of Kragujevac, Serbia

Verified email at [mts.rs](#)

[Computer Science](#) [Intelligent Control](#) [Artificial Intelligence](#) [Machine Learning](#) [Robotics](#)



Cited by

	All
Citations	8516
h-index	64
i10-index	83

3. Gyula Mester

h-index = 62,

g-index = 72,

citations: 6290.

ORCID iD: 0000-0001-7796-2820



Gyula Mester (Orcid ID: 0000-0001-7796-2820)

Professor, [University of Szeged](#), Óbuda University, Hungary, University of Novi Sad, Serbia

Verified email at [inf.u-szeged.hu](#) - [Homepage](#)

[Self-Driving Cars](#) [Flying Cars](#) [Artificial Intelligence](#) [Intelligent Robots](#) [Citation Analysis](#)



Cited by

	All
Citations	6290
h-index	62
i10-index	112

4. Milan Tuba

h-index = 56,

g-index = 82,

citations: 8535.

ORCID iD: 0000-0003-3794-3056



Milan Tuba

[Singidunum University](#), Vice Rector for International Relations, Serbia
Verified email at singidunum.ac.rs

[Artificial Intelligence](#) [Swarm Intelligence](#) [Digital Image Processing](#) [Optimization Metaheuristics](#)
[Computer Networks](#)



Cited by

	All
Citations	8535
h-index	56
i10-index	151

5. Vladan Devedzic

h-index = 37,

g-index = 79,

citations: 6705.

ORCID iD: 0000-0002-5790-0240



Vladan Devedzic

Professor of Computer Science, [University of Belgrade](#), Serbia
Verified email at fon.bg.ac.rs - [Homepage](#)

[Artificial Intelligence](#) [Education](#) [Software Engineering](#)



Cited by

	All
Citations	6705
h-index	37
i10-index	89

6. Igor V. Pantić

h-index = 32,

g-index = 71,

citations: 5325.

ORCID iD: 0000-0001-6589-8964



Igor V. Pantić

[University of Belgrade](#), Serbia; [University of Haifa](#), Israel; [Ben-Gurion University](#), Israel
Verified email at med.bg.ac.rs - [Homepage](#)

[Physiology](#) [Psychiatry](#) [Artificial Intelligence](#)



Cited by

	All
Citations	5325
h-index	32
i10-index	68

7. Zarko Cojbasic

h-index = 30,

g-index = 53,

citations: 3262.

ORCID iD: 0000-0002-4581-1048



Zarko Cojbasic

[University of Nis](#), Mechanical Engineering Faculty, Serbia
Verified email at ni.ac.rs

[artificial intelligence](#) [robotics](#) [control systems](#) [biomedical engineering](#)



Cited by

	All
Citations	3262
h-index	30
i10-index	64

8. Zoran Miljkovic

h-index = 27,

g-index = 49,

citations: 2730.

ORCID iD: 0000-0001-9706-6134



Zoran Miljkovic

Full Professor of Robotics and AI, [University of Belgrade-Faculty of Mechanical Engineering](#)
Verified email at mas.bg.ac.rs - [Homepage](#)

[Robotics](#) [Artificial Intelligence](#) [Intelligent Manufacturing S...](#) [Autonomous Systems](#)
[Machine Learning](#)



Cited by

	All
Citations	2730
h-index	27
i10-index	44

9. Aleksandar Rodić

h-index = 23,

g-index = 39,

citations: 2005.

ORCID iD: 0000-0002-5595-9224



Aleksandar Rodić (Orcid: 0000-0002-5595-9224)

University of Belgrade, Institute Mihajlo Pupin, Serbia
Verified email at pupin.rs - [Homepage](#)

[Robotics](#) [Humanoid and Personalize...](#) [Unmanned Autonomous Sy...](#) [Artificial Intelligence](#)



Cited by

	All
Citations	2005
h-index	23
i10-index	50

10. Ugljesa Marjanovic

h-index = 23,

g-index = 41

citations: 1946.

ORCID iD: 0000-0003-0009-7773



Ugljesa Marjanovic (Orcid: 0000-0002-8389-6927)

Professor of Production Management at the [University of Novi Sad, Novi Sad](#), Serbia
Verified email at uns.ac.rs - [Homepage](#)

[Production Management](#) [Artificial Intelligence](#) [Servitization](#) [Innovation](#) [Digital Education](#)



Cited by

	All
Citations	1946
h-index	23
i10-index	43

11. Vladimir Kurbalija

h-index = 19,

g-index = 30,

citations: 1087.

ORCID iD: 0000-0002-9599-4495



Vladimir Kurbalija

Full professor, [University of Novi Sad](#), Serbia
Verified email at dmi.uns.ac.rs - [Homepage](#)

[Artificial Intelligence](#) [Case Based Reasoning](#) [Time Series](#)



Cited by

	All
Citations	1087
h-index	19
i10-index	34

12. Jelena Pisarov

h-index = 18,

g-index = 32,

citations: 1069.

ORCID iD: 0000-0003-2757-9780



Jelena Pisarov (Orcid: 0000-0003-2757-9780)

Teacher of Physics and IT / [University Óbuda Budapest Hungary](#) & [University of Novi Sad](#)
Serbia
Verified email at nexttechnologies.hu - [Homepage](#)

[Artificial Intelligence](#) [Self-Driving Cars](#) [Safety and Security Sciences](#) [Safety Systems](#) [Flying Cars](#)



Cited by

	All
Citations	1069
h-index	18
i10-index	19

13. Matija Štrbac

h-index = 18,

g-index = 32,

citations: 1056.

ORCID ID: 0000-0002-6831-1943



Matija Štrbac

Tecnalia Serbia Director
Verified email at tecnalia.com

Biomedical Engineering Computer Vision Artificial Intelligence



Cited by

	All
Citations	1056
h-index	18
i10-index	24

14. Branislav Kisacanin

h-index = 17,

g-index = 37,

citations: 1427.

ORCID ID: 0000-0001-7532-1106



Branislav Kisacanin

Nvidia, Faculty of Technical Sciences, University of Novi Sad, and Institute for AI R&D of Serbia
Verified email at nvidia.com

artificial intelligence computer vision autonomous driving embedded vision



Cited by

	All
Citations	1427
h-index	17
i10-index	22

15. Milan Vukicevic

h-index = 17,

g-index = 29,

citations: 874.

ORCID ID: 0000-0002-1631-6531



Milan Vukicevic

Faculty of Organizational Sciences, University of Belgrade, Belgrade, Serbia
Verified email at fon.bg.ac.rs

data mining machine learning meta learning business intelligence artificial intelligence



Cited by

	All
Citations	874
h-index	17
i10-index	22

3. CONCLUSION

The paper presented the ranking of Artificial Intelligence researchers in Serbia for 2025. The ranking is presented primarily according to the researchers' h-index. Researchers with a matching h-index are ranked by the number of citations.

The minimum h-index of the 15 ranked researchers is 17. The ranking is edited using the Google Scholar web database and the Publish or Perish program.

We also presented the ORCID iD numbers and the g-indexes of the researchers.

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